A FIRST STUDY OF NATURAL AND HYBRID VENTILATION SYSTEMS IN THE URBAN ENVIRONMENT

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Abstract
An experimental campaign was organized during the summer period 2002 in Athens, in the framework of the European RESHYVENT Project. The main purpose was to indicate the impact of the urban environment on the natural and hybrid ventilation air flow process in urban canyons. Field and indoor experimental procedures were carried out in two urban canyons, presenting different geometric and urban features. The experiments were organized for more than three consecutive days within three different periods in summer and on a 24-hour basis. Meteorological data around the buildings, inside and outside the street canyons were measured. A number of 114 ventilation experiments were conducted in three urban dwellings, consisting of natural, hybrid and mechanical ventilation, together with indoor environmental measurements. A first analysis of the observed airflow characteristics and the mechanisms driving the airflow inside canyons, as well as, of the estimated air changes for the applied ventilation systems is presented for one of the two studied canyons. The results of the second canyon are in process and will be compared with the present canyon in a future research in order to have general conclusions for the performance of these systems in canyons with different geometric characteristics under various outdoor urban conditions.

Keywords: Urban street canyons; Hybrid ventilation; Field experiments; Ventilation measurements; Airflow characteristics; Air exchange rates.

1. Introduction

The major purpose of the experimental procedures was to indicate the impact of a number of factors that influence natural and hybrid ventilation air flow process in urban canyons. Namely, the influence of the following parameters on the efficiency of the applied ventilation system has been investigated on an experimental basis:

- Canyon geometry
- Canyon orientation
- Air temperature inside/outside canyon
- Wind velocity inside/outside canyon
- Wind incidence angle
- Outdoor air Characteristics
- Ventilation configuration

This paper describes the experimental procedures carried out and presents a first analysis about the temperature distribution and airflow patterns in one of the two urban street canyons. The investigation and understanding of the air flow process in urban canyons is prerequisite and essential for the study of the impact of the urban conditions on the efficiency of natural and hybrid ventilation systems. Furthermore, the estimated airflow rates for the total number of ventilation measurements are presented and a comparison analysis for the different ventilation patterns is made based on single and multi-zone methodologies.

2. Description of experiments

Experiments were organized and carried out in two different urban canyons near the centre of Athens presenting different urban features (Table 1). The total experimental campaign was based on a number of field and indoor experiments.

Table 1
Characteristics of the studied urban canyons.

Canyon	Name	Region	H/W	L/W	Orientation	Category
1.	Ragavi	Gizi	1.4	3.8	ESE –WNW 280° to the North	Symmetrical
2.	Agiou Fanouriou	Pagrati	2.6	9.5	NW- SE 137° to the North	Deep

2.1 Field Measurements

The field experiments that have been performed could be classified in the following categories:

a. Air temperature measurements monitored inside the urban canyon at four different heights (namely at 3.5, 7.5, 11.5 and 15.5 m) from the ground level. The meteorological equipment was installed on a telescopic mast appended onto a mobile meteorological station.
b. Surface temperature measurements conducted with an infrared thermometer at street level along and across the canyon axis and on the building's facades from the ground to the top floor.
c. Wind speed measurements were carried out inside and outside the urban canyon. The horizontal wind speed and direction, V, was measured at the centre of canyon at four different heights (namely at 3.5, 7.5, 11.5 and 15.5 m) from the ground level. The wind speed components (u, v, w) were also measured near the canyon's facades at a distance of 1-2 m from the exterior walls by two 3-axis anemometers. A cup anemometer was used to measure the horizontal wind speed and direction out of the canyon.
d. Outdoor air characteristics were measured through CO_2, CO and TVOC's concentrations inside the urban canyon in the vicinity of the experimental zones with the multi-tracer gas system (Bruel & Kjaer).

Figure 1. Agiou Fanouriou urban canyon and the telescopic mast.

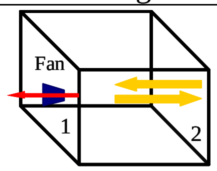
Figure 2. The three-axis anemometer on the right side of Ragavi street (SSW canyon's façade).

