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Technical Note AIVC 61

Natural and Hybrid Ventilation in the Urban Environment

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Natural and Hybrid Ventilation in the Urban Environment

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This report is part of the work of the IEA Energy Conservation in Buildings & Community Systems Programme - Annex V Air Infiltration and Ventilation Centre

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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among the twenty-four IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources and energy research development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use in buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods as well as air quality and studies of occupancy.

The Executive Committee

Overall control of the programme is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial.

To date the following have been initiated by the Executive Committee (completed projects are identified by *):

1 Load Energy Determination of Buildings *
2 Ekistics and Advanced Community Energy Systems *
3 Energy Conservation in Residential Buildings *
4 Glasgow Commercial Building Monitoring *
5 Air Infiltration and Ventilation Centre
6 Energy Systems and Design of Communities *
7 Local Government Energy Planning *
8 Inhabitant Behaviour with Regard to Ventilation *
9 Minimum Ventilation Rates *
10 Building HVAC Systems Simulation *
11 Energy Auditing *
12 Windows and Fenestration *
13 Energy Management in Hospitals*
14 Condensation *
15 Energy Efficiency in Schools *
16 BEMS – 1: Energy Management Procedures *
17 BEMS – 2: Evaluation and Emulation Techniques *
18 Demand Controlled Ventilation Systems *
19 Low Slope Roof Systems *
20 Air Flow Patterns within Buildings *
21 Thermal Modelling *
22 Energy Efficient communities *
23 Multizone Air Flow Modelling (COMIS)*
24 Heat Air and Moisture Transfer in Envelopes *
25 Real Time HEVAC Simulation *
26 Energy Efficient Ventilation of Large Enclosures *
27 Evaluation and Demonstration of Residential Ventilation Systems *
28 Low Energy Cooling Systems *

29 Daylight in Buildings *
30 Bringing Simulation to Application *
31 Energy Related Environmental Impact of Buildings *
32 Integral Building Envelope Performance Assessment *
33 Advanced Local Energy Planning *
34 Computer-aided Evaluation of HVAC Systems Performance *
35 Design of Energy Hybrid Ventilation (HYBVENT) *
36 Retrofitting of Educational Buildings *
36 WG Annex 36 Working Group Extension 'The Energy Concept Adviser' *
37 Low Exergy Systems for Heating and Cooling of Buildings *
38 Solar Sustainable Housing *
39 High Performance Insulation systems (HiPTI) *
40 Commissioning Building HVAC Systems for Improved Energy Performance *
41 Whole Building Heat, Air and Moisture Response (MOIST-EN)
42 The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (COGEN-SIM)
43 Testing and Validation of Building Energy Simulation Tools
44 Integrating Environmentally Responsive Elements in Buildings
45 Energy-Efficient Future Electric Lighting for Buildings
46 Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)
47 Cost Effective Commissioning of Existing and Low Energy Buildings
48 Heat Pumping and Reversible Air Conditioning
49 Low Exergy Systems for High Performance Buildings and Communities
50 Prefabricated Systems for Low Energy Renovation of Residential Buildings

Annex V: Air Infiltration and Ventilation Centre

The Air Infiltration and Ventilation Centre was established by the Executive Committee following unanimous agreement that more needed to be understood about the impact of air change on energy use and indoor air quality. The purpose of the Centre is to promote an understanding of the complex behaviour of air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

The Participants in this task are Belgium, Czech Republic, Denmark, France, Greece, Japan, Republic of Korea, Netherlands, Norway and United States of America.

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Abstract

Because of specific urban characteristics, the potential of natural ventilation can be seriously decreased in the urban environment because of reduced wind speeds, high ambient temperatures and increased external pollutant and noise levels. Besides, the performance of hybrid ventilation systems is also affected and they are expected to work most of the times with mechanical ventilation.

This AIVC Technical Note has been performed in the frame of EU RESHYVENT and URBVENT projects and its main purpose is to highlight the most important constraints and limitations of the urban environment on natural and hybrid ventilation. The report mainly focuses on measurements and prediction of natural and hybrid ventilation in the urban environment, mainly as a result of reduced driving forces and the consequences for indoor air quality and fan assistance, while the consequences of external noise and pollutants are treated sporadically.

A state-of-the-art of natural and hybrid ventilation studies has been performed for urban buildings. Then, detailed information is given concerning the experimental research and computational procedures carried out within RESHYVENT and URBVENT projects in order to investigate the performance of natural and hybrid ventilation systems in urban buildings. The experimental results refer to typical urban canyon configurations with H/W>1.0 for the climatic conditions of Athens.

Furthermore, more general conclusions are discussed through a number of simulations in order to investigate the effect of different urban canyons on the performance of natural and hybrid ventilation systems in different European climates. Finally, a number of recommendations or guidelines are proposed for the use of natural and hybrid ventilation systems in the urban environment.

Nomenclature

Variables

H	canyon height	[m]
W	canyon width	[m]
L	canyon length	[m]
h_b	mean height of buildings	[m]
z_0	aerodynamic roughness length	[m]
z_2	roughness length for the obstructed sub-layer	[m]
y	height above ground level	[m]
k	Karman constant (0.38)	-
d	zero-plane displacement	[m]
u*	friction velocity	[m/sec]
u	along wind speed component	[m/sec]
v	cross wind speed component	[m/sec]
w	vertical wind speed component	[m/sec]
V_h	horizontal wind speed inside the canyon at height h	[m/sec]
V_{tot}	total wind speed inside the canyon	[m/sec]
u_p	horizontal wind speed below rooftops in the obstructed sublayer	[m/sec]
U_0	constant reference speed on the ground level	[m/sec]
u_0	wind speed at the top of canyon (x=W/2, z=H)	[m/sec]
u_r	along wind speed component at reference height z_r	[m/sec]
V	horizontal wind speed outside the canyon	[m/sec]
F	tracer gas injection rate	[kg/h]
V_i	effective volume of zone i	[m^3]
V_{tot}	total effective volume of each apartment	[m^3]
$C_i(t)$	concentration of tracer in zone i	[kg_{tracer}/m^3_{air}]
C_o	concentration of tracer in the outside air	[kg_{tracer}/m^3_{air}]
$C_a(t)$	volume weighted average concentration of a tracer in apartment	[kg_{tracer}/m^3_{air}]
$C_{ai}(t)$	average concentration of a tracer from all measurement points in zone i	[kg_{tracer}/m^3_{air}]
$C_{ai}^*(t)$	dimensionless average concentration of a tracer in zone i	
$C_a^*(t)$	dimensionless volume weighted average concentration in apartment	
$C_{SF6,i}$	concentration of SF_6 in zone i	[kg_{tracer}/m^3_{air}]
$C_{N2O,i}$	concentration of N_2O in zone i	[kg_{tracer}/m^3_{air}]
Q_{oi}	air flow from outside air to zone i	[m^3_{air}/h]
Q_{io}	air flow from zone i to outside air	[m^3_{air}/h]
Q_{ij}	air flow from zone i to zone j	[m^3_{air}/h]
Q_{ji}	air flow from zone j to zone i	[m^3_{air}/h]
Q_{tot1}	estimated total airflow based on the single-zone method with one tracer gas considering the apartment average concentration C_a	[m^3_{air}/h]
Q_{tot2}	estimated total airflow rate based on single-zone method with one tracer gas considering the zero interzonal flows	[m^3_{air}/h]
Q_{tot3}	estimated total airflow rate based on multizone method with one tracer gas	[m^3_{air}/h]
Q^*_{tot1}	estimated total airflow based on single-zone method with two tracer gasses considering the dimensionless apartment average concentration	[m^3_{air}/h]

Q^*_{tot2}	estimated total airflow based on single-zone method with two tracer gasses considering zero interzonal flows	$[m^3_{air}/h]$
Q^*_{tot3}	estimated total airflow based on multizone method with two tracer gasses	$[m^3_{air}/h]$
N_1	ACH based on single-zone method with one tracer gas considering the apartment average concentration C_a	$[h^{-1}]$
N_2	ACH based on single-zone method with one tracer gas considering the zone average concentration C_{ai}	$[h^{-1}]$
N_3	ACH based on multizone method with one tracer gas	$[h^{-1}]$
N_1^*	ACH based on single-zone method with two tracer gasses considering the dimensionless apartment average concentration C_a^*	$[h^{-1}]$
N_2^*	ACH based on single-zone method with two tracer gasses considering the dimensionless zone average concentration C_{ai}^*	$[h^{-1}]$
N_3^*	ACH based on multizone method with two tracer gasses	$[h^{-1}]$
Q_i	mass flow rate	$[kgs^{-1}]$
K_i	mass flow coefficient	[Kg/s@1Pa]
ΔP	pressure difference at link height	[Pa]
P_{out}	outside pressure at link height	[Pa]
P_{in}	inside pressure at link height	[Pa]
n	flow exponent	-

