# Performance of natural, hybrid and mechanical ventilation systems in urban canyons

K. Niachou and M. Santamouris
*Group Building Environmental Studies, Physics Department, University of Athens, Athens, Greece*

S. Hassid
*Environmental and Water Resources Engineering Department, Technion-Israel Institute of Technology, Israel*

ABSTRACT

The performance of natural, mechanical and hybrid ventilation systems was monitored, using the tracer gas decay method, in three typical apartment buildings located in two street canyons, during summer period 2002 in Athens. The multi-zone methodology has been adopted based on the mass balance of two tracer gases ($N_2O$ and $SF_6$) to define the air change rates. The air-exchange efficiency was determined for different ventilation systems, on the basis of the room mean age of air. In spite of the canyon effect, appreciable ventilation rates can be obtained with natural ventilation, especially when cross ventilation with two or more windows is measured. For single-sided ventilation or under calm conditions hybrid ventilation has only a slight advantage over natural, in terms of air exchange rates.

## 1. INTRODUCTION

The primary objective of ventilation in occupied spaces is to supply fresh air and to remove contaminants in order to assure thermal comfort and indoor air quality (Heiselberg, 1996). Monitoring of the performance of ventilation systems is important not only for indoor air quality but also for building maintenance so as to attain the maximum ventilation efficiency (Chao et al., 2004). Researchers use a variety of 'ventilation efficiency parameters' to characterize indoor airflow patterns. One parameter is the air-exchange efficiency that has been defined as the ratio between nominal time constant and the average time it takes to replace the air present in the room (Etheridge and Sandberg, 1996).

The present study is based on a previous work (Niachou et al., 2005), where the indoor exchange rates were estimated using both single and multi-zone approaches for ventilation experiments with one and two tracer gases. Single-zone methods were adapted to analyze multi-tracer experiments. The single-zone methodology consisted of two methods, the zone average concentration $C_a$ and the zero interzonal flows. Multizone methods were also applied for ventilation experiments where one ($N_2O$) and two tracer gases ($N_2O$ and $SF_6$) were used. It was shown that when a single tracer is used then the multizone analysis is inaccurate and in this case the use of single-zone methods is preferable. However, it was shown that for a multizone experiment, a multi-tracer gas is necessary and the multizone analysis is preferable.

In the present study a full comparison analysis, taking into account air-exchange efficiency, of the ventilation performance of different ventilation systems is performed under specific outdoor conditions in urban canyons. A methodology to estimate the room average age of air based on the decay method with two tracer gases is introduced. Finally, the impact of the urban environment on the performance of the studied ventilation systems is also discussed.

## 2. FULL-SCALE MEASUREMENTS

A number of three single-family building apartments have been studied in two urban street canyons, located in two high density residential areas, Gizi and Pagrati, very close the centre of Athens. The characteristics of the street canyons and studied apartments are given in Table 1. The main difference between $A_3$

Table 1: Characteristics of studied apartments.

| Experiment/ Apartment | Canyon | Surface ($m^2$) | Effective Volume ($m^3$) |
|---|---|---|---|
| Gizi/$A_1$ | Ragavi | 65 | 112 |
| Pagrati/$A_2$ | Ag. Fanouriou | 78 | 130 |
| Pagrati/$A_3$ | Ag. Fanouriou | 50 | 120 |

apartment and the other two ($A_1$ and $A_2$) is that both main rooms are on the same side of the same street canyon and unlike the other two apartments there is practically no natural cross ventilation.

A total number of 114 ventilation experiments were conducted consisting of 3 infiltration, 30 natural, 34 mechanical and 47 hybrid ventilation experiments. Each experiment consisted of two parts, one during which tracer was injected inside the rooms, with internal fans used to homogenize to the extend that it was possible the internal concentration and a second one, during which the internal fans were turned off and the tracer gas decay was measured. The single tracer gas decay method has been applied at Gizi experiment. In order to have a more accurate estimate of air exchange rates, the multi-tracer gas decay method with two tracer gases, $N_2O$ and $SF_6$ was performed in Pagrati experiments.