2.2 Indoor Measurements

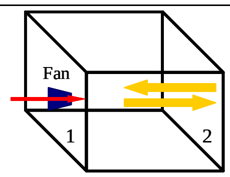
The indoor experimental process was based on indoor climate and ventilation measurements aiming to investigate the impact of the urban environment on the applied ventilation system's efficiency. Namely, the following set of measurements were performed in each experimental zone at the same time with the field experiments:

a. <u>Air temperature</u> was measured during the experimental period at various points in the studied apartments.
b. <u>Surface temperatures</u> were measured on the internal building walls, floor and ceiling.
c. <u>Ventilation experiments</u>, consisting of natural, hybrid and mechanical ventilation using two tracer gases (N2O and SF6) based on the decay method. Two tracer gas systems have been used the a) multi-tracer gas system (Bruel & Kjaer) and the b) single-tracer gas system (BBRI).
d. <u>Indoor air quality</u> was specified through the monitoring of CO_2, CO and TVOC's concentration at different sampling positions in the indoor environment.

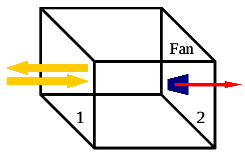
The studied hybrid ventilation system was fan-assisted natural ventilation, where supply and extract fans were used to enhance pressure differences by mechanical fan assistance. A total number of 12 hybrid ventilation configurations were studied in the three urban dwellings as shown in Figure 3.



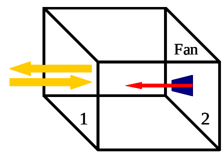
a. Mechanical Exhaust at canyon façade (1) & Natural Ventilation at backyard's façade (2).



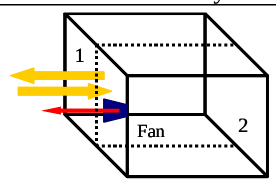
b. Mechanical Inlet at canyon façade (1) & Natural Ventilation at backyard's façade (2).



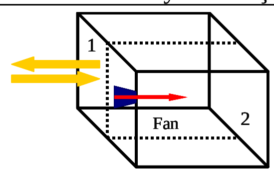
c. Natural Ventilation at canyon façade (1) & Mechanical Exhaust at backyard's façade (2).



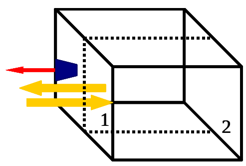
d. Natural Ventilation at canyon façade (1) & Mechanical Inlet at backyard's façade (2).



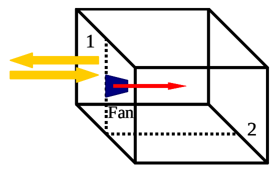
e. Natural Ventilation & Mechanical Exhaust at canyon façade (1).



f. Natural Ventilation & Mechanical Inlet at canyon façade (1).



g. Natural Ventilation & Mechanical Exhaust at canyon façade (1).



h. Natural Ventilation & Mechanical Inlet at canyon façade (1).

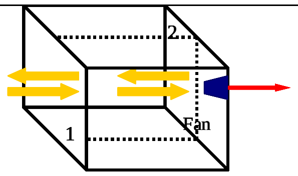
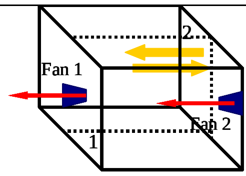
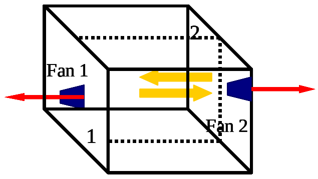
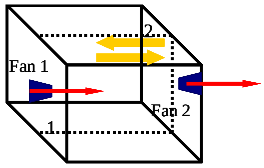
	
i. Natural Ventilation at canyon (1) and at backyard's façade (2) & Mechanical Exhaust at backyard's façade (2).	**j.** Mechanical Inlet at canyon (1) and at backyard's façade (2) & Natural Ventilation at backyard's façade (2).
	
k. Mechanical Exhaust at canyon (1) and at backyard's façade (2) & Natural Ventilation at backyard's façade (2).	**l.** Mechanical Inlet at canyon (1) & Mechanical Exhaust & Natural Ventilation at backyard's façade (2).

Figure 3. The hybrid ventilation systems studied at the ventilation experiments in the three dwellings during summer 2002 in Athens.

3. Analysis of the field experiments

A short description of the methodology followed for the analysis of the field experiments at Ragavi urban canyon is given in the following paragraphs. A detailed representation of the experimental site and of the field measurements during the period 19-23 July 2002 is given in Figure 4.