Indices

p	point
r	reference
b	building
h	height
i	zone i (i=1, 2)
j	zone j (j=1, 2)
o	ambient air
a	average value
tot	total value
SF_6	tracer gas
N_2O	tracer gas
x, y, z	x-, y-, z- direction

1 Introduction

Ventilation aims to increase thermal comfort or indoor air quality, as well as, to reduce or eliminate energy for cooling purposes. Fresh air may be introduced indoors through building openings (natural ventilation), through mechanical forces with the use of fans (mechanical ventilation), or with a combination of openings and fans (hybrid ventilation). Natural ventilation is caused by naturally produced pressure differences due to wind, temperature difference or due its combined effects. Natural ventilation (NV) is achieved by allowing air to flow in and out of the building by opening windows and doors or specific ventilation components like chimneys. The effectiveness of natural ventilation depends on wind speed and direction, temperature difference, size and characteristics of external openings.

According to Wouters et al. (2000) the division between natural and mechanical ventilation has become rather weak. There is a tendency for combining the best of both technologies: intelligent natural ventilation if appropriate, efficient mechanical ventilation if required. This tendency is called hybrid ventilation and it is also valid for ventilation in relation to thermal comfort in summer.

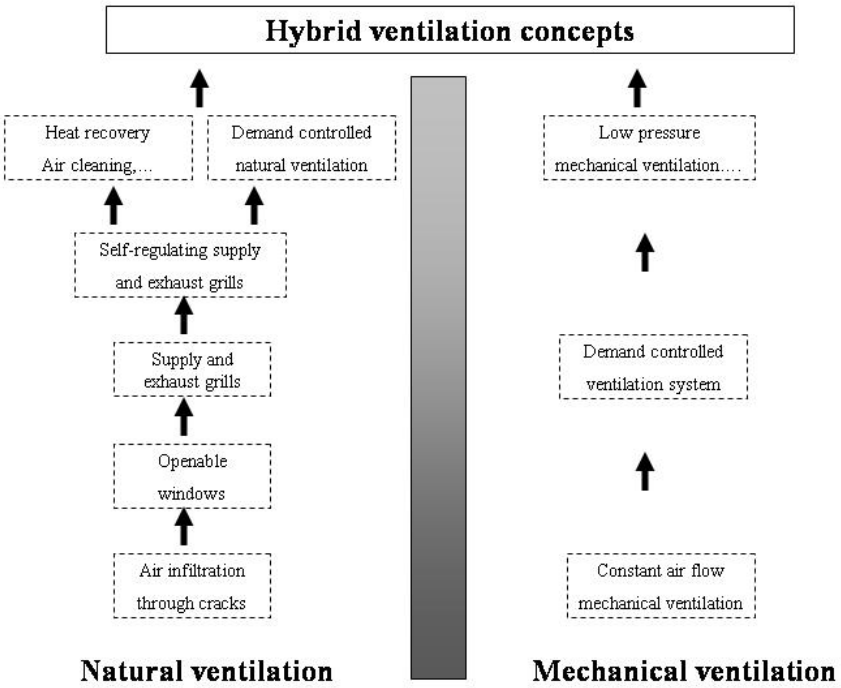

Figure 1.1: Various Types of Components for Hybrid Ventilation Concepts (Wouters et al., 2000)

Hybrid ventilation (HV) is '*a new ventilation concept that combines the best features of natural and mechanical ventilation at different times of the day or season of the year. It is a ventilation system where mechanical and natural forces are combined in a two mode system. The operating mode varies according to the season and within individual days, thus the current mode reflects the external environment and takes maximum advantage of ambient conditions at any point in time*' (Heiselberg, 2002).

The definition of hybrid ventilation is described also by de Gids (2004) in Figure 1.2.

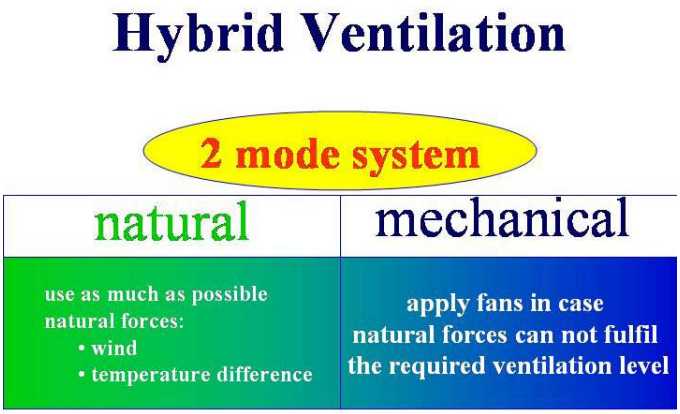

Figure 1.2 : Definition of Hybrid Ventilation (De Gids, 2004)

In order to investigate the impact of the urban environment on natural and hybrid ventilation, a number of experimental and computational procedures were performed in the context of RESHYVENT and URBVENT European research projects. A short description of the two projects and its main purposes are presented in the next paragraphs. Then, the most important limitations or constraints of urban environment which affect the potential of natural and hybrid ventilation are discussed and existing research studies are presented. In addition, a state-of-the-art review has been prepared for natural and hybrid ventilation systems in urban buildings. Hereafter, the major mechanisms of natural air flow process are presented in order to understand how the urban environment can affect the potential of natural and thus of hybrid ventilation. Finally, the most important results of the experimental investigation and computational procedures are presented and a number of recommendations or guidelines are given for the performance of hybrid ventilation systems in the urban environment.

2 The RESHYVENT project

RESHYVENT project was carried out from January 2002 to December 2004 within the Fifth EU Framework Programme and its main purpose was the investigation and development of demand controlled hybrid ventilation systems in residential buildings. The key elements of the RESHYVENT project are reflected in the subtitle of the project 'Cluster Project on Demand Controlled Hybrid Ventilation in Residential Buildings with specific emphasis of the Integration of Renewables'. The aim of the RESHYVENT project was to integrate renewables and hybrid technologies in domestic ventilation systems by researching, developing, and constructing four complete hybrid ventilation concepts for different EU climate zones and by delivering generic output to companies in terms of technical specifications and guidelines including market economical and social aspects.

In order to streamline the actions and also for optimisation of the available resources, this project was a grouping of four industrial consortia collaborating with a multi-disciplinary scientific consortium. The four industrial consortia are composed and located in different European regions. Each consortium develops and constructs a different hybrid ventilation system (Table 2.1) with special attention to its application in its region. A scientific group of 12 partners from research institutes, consultants and universities has carried out the scientific research work for the development of these systems.

The main objective of the RESHYVENT project was to develop and to construct four hybrid ventilation systems, in other words, the final output was the operational demonstration of physical products.

Table 2.1 : Application Fields of The Four Industrial Consortia In RESHYVENT (RESHYVENT, 2002)

	IC1/ Sweden	**IC2/ Netherlands**	**IC3/ Belgium/France**	**IC4/ Norway**
Climate	Cold	Moderate	Mild and warm	Severe
Building type	Apartments	Dwellings Apartments	Dwellings	Single family houses
Renewable	PV Wind With and without heat recovery	PV Wind	PV	Wind Heat recovery
Summer Comfort	No	Limited	Crucial	No
Winter Comfort	Important	Important	Important	Crucial
Supply	Crucial	Important	Important	Crucial
Exhaust	Crucial	Crucial	Crucial	Crucial

The work within RESHYVENT project was characterized by:

- A practical part: the development and construction of components, products and systems, to be demonstrated after completion of the project and, later, commercially exploited and launched on the market by industries.
- A generic part: all developed knowledge (technical, economical, social etc.), as well as, all supporting tools, instruments and documents will be disposable for EU industries.