Natural ventilation experiments were performed with single-sided and cross ventilation configurations. In case of single-sided ventilation, openings were considered either, from the canyon or, the rear canyon facade. Cross ventilation experiments were studied with two or more openings placed at the front and back canyon side. Hybrid ventilation experiments were focused on fan-assisted natural ventilation, where supply and extract fans were used to enhance pressure differences by mechanical fan assistance. The fans were installed to openings adjacent to the canyon and rear façades operating in inlet or extract modes together with natural ventilation through one or two openings. Mechanical ventilation was tested experimentally with one or two fans operating in inlet or extract modes. All possible configurations were studied with the fans placed on both building external walls.

## 3. THEORETICAL BACKGROUND

The term air-exchange efficiency, based on the definition given in Etheridge and Sandberg (1996), can be defined as:

$$<\varepsilon_\alpha> = \frac{\tau_n}{\tau_{exc}} = \frac{\tau_n}{2<\bar{\tau}>} \times 100 \ [\%] \qquad (1)$$

where $\tau_n$ is the nominal time constant and $\tau_{exc}$ is the mean residence time which is twice the room mean age of air, $<\bar{\tau}>$. Based on the use of moments for the decay method, the room mean age of air is the ratio between the first and the zeroth moment of the concentration histories in the exhaust:

$$<\bar{\tau}> = \frac{\int_0^\infty tC_e(t)dt}{\int_0^\infty C_e(t)dt} \qquad (2)$$

Based on the efficiency value, one can distinguish several mixing flow patters: the ideal piston-flow, where ventilation efficiency is 100%, the complete and instantaneous mixing, in which the air-exchange efficiency is 50% and intermediate flow patterns, namely short-circuiting (between 0% and 50%) and ventilation by displacement (between 50% and 100%). When more than one extract openings are involved, one can define an average age of air, which is equal to the flow rate weighted average age of air for each individual opening. The above definition is mainly used for mechanical systems, but it can be generalized for all ventilation systems.

Starting from the conservation equation:

$$V_{tot}\frac{dC_a(t)}{dt} = -\sum Q_{ej}C_{ej}(t) \qquad (3)$$

The average concentration $C_a$ is the volume weighted average concentration of different rooms:

$$C_a(t) = \frac{\sum V_i C_i(t)}{V_{tot}} \qquad (4)$$

Eq.(3) can be integrated between 0 and t, which is the period of decay, considering also the tail of the curve:

$$V_{tot}C_a(0) = \sum Q_{ej} \int_0^t C_{ej}(t)dt \qquad (5)$$

Multiplying Eq.(3) by t and integrating:

$$V_{tot} \int_0^t C_a(t)dt = \sum Q_{ej} \int_0^t C_{ej}(t)dt \qquad (6)$$

Dividing Eq.(5) by Eq.(4), then the room average age of air from Eq.(2) becomes:

$$<\tau> = \frac{\int_0^\infty tC_e t dt}{\int_0^\infty C_e dt} = \frac{\int_0^t C_a(t)dt}{C_a(0)} \qquad (7)$$

From Eq.(7), one can identify that the average age of all air present in the room is <τ> is the normalized zeroth moment of the volume weighted average concentration of the ventilated space. This is equal to the inverse ratio of the volumetric flow rate of air entering the space and the volume of the ventilated space, which was estimated by Niachou et al. (2004), using the zone average concentration method. Thus, the air-exchange efficiency can be defined as the ratio between the nominal time constant, calculated using the multizone method, to twice the average age of all present in the room based on volume-weighted average concentration of the ventilated space.

Indeed, the efficiency calculated in the above way avoids having to calculate the concentration of a tracer at the exhaust point of a room and it is related with the spatial average age of air in the ventilated space, ignoring the differences in the concentration of different exhausts. This is also in agreement with Etheridge and Sandberg (1996) who suggested that the average residence time of the air in the room is a better measure of the effectiveness than the mean age of air in the extract, because it depends on the mixing in the room.