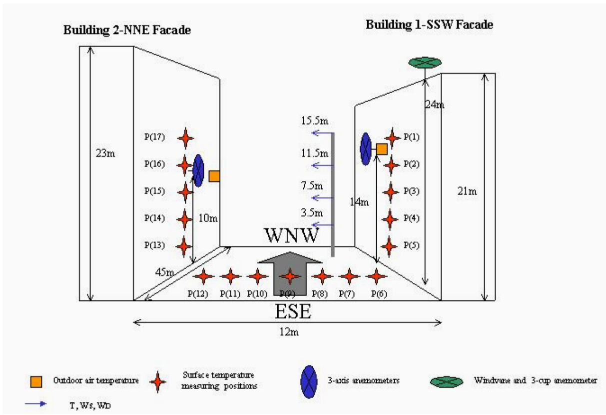


Figure 4. A schematic representation of the field experiments performed at Ragavi urban canyon within the period 19-23/7/2002.

3.1 Analysis of surface temperatures

3.1.1 Surface temperatures at street level

The surface temperatures, measured at a cross section from SSW to NNE façade, were performed at a number of seven points on materials consisted of dark pavement tiles near the two opposite buildings and of asphalt tiles on the street (Figure 4). During the 24-hour period, the absolute maximum surface temperature measured was, as high as 64^{o}C, while the absolute minimum temperature was close to 26^{o}C. Maximum daily amplitudes at the different measured points varied between 29^{o}C and 31^{o}C due to the incident solar radiation. The differences between the daily maximum temperature values across the canyon reached up to 33^{o}C, as a function of the materials' optical and physical properties and the variability of solar radiation. However, for the same construction materials the corresponding values ranged between 9^{o}C at the sidewalks to 28^{o}C at the asphalt street.

3.1.2 Surface temperatures on the canyon facades

The surface measurements of the canyon opposite facades have been performed from the ground level up to the forth floor on each canyon façade and on an hourly basis. Surface temperatures vary as a function of the incident solar radiation and the optical characteristics of the building materials used on the opposite canyon external walls.

As expected, the SSW façade presented higher temperatures than the opposite façade. The absolute maximum surface temperatures measured during the day period are 35°C and 39°C, respectively for the NNE and SSW facing walls. The corresponding absolute minimum surface temperature values during the night period are 24°C and 26°C. The maximum daily surface temperature ranges are 13°C at the SSW and 7°C at the NNE facade, while during the night period these values are close to 6°C and 5°C. The temperature differences of the two opposite walls presented the highest value at the fourth floor of the two opposite buildings and the lowest at the first floor. This can be attributed to the fact that the lower level surfaces receive much less radiation than the upper levels and thus the upper floors present higher surface temperatures. Taking into account that the NNE façade receives lower radiation levels, this justifies the highest temperature difference of the upper floors. Also, surface temperature decreases as a function of height within the canyon. This could be explained by the fact that lower level surfaces have lower sky view factors and thus radiative losses to the sky are lower.

3.2 Analysis of air temperatures

The absolute maximum value of air temperature inside canyon during the day is found 36.9°C (at 3.5m near the centre of canyon), while the absolute minimum is 31.4°C (at 10m near the NNE façade). In the night period the absolute maximum measured air temperature is 30°C, while the minimum is 26°C. The average values at the various measured levels range from 29.2°C (at 10m) to 33.9°C (at 3.5m). The mean air temperature at the four measured levels at the centre of canyon is shown in Table 2.

Table 2

Mean air temperatures during day and night at the centre of canyon.

Measured level	3.5m	7.5m	11.5m	15.5m
Day	31.9°C	31.5°C	31.8°C	31.6°C
Night	27.6°C	27.3°C	27.6°C	27.4°C

Based on the F-test of the differences of the means (Zar, 1974), the differences between the mean air temperatures at the four measured levels are considered statistically significant.

The air temperature stratification has been found up to 1.5°C during the day and 0.7°C during the night between the lower and the upper level near canyon main axis (3.5m-15.5m). Usually the higher temperatures are observed near the ground level (at 3.5m) and the lower at the higher air layers (at 15.5m). The air temperature distribution across the canyon main axis shows that the SSW façade presents higher air temperatures in comparison to the NNE facade but differences rarely exceed 1.4°C.