To come to the final output and deliverables of the practical and generic part, a number of supporting research activities were undertaken in scientific support units and the following work packages were distinguished:

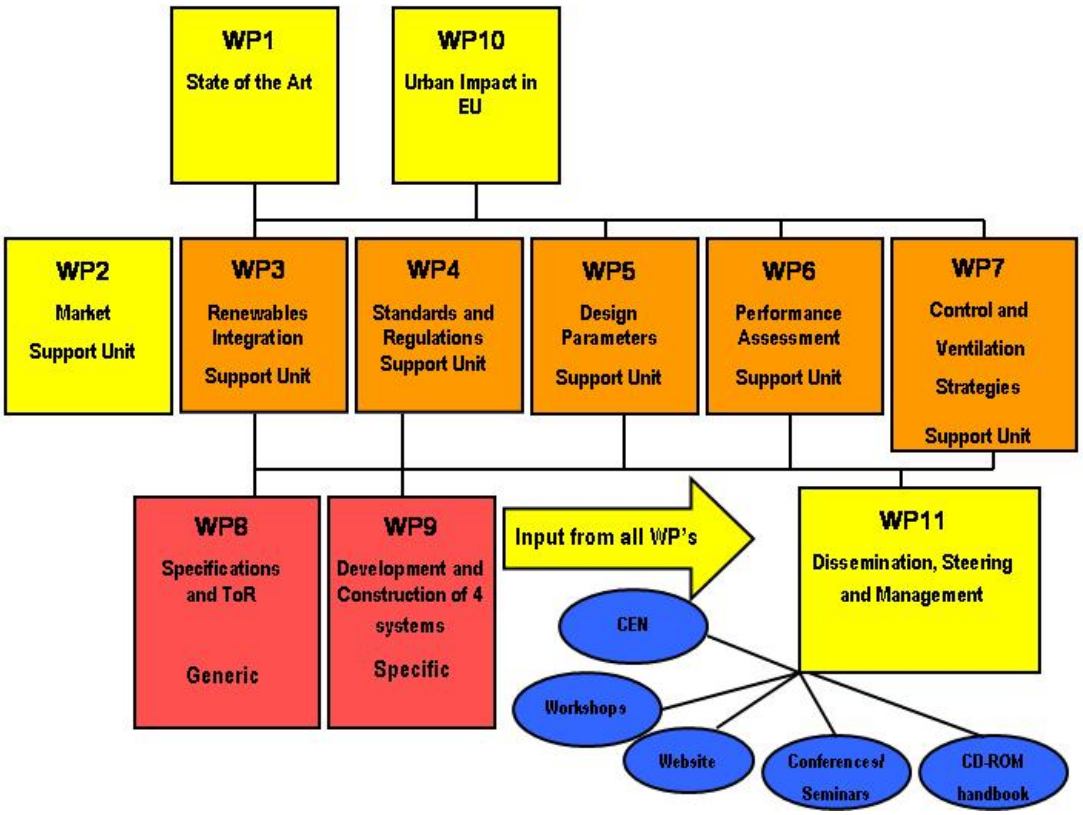

Figure 2.1 : WP Structure in RESHYVENT European Programme (2002)

Work package 10 dealt with the impact of the urban environment on the hybrid ventilation air flow process through experimental and computational procedures performed at a number of different configurations that affect the performance of natural and hybrid ventilation, in urban canyons.

The overall work was coordinated by the National and Kapodestrian University of Athens (NKUA) and it was split into the following work tasks:

- Task 1. Inventory on the impact of the urban environment on hybrid ventilation
- Task 2. State of the art and potential of hybrid ventilation in urban canyons
- Task 3. Classification of configurations affecting hybrid ventilation in urban canyons
- Task 4. Experimental research of hybrid ventilation in urban canyons
- Task 5. Evaluation of the experimental results in urban canyons
- Task 6. Computational calculations of air flow characteristics in urban canyons
- Task 7. Integration of traffic into the studies on urban impact

Other detailed information about RESHYVENT project and its specific work packages can be found on the website: www.reshyvent.com

3 The URBVENT project

The main objective of URBVENT project was to develop a design methodology and performance criteria for best practice design of naturally ventilated buildings. The aim was to optimise the façade of urban buildings to better exploit natural resources and maximise natural ventilation performance, giving credit for energy conservation, improved indoor air quality and best use of renewable energy sources.

The overall work was split into the following work tasks:

- ***Work Task 1.*** Definition of the urban building configurations related to naturally ventilated buildings and definition of architectural scenarios for naturally ventilated buildings and theoretical evaluation of the air flow through the buildings.
- ***Work Task 2.*** Experimental investigation of air flow in specific canyons.
- ***Work Task 3***. Development of a methodology for optimum opening design.

The strategy followed is shown in Figure 3.1.

As it concerns the work task 1, specific urban canyon and architectural configurations have been defined. Architectural scenarios are related with the following variables:

- The building type, namely as they allow cross ventilation or single-sided ventilation only;
- The canyon geometry, consisting of the ratios of geometric variables (height of the buildings, width and length of the canyon). Canyons under study in this project present different geometric ratios.

In terms of building geometries, three main types of buildings have been considered:

- Small offices and apartments, typically behaving as single-sided ventilation cases.
- The same as in the previous point, but with a chimney linking them to the roof of the building.
- Larger size apartments and offices, typically allowing for cross-ventilation (openings in more than one façade).

For each case, two types of façades are possible:

- Flat façades.
- Façades with obstacles, such as balconies, overhangs or other elements creating complex wind patterns and pressure distributions on the openings.

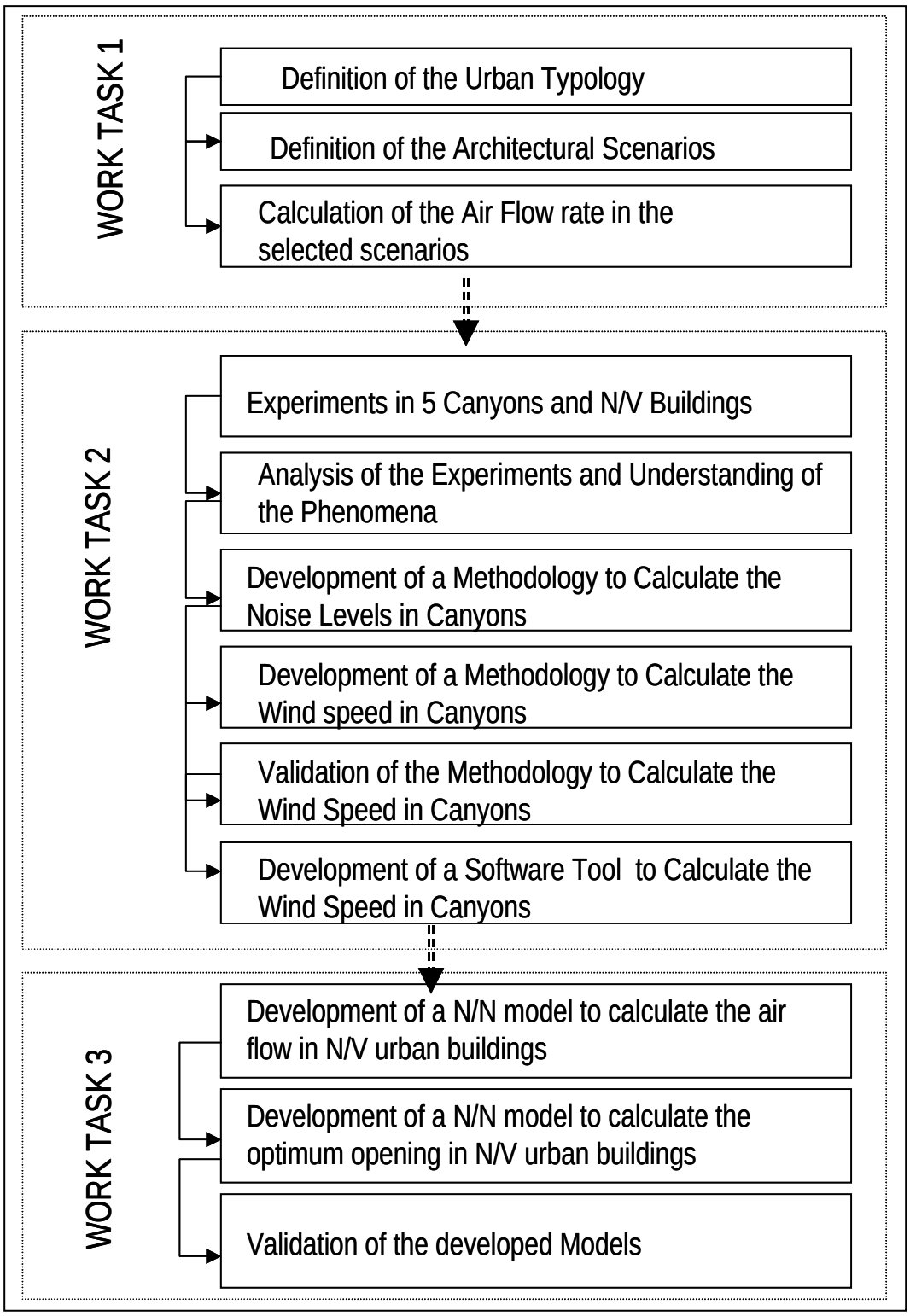

Figure 3.1 : WP Structure in URBVENT European Programme (2001)

The study was concentrated in two typical geometries which are not dependent on Cp knowledge:

- Single sided ventilation and
- Cross ventilation of apartments with openings in a single façade plus a chimney linking them to the roof of the building, in the absence of wind (stack-induced flow).