Finally, a methodology to determine the ventilation efficiency in two tracer gas experiments is proposed in the present study. Namely, one can estimate the ventilation efficiency from Eq.(3), however for the estimation of $<\tau>$, in Eq.(7) a dimensionless form of the volume-weighted average zone concentration in multi tracer gas experiments is needed. Thus, in case of two tracer gases the normalized concentration at a measured point of a room i is defined as:

$$S_i(t) = \frac{C_{i,N_2O}(t)}{C_{N_2O}(0)} + \frac{C_{i,SF_6}(t)}{C_{SF_6}(0)} \qquad (8)$$

where $C_{N_2O}(0)$ and $C_{SF_6}(0)$ are the initial average concentrations of the two tracers in those rooms in which they were injected. In case of two tracer gases the dimensionless form of the volume weighted average concentration is:

$$C_a^*(t) = \frac{\sum V_i S_i(t)}{V_{tot}} \qquad (9)$$

Thus, in case $A_2$ and $A_3$ apartments the room average age of air, $<\tau>$, was calculated using the dimensionless form of concentration, $S_i$.

## 4. EXPERIMENTAL RESULTS

### *4.1 Air-Exchange rates*

The estimated air-exchange rates for the three apartment buildings are illustrated with the form of boxplots in Figure 1a. The average air-

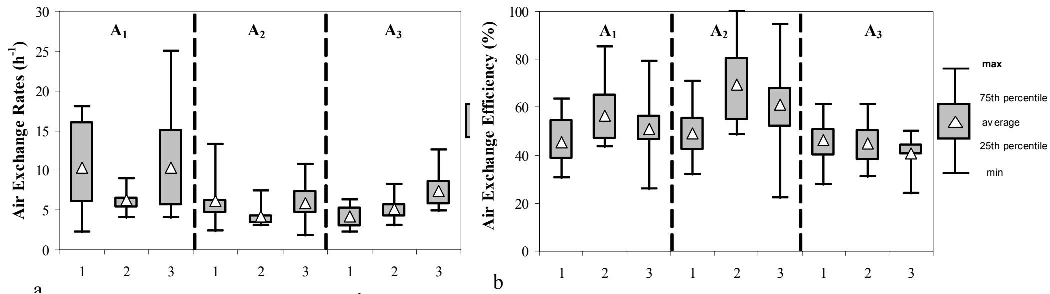


Figure1: Estimated air-exchange rates ($h^{-1}$) and efficiency values (%) for natural (1), mechanical (2) and hybrid (3) ventilation experiments in the three studied apartments.

exchange rates, according to each ventilation mode are summarized in Tables 2-4. The infiltration rates vary from $0.25h^{-1}$ up to $0.5h^{-1}$. Remarkably, infiltration is highest in the third apartment, where there is only one external facade and the canyon effect is expected to be greatest, since the apartment is on the first floor and far away from the street corners, unlike the other two apartments. Single-sided natural ventilation with one window ranges from $1.4h^{-1}$ up to $6.3h^{-1}$ in all building apartments under different ambient conditions, while it has an average value of the order of $3.1\text{-}4.5h^{-1}$. Single-sided ventilation when two windows are open, as in case of $A_3$ apartment is shown to be more effective, namely, of the order of $5.2h^{-1}$. In case of natural cross ventilation with two or more windows, then the estimated air changes per hour have an average value of $9.8\text{-}15.2h^{-1}$, even in periods with relatively small ambient wind speeds (0.5m/s or lower).

Mechanical ventilation rates range from$3h^{-1}$ up to $9h^{-1}$ in all studied buildings. When one supply or exhaust fan is used then the average ACH values in the three apartments are from $3.2h^{-1}$ up to $5.7h^{-1}$, while with two fans the average ACH are between $5h^{-1}$ and $8.8h^{-1}$. The greater ACH rates are measured in $A_1$ experiment probably, because the apartment was smaller.