3.3 Wind Distribution

3.3.1 Wind Flow out of the canyon

The predominant wind direction is from Southwest, with a relative frequency of 25%. Absolute maximum ambient wind speeds are measured up to 30m s^{-1}. However, from the total wind speeds, 90% of the data is lower than 9m $s^{-1}$and almost 50% lower than 3m s^{-1}.

3.3.2 Flow field inside the urban canyon

In order to study in more detail the air flow field inside the urban canyon a classification of the undisturbed wind speed is made relative to the canyon long axis. Thus, the airflow characteristics inside the street canyon are discussed for parallel, perpendicular and oblique ambient winds.

3.3.2.1 Parallel Flow

The ambient flow parallel to the main axis of the urban canyon is either from western ($280^o \pm 20^o$) or eastern directions ($100^o \pm 20^o$). The number of uplifts, downlifts and calms near the two canyon facades is given in Table 3.

Table 3

Uplifts, downlifts and calms near the opposite canyon facades for the two classes of parallel flow.

	$100^o \pm 20^o$		**$280^o \pm 20^o$**	
	SSW Facade	NNE Facade	SSW Facade	NNE Facade
Uplifts (%)	43	1	54	7
Calms (%)	21	87	16	71
Downlifts(%)	36	12	30	21

What is really interesting is the total number of calms near the NNE façade. This can be explained by the lower surface temperatures at this façade because of the lower radiation levels. The uplift motion along the canyon walls is explained, as the airflow is retarded by friction at the building walls and at the street surface. The downward air movements observed close to the canyon walls for the two classes of parallel flow can be attributed to intermittent vortices created at the building corners and are responsible for the mechanism of downward advection flow from the building corners to the mid-block position in the canyon.

3.3.2.2 Perpendicular Flow

For perpendicular ambient wind speeds, the mechanisms determining the airflow characteristics are either the creation of a circulatory vortex or the “end” canyon effects (Santamouris, 2001). The vortex is established in the canyon because of the transfer of momentum across a shear layer of roof height. The “end” canyon effects are related to intermittent vortices shed on the building corners to mid-block creating a convergence zone in the mid block region of the canyon (Yamartino et al., 1986; Hoydysh et al., 1988). In deep canyons, wind tunnels research (Chang et al., 1971) and field studies, (De Paul et al., 1986) have found two vortices developed, an upper one driven by ambient airflow and a lower one driven in the opposite direction by the circulation above. Also the study of the air flow characteristics in a deep pedestrian canyon showed that for perpendicular wind speeds a circulatory vortex is created driven by the ambient air flow (Santamouris et al., 1999).

In the present experiment, the perpendicular ambient flow is either from northern ($10^o \pm 20^o$), or southern directions ($190^o \pm 20^o$). The measured data inside canyon show an along canyon flow with direction from WNW to ESE, as shown in Figures 5-6. In case of the southern ($190^o \pm 20^o$) directions, a secondary flow is found near the NNE façade, blowing from ESE directions (Figure 6).

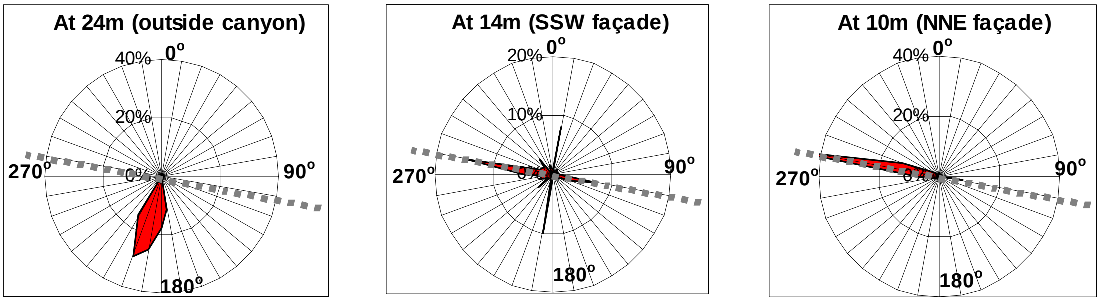


Figure 5. Horizontal wind direction outside canyon and near canyon facades, when the ambient wind comes from southern directions (190°±20°).