Six geometric variables related to room and opening dimensions were considered. All these variables were changed allowing for different combinations between them all. This has created thousands of different architectural scenarios that provide a deep insight into the magnitude of airflows under different circumstances.

To evaluate the natural ventilation potential in the two described situations, two methodologies were followed. For the single-sided ventilation cases, simulations have been performed with the AIOLOS software while the stack-induced cases have been studied with COMIS because AIOLOS could not cope with the geometry of the stack-induced created scenarios.

Once the architectural scenarios and the climatic conditions of the study were defined, the airflow rates and the air changes for the single-sided ventilation situation were calculated. More than 1.5 million values were produced. Due to the magnitude of this number, these results had to be grouped in three hundred EXCEL files, in order to be manageable. In each one of these files, for a certain volume, and for the defined climatic data, it is possible to find the air changes and the airflow rates in the room for the different combinations considered. As it concerns, stack induced ventilation, a matrix containing 2.6 million values is used as the database for stack induced ventilated rooms.

For work task 2 specific experiments have been carried out in five urban canyons presenting different characteristics. The vertical distribution of the wind speed in the canyons as well as the wind speed at selected points in the canyons and the undisturbed wind speed were measured. In parallel, the air and surface temperature distribution inside the canyons have been measured. The air flow rates have been measured in single side and cross ventilated buildings located in the measured canyons. Measurements have been performed at least for three days for each canyon. A very important data base has been created that has been used to better understand the air flow processes in urban canyons as well as to develop theoretical models.

For each canyon a very specific analysis of the air flow has been performed and conclusions have been drawn regarding the specific climatic conditions in the urban environment.

Using the experience gained through the specific experiments, a theoretical model to calculate the wind speed at any point in a canyon has been developed. The method is compared against the existing models and the experimental data and is found to be very accurate. The overall method has been incorporated in a software tool developed under the MATLAB Code.

A series of noise measurements were made in ‘canyon’ streets in Athens with aspect ratio (height/width) varying from 1.1 to 5.3. The main purpose of the measurements was to examine the vertical variation in noise in the canyons in order to give advice on natural ventilation potential. A simple model of the noise level has been developed using a linear regression analysis of the measured data. The model can be used to predict the fall-off (attenuation) of the noise level with height above street level.

As it concerns the third task a methodology to calculate the optimum opening of naturally ventilated buildings located in urban canyons has been developed. The overall work is based on the development of a recurrent neural network model that calculates the air flow in natural ventilated apartments in buildings located in urban canyon under:

- specific climatic conditions
- specific canyon characteristics
- specific openings of a building
- specific building geometrical and operational characteristics

As inputs to the neural network, the data obtained during the first task of the work package have been used. At a second phase an adverse model has been developed where the openings characteristics are calculated when the requested ventilated performance is specified.

Finally, using the experimental data regarding the air flow in naturally ventilated buildings, the developed models have been validated. It is found that the proposed model to calculate the air flow in

naturally ventilated buildings located in urban environment as well as the model to calculate the optimum opening are very accurate and can be used to design naturally ventilated buildings in dense urban environments.

4 Impact of Urban Environment on the Potential of Natural and Hybrid Ventilation Systems

Urban environment presents disadvantages for the application of natural ventilation: lower wind speeds, higher temperatures due to urban heat island, increased noise and pollution levels. Recent research has shown that in (southern) European cities, the more important limitation of natural ventilation techniques is because of the specific climatic conditions of cities. Because of the specific urban characteristics, there is a serious increase of the ambient temperature and a serious decrease of wind speed in urban canyons. Both reasons decrease seriously the potential of natural and hybrid ventilation techniques. However, in some cases, the reduced wind speed might not be a problem, since it dampens the huge changes in pressure differences (due to large variations in wind speeds) and makes ventilation control much easier when natural ventilation relies mainly on thermal buoyancy. In north Europe and Scandinavia traffic noise and air pollution are the most important problems.

Wind speeds within the urban canopy are usually reduced in comparison with rural winds at the same height. As roughness length is greater in an urban area than in the surrounding countryside, the wind speed u at any height z is lower in the urban area, and much lower within the obstructed area. Simultaneous measurements of wind speed inside various canyons in Athens, Greece, are reported by Santamouris et al. (1998). The analysis of the measured wind speeds inside the urban canyons and at the airport shows clearly that although wind speed at the airport may vary up to 6 m/sec, the wind speed inside the canyon never exceeds 1 m/sec.

The temperature distribution in the urban canopy layer is highly affected by the urban net radiation balance. The incident solar radiation on urban surfaces is absorbed and then it is transformed to sensible heat. Most of the solar radiation impinges on roofs, and on the vertical walls of buildings and only a relatively small part reaches the ground level. Because the radiant heat loss is slower in urban areas the net balance is more positive than in the surrounding rural areas and thus higher temperatures are presented. The urban heat island effect is the best documented example of inadvertent climate modification (Oke, 1987).

Outdoor pollution is a major problem in urban places and can restrict the use of natural ventilation. Increased outdoor concentrations seriously affect the indoor concentration of pollutants. Numerous studies reported during the last years, show the serious impact of the outdoor environment to the indoor air quality (Godish, 1989). Stanners and Bourdeau (1995), have estimated that in 70 to 80 percent of European cities with more than 500 000 inhabitants, the levels of air pollution, regarding one or more pollutants exceeds the WHO standards at least once per year. Solutions to indoor air pollution problems include source control, avoiding or attenuating the emission of contaminants, air cleaning and appropriate use of ventilation. Air cleaning through filtration can be applied when mechanical or hybrid ventilation systems are used. Installation of suitable filters and the application of effective control strategies are very important tasks for the use of hybrid ventilation systems in polluted areas.

Noise is one urban form of pollution affecting seriously the quality of life. The most important source of noise pollution is the road traffic, aircrafts and railways. The work places for many of the city inhabitants can also be of importance in respect with noise problems. Stanners and Bourdeau (1995), reported that unacceptable noise levels of more than 65 dB(A), affect between 10 to 20 percent of urban inhabitants in most European cities. In parallel, as estimated by OECD (OECD, 1991), almost 130 millions of people in OECD countries are exposed to noise levels that are unacceptable. The integration of noise reduction techniques is a very important aspect and it should taken into consideration when designing hybrid ventilation systems for urban buildings.

The present chapter aims to discuss the most important constraints of the urban environment on the ventilation efficiency of natural and hybrid ventilation systems.

4.1 Wind Distribution in the Urban Environment

The urban wind field is complicated. Small differences in topography may cause irregular airflows. As air flows from rural to urban environment, it must adjust to the new boundary conditions defined by the cities. Wind speeds within the urban canopy are usually reduced in comparison with rural winds at the same height (Oke, 1987).

The wind distribution in urban canyons is determined by the prevailing airflow direction with respect to the canyon axis. Thus, the following wind incidence angles can be observed:

- Perpendicular Wind: When the predominant direction of the airflow is approximately normal (say ± 30 degrees), to the long axis of the street canyon.
- Parallel wind: When the airflow is along the canyon axis.
- Oblique wind: When the airflow is at an angle to the canyon axis.

Different types of air flow regimes are observed as a function of wind incident angle, building (L/H) and canyon (H/W) geometry.

4.1.1 Perpendicular Wind

Three type of air flow regimes are observed as a function of building (L/H) and canyon (H/W) geometry, (T.R. Oke 1988, Hussain and Lee, 1980) (Figure 4.1).

- When the buildings are well apart, (H/W>0.05), their flow fields do not interact. At closer spacing, the wakes are disturbed and the flow regime is known as "Isolated Roughness Flow" (Figure 4.1a).
- 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 (Figure 4.1b). This is characterized 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 (Figure 4.1c). Because high H/W ratios are very common in cities, skimming air flow regime has attracted considerable attention.