Hybrid ventilation gives different ACH values depending on the relative configuration of the studied ventilation system. In $A_1$ experiment the highest average air exchange rates ($9.9h^{-1}$) were obtained, when one opening is combined with an exhaust fan rather than when the inlet

Table 2: Estimated ACH, based on multizone method and average room mean age of air, $<\tau>$ and air-exchange efficiency values (%), $<\varepsilon_a>$, for natural ventilation.

| Natural Ventilation | Description | No | ACH ($h^{-1}$) | Average Room Mean Age of Air (h), $<\bar{\tau}>$ | Average Efficiency (%), $<\varepsilon_\alpha>$ |
|---|---|---|---|---|---|
| $A_1$ | Infiltration | 1 | 0.25 | 4.00 | 50.0 |
| | Single-Sided with one window | 3 | 3.05 | 0.39 | 45.4 |
| | Cross Ventilation with two windows | 4 | 15.20 | 0.08 | 44.0 |
| | Cross Ventilation with more than two windows | 4 | 10.95 | 0.11 | 47.3 |
| $A_2$ | Infiltration | 1 | 0.33 | 2.63 | 57.6 |
| | Single-Sided with one window | 7 | 4.51 | 0.25 | 47.4 |
| | Cross Ventilation with two windows | 3 | 9.77 | 0.10 | 52.6 |
| $A_3$ | Infiltration | 1 | 0.50 | 2.08 | 48.0 |
| | Single-Sided with one window | 6 | 4.20 | 0.33 | 46.1 |
| | Single-Sided with two windows | 3 | 5.24 | 0.19 | 55.0 |

Table 3: Estimated ACH, based on multizone method and average room mean age of air, $<\tau>$ and air-exchange efficiency values (%), $<\varepsilon_a>$, for mechanical ventilation.

| Mechanical Ventilation | Description | No | ACH ($h^{-1}$) | Average Room Mean Age of Air (h), $<\bar{\tau}>$ | Average Efficiency (%), $<\varepsilon_\alpha>$ |
|---|---|---|---|---|---|
| $A_1$ | One exhaust fan | 4 | 5.70 | 0.18 | 51.4 |
| | Two supply/exhaust fans | 4 | 5.45 | 0.14 | 67.5 |
| | Two exhaust fans | 2 | 8.80 | 0.13 | 44.9 |
| $A_2$ | One exhaust fan | 5 | 3.84 | 0.20 | 69.3 |
| | Two supply/exhaust fans | 3 | 4.80 | 0.15 | 79.1 |
| | Two exhaust fans | 2 | 4.05 | 0.22 | 59.1 |
| $A_3$ | One exhaust fan | 4 | 5.30 | 0.24 | 42.1 |
| | One supply fan | 2 | 3.15 | 0.32 | 41.3 |
| | Two supply/exhaust fans | 6 | 4.98 | 0.19 | 49.8 |
| | Two exhaust fans | 2 | 5.15 | 0.20 | 40.8 |

Table 4: Estimated ACH, based on multizone method and average room mean age of air, $<\tau>$ and air-exchange efficiency values (%), $<\varepsilon_a>$, for hybrid ventilation.

| Hybrid Ventilation | Description | No | ACH ($h^{-1}$) | Average Room Mean Age of Air (h), $<\bar{\tau}>$ | Average Efficiency (%), $<\varepsilon_\alpha>$ |
|---|---|---|---|---|---|
| $A_1$ | One exhaust fan and natural ventilation with one window | 4 | 9.93 | 0.12 | 45.9 |
| | One supply fan and natural ventilation with one window | 3 | 4.77 | 0.17 | 64.1 |
| | One exhaust fan and natural ventilation with more than one windows | 3 | 13.23 | 0.11 | 48.1 |
| | Two supply/exhaust fans and natural ventilation with more than one windows | 2 | 15.40 | 0.07 | 46.1 |
| $A_2$ | One exhaust fan and natural ventilation with one window | 7 | 5.84 | 0.20 | 52.2 |
| | One supply fan and natural ventilation with one window | 3 | 5.52 | 0.18 | 68.5 |
| | One supply/exhaust fan and natural ventilation with more than one windows | 5 | 5.86 | 0.17 | 66.6 |
| | Two supply/exhaust fans and natural ventilation with one window | 4 | 6.08 | 0.13 | 66.5 |
| | Two exhaust fans and natural ventilation with one window | 2 | 6.75 | 0.15 | 55.1 |
| $A_3$ | One exhaust fan and natural ventilation with one window | 8 | 6.71 | 0.18 | 42.4 |
| | One supply fan and natural ventilation with one window | 6 | 8.23 | 0.17 | 38.3 |