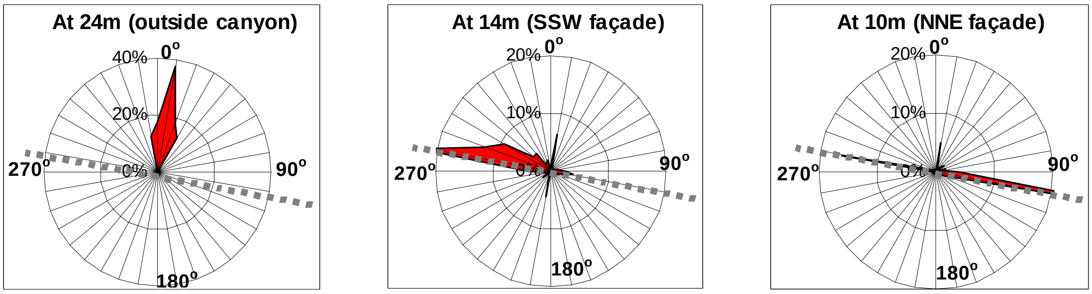


Figure 6. Horizontal wind direction outside canyon and near canyon facades, when the ambient wind comes from northern directions (10°±20°).

Considering the ambient flow coming from the South and normal to the canyon axis, it is found that in almost 40% of the cases the air moves down near the SSW façade, while the along wind speed is from the WNW to ESE direction (280° to 100°). The measured air speed across the canyon near SSW facade, v, is either parallel or opposite to the ambient flow indicating that no vortex motion is developed inside the canyon. Taking into account that the position of the 3-axis anemometer is 12m from the right side corner of the street canyon, when its total length is 45m, it seems that the observed airflow characteristics at the measured positions are mostly related with the "end" canyon effects rather than a circulatory vortex. Except for the "end" canyon length effects, it has been found that the increased surface temperatures near the windward façade, especially on the ground level, and the vertical stratification up to 5°C near the south facing wall have an important role on the upward movements. Regarding the NNE façade, it is found than in 46% of the cases the air moved down, while the along canyon wind speed direction is again from the WNW to ESE directions. Again the across canyon speed, v, is either positive (from north to west) or negative (from south to west).

A rather important correlation is found between the along canyon air speed u, and the vertical air speed, w, (Figure 7). Considering that the position the 3-axis anemometer at the north facing building is closer to the buildings' corner, namely 10m, this makes stronger the assumption that air flow at this measured position is the result of the "end" canyon effects, as stronger wind speed intensifies the intermittent corner vortices and thus the advection from the building corners inside canyon. When the ambient wind is perpendicular to the canyon axis and from northern directions (10°±20°), the windward façade is not characterized by downward movements in order to assert for the creation of a circulatory vortex driven by the ambient wind. It is really interesting that near the NNE façade the air moves down only in 10% of the cases, while in more than 82% there were no vertical movements. To further study the impact of the wind on the airflow characteristics in the canyon, a similar study has been performed when the ambient flow is above the critical value of 4m s^{-1}. The analysis confirmed again that when the ambient flow is normal to the canyon axis the observed airflow inside canyon at the measured positions is mainly driven by the mechanism of the "end" canyon effects.

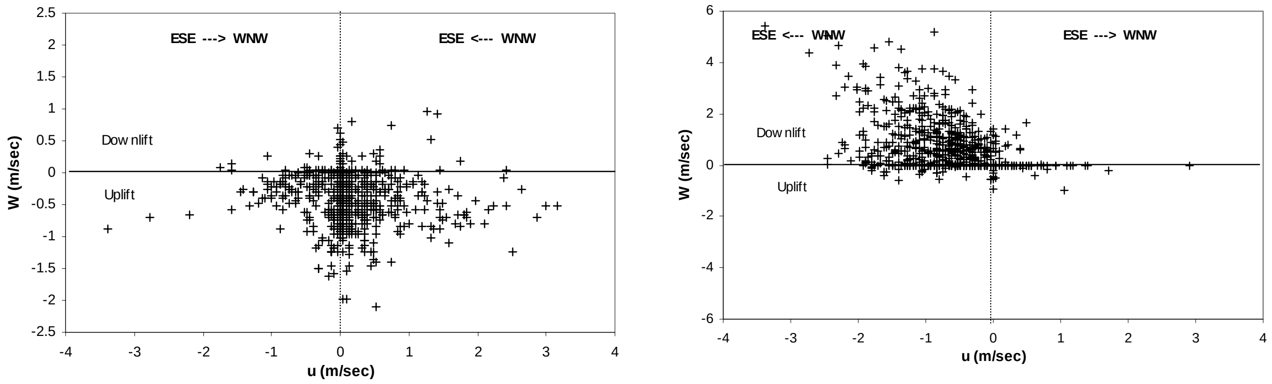


Figure 7. Along canyon wind speed, u, against vertical wind speed, w, near a) SSW and b) NNE façade, when the incidence angle of the ambient wind is perpendicular to the canyon axis from southern directions ($190^o \pm 20^o$).