Transition between these three regimes occurs at critical combinations of H/W and L/H. Oke (1988), has proposed threshold lines separating the different flow regimes as a function of building (L/H) and canyon (H/W) geometry. The proposed threshold lines are given in Figure 4.2.

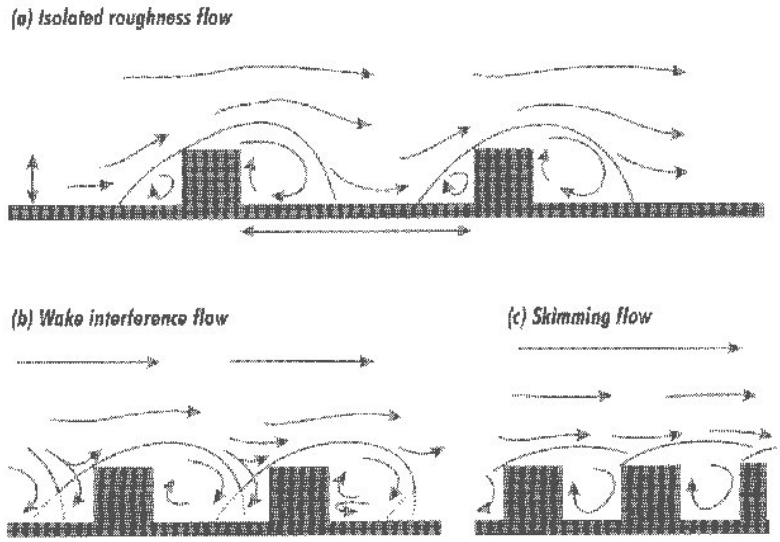

Figure 4.1 : The Flow Regime in Canyon Geometries with Increasing H/W for Perpendicular Wind Incidence Angles (Oke, 1988)

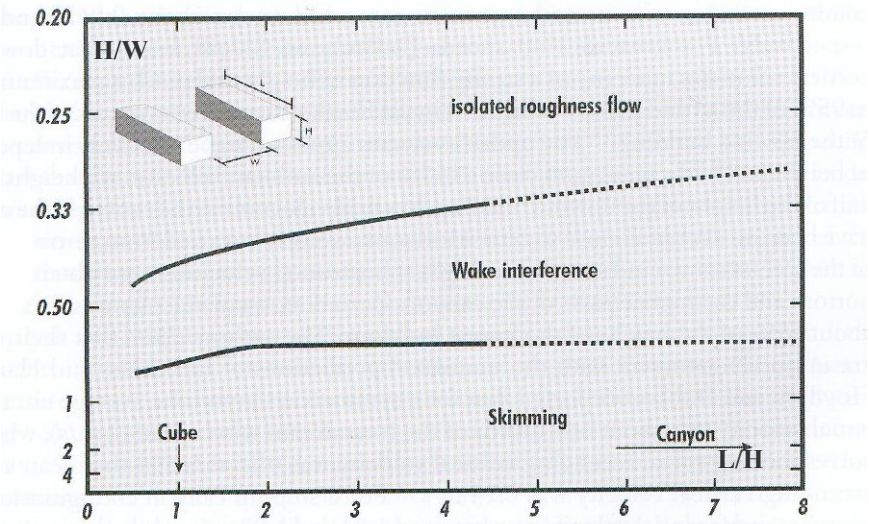

Figure 4.2 : Threshold Lines Dividing Flow into Three Regimes as a Function of Building (L/H) and Canyon (H/W) Geometry (Oke, 1988)

4.1.2 Parallel Wind

Parallel ambient flow generates a mean wind along the canyon axis, (Wedding et al., 1977, Nakamura and Oke 1988), with possible uplift along the canyon walls as airflow is retarded by friction by the building walls and street surface, (Nunez and Oke, 1976). This is verified by Arnfield and Mills (1994), who found that with no along canyon winds the mean vertical canyon velocity is close to zero.

4.1.3 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, (Nakamura and Oke, 1988). 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.

(1973) and Wedding et al. (1977) have also shown that a helical flow pattern develops inside the canyon.

4.2 Wind Profile in Urban Environment

Various empirical models have been developed to describe the flow within and above a street based on field (Louka, 1998) and wind tunnel measurements (Uehara et al., 2000, Davidson et al., 1996). Nicholson (1975) used an exponential formula to describe the wind profile inside a street for perpendicular winds, which approximated the profile in a dense canopy and it will be discussed in detail in the next paragraph.

However, an exponential formula cannot describe adequately the profile with skimming flow characterized by a recirculation-vortex, that limit leads to inverse flow near the canyon floor. Jackson (1978) suggested a power law to describe the mean horizontal velocity at different heights within the street and above the buildings, where the values of the power law exponent varied with wind direction. Besides, Rotach (1995) found that the scaled profiles of mean wind speed within and a real urban street canyon were strongly dependent on stability.

4.3 A Model to Translate Undisturbed Wind Speed in Canyon Data

Knowledge of the air speed inside urban canyons is of high importance for passive cooling applications and especially for hybrid and naturally ventilated buildings. Various methods, simplified or detailed have been proposed to calculate the wind speed inside a canyon. A detailed presentation of the existing methods to calculate the wind speed in urban canyons has been presented by Santamouris (2001). However, air flow in canyons is not always a deterministic problem and prediction algorithms may not be appropriate for any case. In parallel, the boundary conditions are difficult to be defined and are rarely known. Thus, a complete methodology to predict and estimate wind speeds in canyons should be a combination of deterministic and empirical methods.

Based on existing knowledge, an algorithm to estimate the wind speed in canyons, as a function of the geometrical characteristics, the undisturbed wind speed and other boundary conditions has been developed in the framework of URBVENT European Project (2001). The flow chart of the proposed model is presented in Figure 4.3. The inputs of the model are orientation and geometrical characteristics (width, height and length or distance between two main intersections) of the canyon and undisturbed wind speed (wind speed and direction outside canyon). The output is wind speed value at any specific point inside the canyon which is defined by coordinates (x, y, z).

1. If the aspect ratio is lower than 0.7 then it is not considered as a canyon situation and according to Oke (1988) the flow regime is known as “Isolated Roughness Flow” or “Wake Interference Flow” and thus the proposed model cannot be applied. Otherwise one proceeds to the next step.
2. The next calculation is if the ratio of the canyon length and width (L/W) is greater than 20. If not, the end effects dominate (Yamartino and Wiegand, 1986) inside the canyon and extended experimental analysis indicated that a wind speed value of 0.5m/s could be considered as mean (Ghiaus et al., 2005). If it is greater than 20, there is a wind circulation in the canyon and the calculations of the model continue.
3. If the wind speed outside the canyon is greater than 4 m/s, then the algorithms used depend on the wind incidence angle above the building roofs relative to the main canyon axis.
4. If the wind speed outside the canyon is less than 4 m/s and its direction is perpendicular or oblique to the canyon, the empirical values from Table 4.1 can be used, which have been resulted from the experimental measurements (Georgakis and Santamouris, 2005a).