fan is used. When two fans were combined with natural ventilation through one opening or one fan with natural ventilation with two openings then, $13.2h^{-1}$-$15.4h^{-1}$ are estimated on average. In $A_2$ experiment when one has one fan and one or more windows open, one obtains approximately $5h^{-1}$-$6h^{-1}$, whereas with two fan one has rather higher air exchanges ($6.1h^{-1}$-$6.8h^{-1}$). In the case of $A_3$ experiment (with the open window and the fan being on the same side of the apartment) the air changes per hour ($h^{-1}$) are of the order of $6.7h^{-1}$-$8.2h^{-1}$. $A_3$ experiment is different from the other two because natural ventilation is only single-sided and because of the existence of windless ambient conditions. As a result, slightly lower ventilation rates were obtained when compared to other two experiments. Hybrid ventilation, in $A_3$ experiment, was shown to perform slightly better than natural ventilation, especially during calm periods.

Concluding, natural cross ventilation was proven to very effective in spite of the canyon effect. The main parameter making a difference was whether natural ventilation was single-sided or cross ventilation. Hybrid and mechanical ventilation was shown to result in a lower ventilation rates than natural cross ventilation. 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. However, the existing variability in natural ventilation rates is greater in $A_1$ experiment in comparison with the other two, due to implementation of cross ventilation experiments between more than two windows. 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 characterized 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. Even under calm conditions (wind speed lower than 0.2m/s) natural ventilation is not eliminated, since the temperature difference between inside and outside compensates for the reduced wind effect. From the limited number of ventilation experiments performed under calm conditions, it has been found that hybrid ventilation has a small advantage over natural ventilation with regard to ACH values (Niachou et al., 2005).

*4.2 Air-Exchange Efficiency*

In order to complete the work on the performance of different ventilation systems, the air-exchange efficiency values were calculated (Figure 1b). The average efficiency values for different groups of experiments are summarized in Tables 2-4 for different ventilation modes.

The ventilation efficiency under single-sided ventilation in all studied apartments varies from 45% to 47%, corresponding to almost complete mixing. However, a higher average efficiency value (55%) is obtained in $A_3$ apartment, with two windows open (in different zones which both face the canyon side). In case of natural cross ventilation the air-exchange is shown to be only marginally better (44%-47%) for $A_1$ apartment in comparison with single-sided experiments, whereas a larger difference can be seen in $A_2$ apartment where the average ventilation efficiency is of the order of 53%, namely more than perfect mixing, but much less than displacement ventilation.

From the monitoring of mechanical ventilation, it has been found that with an exhaust fan an average value of 51% efficiency is achieved in $A_1$ and 69% in $A_2$ apartment and a rather lower average efficiency of 42% for $A_3$ single-sided apartment. When two exhaust fans are used, then the efficiency is reduced in all cases, but when a supply and an exhaust fan are used together there is an improvement in all experiments, in comparison with one fan in the exhaust mode.

For hybrid ventilation, the results obtained are definitely higher than in case of single-sided ventilation. In most cases, there is also an improvement relatively to natural cross ventilation. However, it should be stated that in all cases the differences between the results for each ventilation mode are characterized by a high variability and in many cases there are relatively big differences between the absolute maximum and absolute minimum efficiency values.

## 5. CONCLUSIONS

The air exchange rates were measured in three typical building apartments located in two urban street canyons in Athens using the tracer gas decay method. Different ventilation systems were compared, namely, natural, mechanical ventilation using one or two supply/exhaust fans and hybrid or fan-assisted natural ventilation. A methodology to estimate air-exchange efficiency in two tracer gas experiments has been introduced.