3.3.2.3 Oblique Flow

The most common case is where the air flows at a particular angle relative to the canyon main axis. However, the most up-to-date research on this topic is considerably smaller in comparison with that for parallel and perpendicular flow. The existing knowledge comes mainly from wind-tunnel experiments and numerical simulations rather than field experiments. The main result of research, so far, shows that when the flow above the roof is at some angle to the canyon axis, a spiral or corkscrew vortex is induced along the length of the canyon (Santamouris et al., 2001). Wind-tunnel research has also shown that a helical flow pattern develops in the canyon. According to Yamartino et al. (1986), for intermediate angles of incidence to the canyon long axis, the canyon air flow is the product of both the transverse and parallel components of the ambient wind, the former driving the canyon vortex and the latter determining the along-canyon stretching of the vortex.

In the present experiment, 67% of the undisturbed wind speed data correspond to air flows incident to a certain angle relative to the long axis of the canyon. Namely, almost half of these correspond to Southwest directions, one-quarter to Southeast, 23% to Northwest and the rest to Northeast directions. The concluding results for the four different components of oblique flow confirmed again that the aiflow at the studied positions is mostly related with the "end" canyon effects, the mechanisms of which have been discussed above.

4. Theoretical Analysis for the estimation of air exchange rates

The single tracer gas decay method –using as tracer N_2O- has been applied at the Gizi experiment. A number of 34 ventilation experiments were performed on a circular basis during the whole period of the day consisting of 1 infiltration, 11 natural, 12 hybrid and 10 mechanical ventilation experiments. The natural ventilation is categorized in single-sided and cross ventilation experiments, while the hybrid ventilation in mechanical exhaust or inlet together with natural ventilation. The air exchange rates (1/h) have been estimated based on single-zone and multi-zone methods**.** The equations for interpreting tracer gas measurements are based on the conservation of mass of tracer and the mass of air while considering the concentration of the tracer gas in the outside air negligible. Considering the single-zone method two methodologies are considered:

(i) The zone average concentration Ca

In this methodology, the total airflow Q_{tot-1} is based on the estimation of a single average concentration, Ca, for the whole apartment which is the volume weighted average of the concentrations, Ci, of the different rooms.

(ii) The no-mixing method

This methodology consists in considering each volume separately disregarding the air exchange with the adjacent rooms. For each room, the ventilation rate, Qi, towards the surroundings is calculated from the room average concentration Ci. The total airflow Q_{tot-2} is the sum of the single Qi.

The multizone methodology with single-tracer gas experiments has been found in the work of Afonso and Maldonado (1986).The estimated air exchange rates (1/h) based on the single zone (1,2) and multizone (3) methodologies are presented in Figures 8 and 9, with the form of boxplots. In each case outliers are extreme values that do not fulfil the test of the confidence limits (Livada et. al, 2002) at a confidence level of 5%.

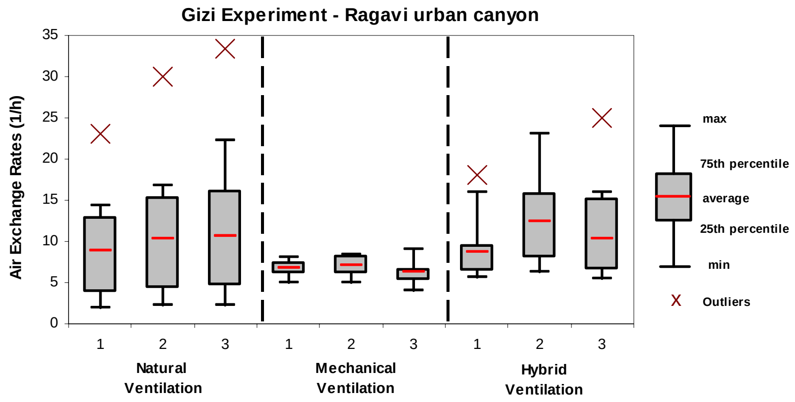


Figure 8. Estimated air exchange rates (1/h) for the total number of ventilation experiments.