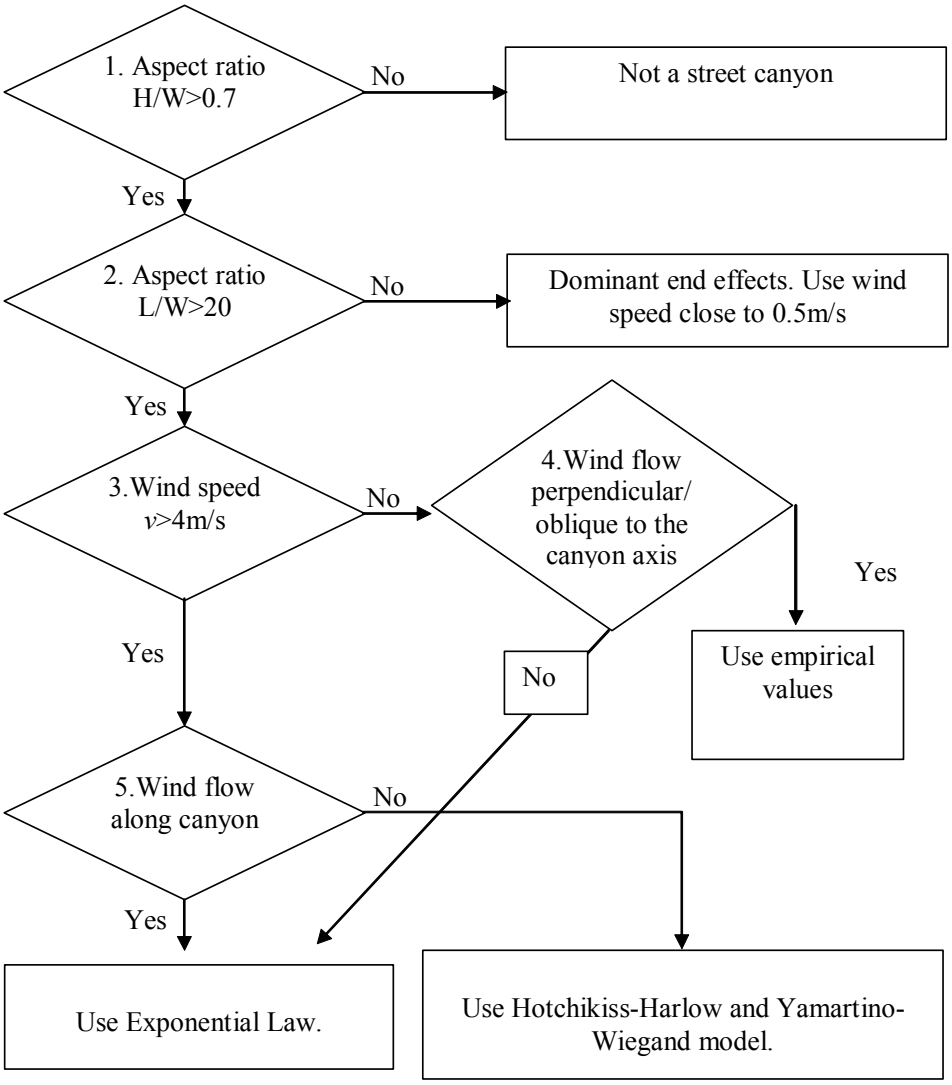

Figure 4.3 : Flow-Chart of the Algorithms and the Empirical Values Used in the Empirical Model for Estimating Wind Speed inside Street Canyons (Georgakis and Santamouris, 2005a)

Table 4.1: Empirical Wind Speed Values Inside Canyon For Perpendicular/Oblique Incidence Airflow Lower than 4m/s (Georgakis and Santamouris, 2005a)

Wind speed outside the canyon (V)	**Wind speed inside the canyon**		
	Near the windward facade of the canyon		**Near the leeward facade**
	Lowest part	Highest part	
V=0	0 m/s	0 m/s	0 m/s
0<V<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

5. a) If the wind incidence angle is parallel to the main canyon axis (with wind speed greater or less than 4 m/sec) the following algorithms are used:

In the obstructed sublayer $0 \leq z \leq h_b$ the following exponential law describes the variation of horizontal wind speed, u_p, with height below rooftops (Nicholson, 1975):

$$u_p = U_0 \exp(\frac{y}{z_2}) \quad (1)$$

and

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

where U_0 is a constant reference speed on the ground level, z_0 is the aerodynamic roughness length and h_b is the mean height of buildings.

The aerodynamic roughness length z_0 is defined as the height where the wind speed becomes zero. Although z_0 is not equal to the height of the individual roughness elements on the ground, there is one to one correspondence between those roughness elements and the aerodynamic roughness length. Once z_0 is determined for a particular surface, it does not change with wind speed, stability and stress.

Typical values of z_0 are given by Oke, (1987) in Table 4.2.

Table 4.2: Typical roughness length values, z_0, for urbanized terrain (Oke, 1987)

Terrain	z_0 (m)
Scattered Settlement (farms, villages, trees, hedges)	0.2-0.6
Suburban Low density residences and gardens High Density	 0.4-1.2 0.8-1.8
Urban High Density, < 5 story row and block buildings Urban high density plus multi - story blocks	 1.5-2.5 2.5-10

5. b) If the wind incidence angle is perpendicular/oblique to the canyon main axis and the wind velocity is greater than 4 m/sec, the following algorithms are used:

In this case the proposed algorithms are based on the study of Hotchkiss and Harlow (1973) and permit the calculation of the cross and vertical wind speed components (v, w). The algorithms consider 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.

The proposed algorithms are the following:

$$v = \frac{\mathrm{A}}{k} \cdot \left[e^{ky}(1+ky) - \beta \cdot e^{-ky}(1-ky) \right] \cdot \sin(kx) \quad (3)$$

and

$$w = -\mathrm{A} \cdot y \cdot \left(e^{ky} - \beta \cdot e^{-ky} \right) \cos(kx) \quad (4)$$

Where

$$k = \pi / W \quad (5)$$

$$\beta = \exp(-2kH) \quad (6)$$

$$A = ku_0 / (1 - \beta) \quad (7)$$

$$y = z - H \quad (8)$$

And u_0 is the wind speed at the top of canyon and at point x=W/2, z=H.

The above-mentioned algorithms were tested and approved by Yamartino and Wiegard (1986). Additionally, the same authors have proposed the following expression to calculate the along canyon wind speed component, *u(z)*:

$$u(z) = u_r \cdot \log[(z + z_0)/z_0] / \log[(z_r + z_0)/z_0] \quad (9)$$

Where u_r is the wind speed value at reference height z_r and z_0 is the surface roughness.

The horizontal wind speed inside the canyon is:

$$V_h = (u^2 + v^2)^{0.5} \quad (10)$$

Also, the total wind speed inside canyon at any point (x , y , z) is:

$$V_{tot} = (V_h{}^2 + w^2)^{0.5} \quad (11)$$

A drawing to explain the various wind speed components (u, v, w, V_h and V_{tot}) is illustrated in Figure 4.4.

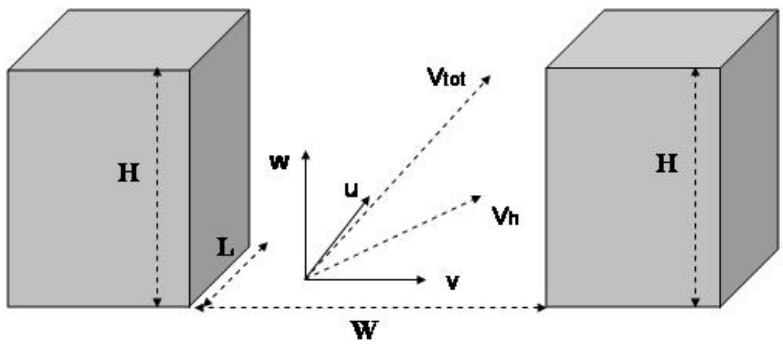

Figure 4.4 : Illustration of Various Wind Speed Components

The above described methodology has been integrated into a software tool (Georgakis and Santamouris, 2005c), running under Matlab 6.5 programming environment (Figure 4.5).

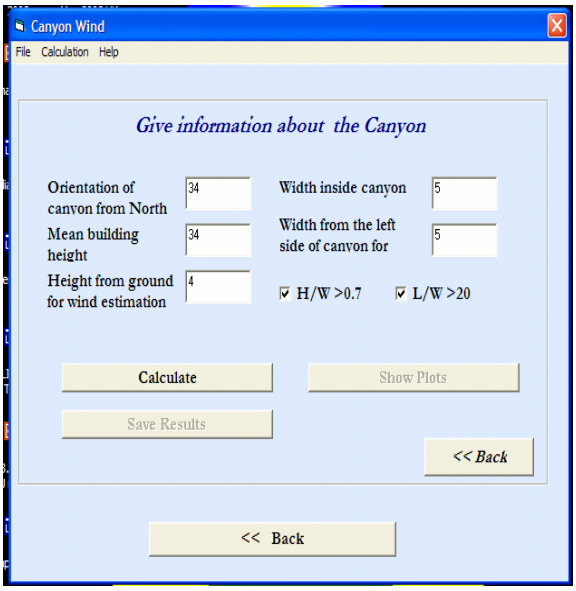

Figure 4.5 : Canyon Tool Used for the Estimation of Wind Speed Inside a Canyon Based on the Undisturbed Wind Flow (Georgakis and Santamouris, 2005c)

4.3.1 Experimental Validation of the Model of Wind Speed in Street Canyons

The empirical model proposed for the estimation of wind speed inside canyons has been validated with the experimental data from the measurements conducted in the framework of the URBVENT project. Experiments were performed in five different pedestrian streets, located in different neighbourhoods in the centre of Athens, during summer 2001.