Natural cross ventilation has been shown to lead to higher ACH values than single-sided natural ventilation. Hybrid ventilation has been shown to be associated with rather lower ACH than natural cross-ventilation, but slightly higher ACH under single-sided ventilation or calm conditions. This, of course, does not mean that hybrid ventilation may not be of use during winter times, or during those few days during the summer that natural ventilation is not an effective means of cooling, either due to low winds or due to high ambient temperatures.

Nevertheless, there is more to evaluating hybrid ventilation than comparing the mean values of the air exchange rates, which have a relatively high spread for natural ventilation. Although the small number experiments performed under calm conditions, it was confirmed that hybrid ventilation has an advantage over natural under windless conditions. It should also be stated that apart from the comparison of estimated air exchange rates, there is a qualitative difference between natural and hybrid ventilation, in terms of air-exchange efficiency. Higher air-exchange efficiency values have been estimated in hybrid ventilation experiments in comparison with single-sided ventilation. In most cases, there is also an improvement relative to natural cross ventilation.

## NOMENCLATURE

t: time during decay period (h).
$V_i$: effective volume of room i ($m^3$).
$V_{tot}$: total effective volume of ventilated space ($m^3$).
ACH: air exchange rate estimated from the multizone method ($h^{-1}$).
$<\varepsilon_a>$: air-exchange efficiency.
$\tau_n$: nominal time constant (h).
$\tau_{exc}$: mean residence time (h).
$<\bar{\tau}>$: room mean age of air (h).
$C_a(t)$: volume weighted average concentration of a tracer in the ventilated space at time t ($kg_{tracer}/m^3_{air}$).
$C_a(0)$: initial value of volume weighted average concentration of a tracer in the ventilated space ($kg_{tracer}/m^3_{air}$).
$S_i(t)$: instantaneous normalized concentration at a point of room i with two tracer gases.
$C_{i,N_2O}(t)$: instantaneous concentration of $N_2O$ at point of room i ($kg_{tracer}/m^3_{air}$).
$C_{i,SF_6}(t)$: instantaneous concentration of $SF_6$ at point of room i ($kg_{tracer}/m^3_{air}$).
$C_{N_2O}(0)$: initial average concentration of $N_2O$ in the rooms in which it was injected ($kg_{tracer}/m^3_{air}$).
$C_{SF_6}(0)$: initial average concentration of $SF_6$ in the rooms in which it was injected ($kg_{tracer}/m^3_{air}$).
$C_a^*(t)$: instantaneous dimensionless form of the volume weighted average concentration in the ventilated space ($kg_{tracer}/m^3_{air}$).

## ACKNOWLEDGEMENTS

The present research has been performed in the framework of the research project RESHYVENT and it is financed by the Fifth Framework Programme of the European Commission, Directorate General for Science, Research and Technology under the contract ENK6-CT2001-00533. The contribution of the Commission is gratefully acknowledged.

## REFERENCES

Chao, C.Y., M.P. Wan and A.K. Law, 2004. Ventilation Performance Measurement Using Constant Concentration Dosing Strategy, Building and Environment, 39, pp. 1277-1288.

Etheridge, D. and M. Sandberg, 1996. Building Ventilation- Theory and Measurement, John Wiley & Sons, pp.722.

Heiselberg, P., 1996. Room air and contaminant distribution in mixing ventilation, ASHRAE Transactions 1(4), pp.322-329.

Niachou, K., S. Hassid, M. Santamouris and I. Livada, 2005. Comparative Monitoring of Natural, Hybrid and Mechanical Ventilation Systems in Urban Canyons, Energy and Buildings, 37(5), pp.503-513.

RESHYVENT, 2002. Cluster Project on Demand Controlled Hybrid Ventilation in Residential Buildings with specific emphasis of the Integration of Renewables, European Joule Project, Contract No ENK6-CT2001-00533.