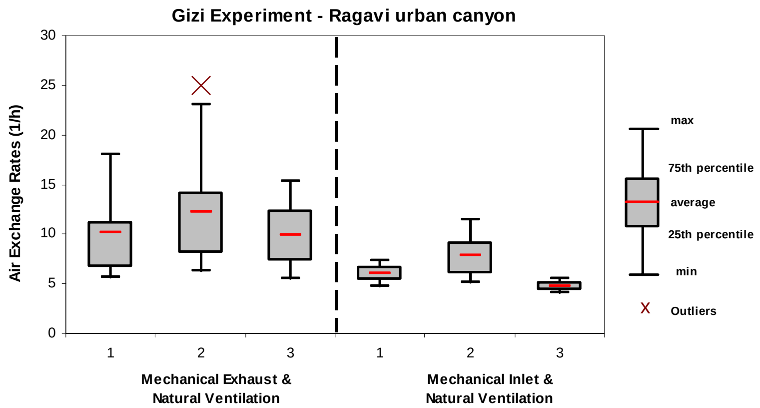


Figure 9. Estimated air exchange rates (1/h) for the hybrid ventilation experiments.

The observed extreme values (Figure 8) for the natural ventilation experiments are air exchange rates (1/h) corresponding to cross ventilation. For the hybrid ventilation the outliers are values that refer to mechanical exhaust and natural with three windows. The average air exchange rates based on the single-zone and multi-zone methodology have been estimated equal to 10 h^{-1}, 6.7 h^{-1} and 10.5 h^{-1} respectively for the total number of natural, mechanical and hybrid ventilation experiments. Similarly, the average differences between the max and min values were found 15.6 h^{-1} for the natural, 3.8h^{-1} for the mechanical and 12.5 h^{-1} for the hybrid ventilation experiments.

In case of hybrid ventilation experiments, the extreme values are observed in Figure 9 refer again to the previous mentioned experiment. The average air exchange rates are greater for mechanical exhaust & natural (10.7 h^{-1}) and lower for mechanical inlet & natural ventilations (7.3 h^{-1}). The average differences between the max and min values for the two studied patterns were estimated equal to 12.9 h^{-1} and 14.5 h^{-1}.

5. Conclusions

The study of the airflow characteristics inside Ragavi urban canyon for parallel, perpendicular and oblique ambient wind speeds relative to the canyon main axis revealed the impact of the “end” canyon effects. Moreover, a strong relation between the along canyon axis, u, and the vertical wind speed, w, is observed at both facades, when the incident ambient wind is perpendicular to the canyon main axis from southern directions (170^o-210^o). This is more evident at the NNE façade due the closest proximity of the 3-axis anemometer to the street corner. Finally, in case of perpendicular flow the role of the surface temperature distribution on the ground level and on the canyon opposite facades is considered significant for the observed airflow patterns especially during the daytime period.

It is obvious that the average differences between the maximum and minimum air exchange values are greater for the natural experiments and lower for mechanical ventilation experiments (Figure 8). This can be explained due to the driving forces affecting the airflow process during the different ventilation patterns. In natural ventilation a wider range of air flow rates exist because of the variability of the driving forces caused by the wind effect and temperature difference inside and outside. During the natural ventilation experiments the climatic conditions were not stable and this led to the variation in the measured airflow rates. Contrary to natural ventilation, mechanical ventilation gives a constant flow, irrespectively of the climatic conditions. As a result, the mechanical ventilation experiments gave airflow rates characterised by smaller ranges. Hybrid ventilation airflow rates varied according to their pattern. In general, they presented a smaller variability than the natural air exchanges but greater than the mechanical ones. The existing variation, during the hybrid -fan assisted- airflow process, is caused by the natural driving forces affected by unstable meteorological conditions. Nevertheless, the range of this variability is also affected by the existing supply/extract fans providing controllable airflow rates.

The analysis of the results for the other canyon is in progress and in a future research they will be further compared with that of the present canyon in order to have a general view of the impact of the urban environment on the performance of natural and hybrid ventilation systems.

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