4.3.1.1 Field Experiments in Urban Canyons

The geometrical characteristics of each canyon, as well as, the description of the experimental measurements are given in Table 4.3.

The meteorological station of the University of Athens was placed in the centre of each urban canyon for three days, on a 12-hour basis during day period. The mobile meteorological station was installed on a vehicle equipped with a telescopic mast of 15.5m. On the telescopic mast, anemometers and thermometers were placed at four different heights (3.5m, 7.5m, 11.5m and 15.5m) in order to record every 30 seconds the following measurements in the middle of the canyon:

- Air temperature and
- Wind speed and direction

Simultaneously, wind speed on three orthogonal axes was measured near the façades of the canyon, as well as, the air temperature and wind speed and direction outside the canyon. Every hour, infrared measurements of the temperature of canyon façades were recorded. The above types of measurements have been performed with the experimental instrumentation, which is described below:

- ***Air temperature measurements outside the canyon:*** A miniature ambient air temperature sensor was placed in the top of each canyon, on the roof of one building. The sensors were shielded inside a white-painted wooden cylinder, opened on two sides in order to allow air circulation.
- ***Surface temperature measurements:*** An infrared thermometer equipped with a laser beam measured the surface temperature. The surface temperatures of the exterior façades of the buildings were measured on a grid of 1m. All measurements were performed from the street level. The pavement and road temperatures were measured, as well, at different points along the width of the canyon in both sections defined above. All measurements were performed on an hourly basis for 12 hours during daytime period.
- ***Wind speed measurements near canyon façades:*** A three-axis anemometer was used to measure the three components of the wind speed inside the canyon near the façades of the canyon. The

anemometer was mounted on the exterior façade of a building in the canyon and at a distance of 1 to 2m from the wall.

- ***Wind speed and direction measurements outside the canyon:*** A cup anemometer has been placed on the top of the canyon at a distance of 6m from its top level in order to measure the wind speed and direction out of the canyon.

4.3.1.2 Validation of the Airflow Model

The concise model for the estimation of wind speed in street canyons was validated with the experimental data from URBVENT Program. The validation of the previously discussed model is presented in Figure 4.6. The results of the experimental procedure are given in the form of box-plots for various clusters of the measured horizontal wind speed component, V, above the top of the buildings. A box-plot was used as a graphic representation of the data distribution, which 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. In each box plot two red lines are plotted in order to present the calculated values derived from the model. For the goodness of fit between the experimental measurements of wind speed inside a canyon and the estimated values, the t-test of the differences of mean values was applied, taking into account the variation of the samples (Georgakis et al., 2004). The comparison for the two set of values led to the conclusion that the predicted values could be characterized as satisfactory. This statistical analysis indicated a very good agreement between experimental and model values. Occasionally, the described models lead to an overestimation of wind speed values outside a canyon of greater than 7m/s.

Table 4.3: Description of Canyon Geometries and Experimental Measurements During Summer 2001 (Urbvent, 2001)

Canyon		**Ermou**	**Miltiadou**	**Voukourestiou**	**Kaniggos**	**Dervenion**
Orientation from the North (0°)	(degrees)	92°	45°	45°	12°	327°
Canyon width	(metres)	10m	5m	10m	9m	7m
Canyon length	(metres)	200m	100m	100m	70m	200m
Canyon height	(metres)	20m	15m	15m	22m	23m
Canyon aspect ratio	(*H/W*)	2	3	1.5	2.5	3.3
Air temperature measured inside the canyon	(metres from ground)	3.5m, 7.5m, 11.5m, 15.5m	3.5m, 7.5m, 11.5m, 15.5m	3.5m, 7.5m, 11.5m, 15.5m	3.5m, 7.5m, 11.5m, 15.5m	3.5m, 7.5m, 11.5m, 15.5m
Wind speed and direction inside the canyon	(metres from ground)	3.5m, 7.5m, 11.5m, 15.5m	3.5m, 7.5m, 11.5m, 15.5m	3.5m, 7.5m, 11.5m, 15.5m	3.5m, 7.5m, 11.5m, 15.5m	3.5m, 7.5m, 11.5m, 15.5m
Height of the two three-axes anemometer	(metres from ground)	7.5–10.5m	8–8m	5–12m	5–10m	20–9m
Height of the wind speed and direction anemometer outside the canyon	(metres)	26m	21m	21m	28m	29m
Height of the thermometer outside the canyon	(metres)	20m	15m	15m	22m	23m
Duration of experiment	(days)	28, 29 June, 3 August 2001	31 July, 2, 3 August 2001	7, 9, 10 August 2001	27, 28, 29 August 2001	4, 5, 6 September 2001

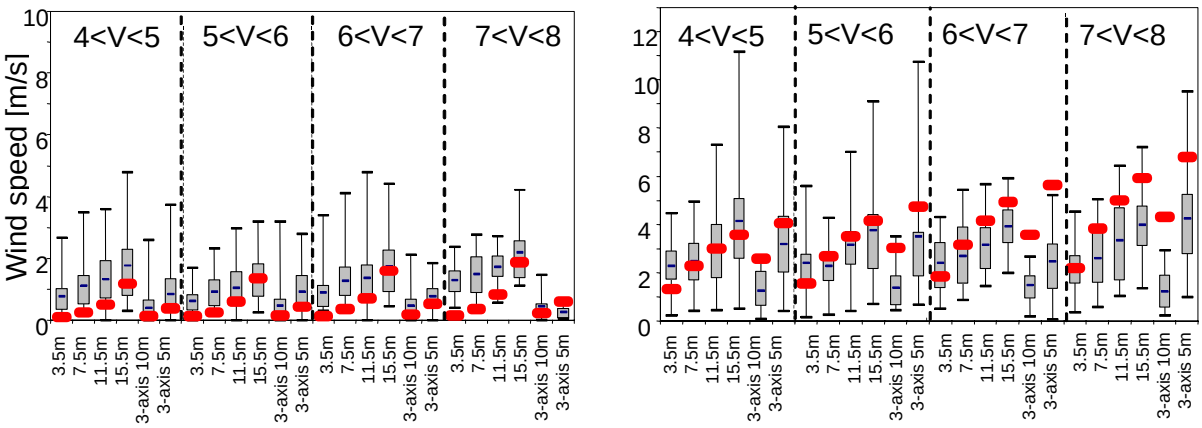

Figure 4.6 : Examples of validation of wind speed in street canyons: (a, left) Nicholson Model; (b, right) Hotchkiss Model. The experimental data are shown with the form of boxplots, the prediction of the model is figured in bold segments (Georgakis et al., 2004)

4.4 Temperature Distribution in the Urban Environment

The temperature distribution in the urban canopy layer is highly affected by the urban net radiation balance. The incident solar radiation on urban surfaces is absorbed and then it is transformed to sensible heat. Most of the solar radiation impinges on roofs, and on the vertical walls of buildings and only a relatively small part reaches the ground level. Because the radiant heat loss is slower in urban areas the net balance is more positive than in the surrounding rural areas and thus higher temperatures are presented.

The optical and thermal characteristics of materials used in urban environments, especially the albedo for solar radiation and emissivity for long-wave radiation, have a very important impact on the urban energy balance. The use of high albedo materials reduces the amount of solar radiation absorbed in building envelopes and urban structures and keeps their surfaces cooler. Materials with high emissivity are good emitters of long-wave radiation and readily release the energy that has been absorbed as short-wave radiation. Lower surface temperatures decrease the temperature of the ambient air because heat convection intensity from a cooler surface is lower (Santamouris, 2001).

4.5 Urban Pollution

Outdoor pollution and inadequate ventilation may be the primary causes of poor indoor air quality in buildings. Air pollution, noise and traffic are of major concern. The relative importance of different air pollutants and sources has changed with time and culture in the different geographical areas. Nowadays, the dominant sources of atmospheric pollution, in certain European cities, are motor vehicles and combustions of gaseous fuels. Monitoring of 356 buildings with public access has shown that in approximately 50% of the buildings, incorrect ventilation rates were the primary cause of illness complaints and poor air quality (Wallingford and Carpenter, 1986). Increased outdoor concentrations seriously affect the indoor concentration of pollutants.

The significance of urban pollution in relation to ventilation air supply was studied by Ajiboye et al. (1997) at five urban sites in England. Three places were located in London and the other two in Birmingham and in Cardiff. The studied pollutants were NO_2, SO_2, O_3 and PM_{10}. Newly proposed DOE figures defining poor air quality have been used to examine the frequency of excess pollution events between 1992 and 1995. The results identify the most appropriate periods for natural ventilation of offices in urban areas. Preliminary in-situ experiments also demonstrate that both PM_{10} and NO_2 concentrations decrease with increasing height from the ground in a busy road.

4.5.1 Outdoor/Indoor Pollutant Concentration Ratios

Green et al. (1998) investigated experimentally the impact of traffic pollution on a naturally ventilated building in Nottingham, UK, situated close to a busy road. They showed that when the building was downwind of the traffic source the concentration of CO was on average four times higher in a ground-floor room than when the wind was from a large traffic-free area. The relationship between indoor and outdoor CO concentrations was found to change during the day depending on the relationship between outdoor concentration on the ground level and at the first-floor windows.

Liao et al. (2004) applied a simple size-dependent indoor air quality model to predict the size-dependent I/O ratios of PM mass and selected chemical species of sulphate and nitrate for urban and suburban naturally ventilated homes in Taiwan and compared the results with empirical evidence. The ambient particle concentrations were measured on a 24-hour basis samples over a weeklong period during April 2001. The results demonstrated that the PM I/O ratios for a wind-induced natural ventilated airspace depended strongly on the ambient particle distributions, building openings design (e.g. height-to-length ratio of openings and roof slope), wind speed, wind angle of incidence and outdoor PM metrics.

Ghiaus et al. (2006) reported that for the study of indoor pollutant concentrations, two very important aspects are the type and level of outdoor pollution. Experiments in URBVENT (2001) and PRIMEQUAL (2001) projects showed that the indoor–outdoor pollutant ratios (I/O) depend on the facade airtightness and the outdoor pollutant concentrations. A number of real-scale experiments were conducted for the measurement of I/O ratios of ozone, nitrogen dioxide and PM. The most important reduction was found for ozone, with I/O ratio varying from 0.05 to 0.33 (higher I/O ratio was measured for higher outdoor ozone concentration). The I/O ratios for nitrogen dioxide were between 0.05 and 0.95, while the smaller values were observed for higher outdoor concentrations. For PM, the I/O ratios ranged between 0.20 and 0.70, with the measured values depending on the outdoor concentration and on the size of the particles.

Other existing experimental research studies for I/O concentration ratios in residential buildings have been summarized by Sherman and Matson (2003) and are reported by Clayton et al. (1993), Wilson and Suh (1997), Levy et al. (1998), Thatcher et al. (2001), Shelton et al. (2002), LaRosa et al. (2002), Wallace and Howard-Reed (2002). The studied pollutants were NO_2, total fungi, ozone and PM. Similar measurements have been reported by Flachsbart (1999) for CO in offices and other occupational settings). In all these studies the most significant factors controlling the I/O ratio were the presence of indoor sources, the geometry of infiltrating route, the loss mechanisms such as deposition and the particle sizes in case of particle pollutants.

4.5.2 Ventilation Strategies to Reduce Exposure to Outdoor Pollutants

In order to provide indoor air quality in buildings, the best strategy is to dilute indoor sources with outdoor air. This strategy assumes that the outdoor air does not have pollutants at harmful levels or that the outdoor air is, at least, less polluted than the indoor air. When this is not the case, as it happens in the urban environment then more sophisticated solutions need to be employed. Ajiboye (1998) has developed an interactive design tool that provides best practice guidelines for sizing, locating and determining pollution attenuation features of air inlets suitable for naturally ventilated office buildings in urban areas. Location of ventilation air inlets affects the quality of indoor air, therefore it is essential that they are located in ways that minimise the ingress of external pollutants. Potential pollution avoidance strategies include locating vents on sheltered facades and positioning central inlets at a sufficient height from emissions. Wind flow patterns around buildings have an important impact on air quality and a simple model is discussed that determines the decrease in pollutant concentrations between emission sources and air intakes.

Kukadia et al. (1998) has prepared a review which examines available information relating to the ingress of external pollutants into naturally ventilated buildings. The purpose of the review was to guide this project whose longer term aim was to provide guidance on ventilation strategies for

naturally ventilated buildings in polluted urban areas. It covers current ventilation strategies, existing measurements of internal/external pollution levels, urban air quality and long term air quality strategies, building ventilation and the dispersion of pollutants around buildings as they affect the ingress of pollutants. '*The review confirms the need for the investigatory part of the project, which is to monitor internal/external pollution levels and carry out a common experiment looking at pressures and concentrations on the surfaces of buildings in urban areas'*.

Guidance on the use of ventilation control to reduce the effect of outdoor pollution on IAQ was prepared by Fletcher (1998). Ventilation control is defined as the control of ventilation as a function of outside air pollution. '*The guidance shows building operators how to reduce the impact of traffic emissions on the indoor air quality of their buildings, by determining if outdoor air quality is poor, assessing alternative ventilation control strategies if outdoor air quality is found to be poor, and selecting and implementing an appropriate control strategy'*. The publication includes detailed control configurations for use by control companies or system houses. Guidance on suitable sensors and the integration of ventilation controls with existing IAQ controls is provided based on computer modelling and the results of strategy tests in actual buildings.

Besides, CIBSE (1999) has prepared a technical note which provides guidance on the nature and characteristics of pollutants in the outdoor air and how this impacts on indoor air quality. This Technote aimed to help designers considering carefully the position of ventilation inlets in order to minimise cross contamination from a range of polluting sources. Besides, a generalised method is described for the prediction of indoor air quality for any ventilation strategy and a defined profile of external air quality and internal pollution load. Furthermore, a number of ventilation strategies for modern buildings may be found in Liddament (2000).

Sherman and Matson (2003) discuss a number of different strategies which could be applied in residential buildings in order to ensure adequate indoor air quality against potentially income hazardous outdoor pollutants, including widespread pollutants, accidental events and potential attacks. These strategies include ventilation systems (supply ventilation with filtration or exhaust ventilation), filtration (gas phase filtration, stand-alone high efficiency particle filtration system) and other measures.

4.6 Urban Noise

Noise is one of the most important considerations when the potential for natural ventilation is to be assessed in an urban site. As a result, noise is often used as an argument against natural ventilation and thus air-conditioning is used instead. Methods of estimating noise levels in urban canyons are necessary if the potential for naturally ventilated buildings is to be assessed.

Existing research related to the noise limitations on the use of natural ventilation in urban areas has been reported by Wilson (1992) and Nicol et al. (1997). Nicol and Wilson (2004) describe a series of noise measurements that which made in nine street canyons, with aspect ratio (height/width) varying from 1.0 to 5.0, in Athens during September 2001. The main purpose of the measurements was to examine the vertical variation of noise inside the canyons in order to give advice on natural ventilation potential. '*A simple model to predict the fall-off (attenuation) of the noise level with height above street level has been developed using a linear regression analysis of the measured data. The attenuation is found to be a function of street width and height above the ground but the maximum level of attenuation (at the top of the canyon) is almost entirely a function of the aspect ratio except in narrow streets'*.

4.6.1 Noise Control Strategies for Natural Ventilation

A number of noise control strategies for natural ventilation systems have been reviewed by Salis et al. (2002) and analysed with respect to their noise insulation and airflow characteristics. Theoretical analysis of airflow and sound reduction index to road traffic was performed for a typical facade containing a treated aperture. It was suggested that with appropriate design of noise insulation,

adequate airflow rates can be provided in buildings to ensure indoor air quality. The authors have pointed out that further research into the use of hybrid ventilation is needed in order to enhance the possibility to apply natural ventilation in areas with increased noise levels.

5 State of the Art of Natural and Hybrid Ventilation in the Urban Environment

5.1 Experimental Studies of Natural Ventilation and IAQ

5.1.1 Full-Scale Experiments

A study by Phillips et al. (1993) of four naturally ventilated buildings in UK concluded that the air change rate was the determining factor for air quality, namely, the greater the supply of external air, the greater the presence of external pollutant indoors.

Kukadia et al. (1996,1998) and Kukadia and Palmer (1998) carried out ventilation and air pollution measurements, over a one-week period in winter 1996, to investigate the internal and external air pollution levels in two adjacent buildings, one naturally ventilated and the other one air-conditioned in an urban area, in the centre of Birmingham. The concentrations of sulphur dioxide, nitrogen oxides, carbon monoxide and carbon dioxide were monitored inside and outside the buildings, in order to investigate their relative indoor attenuation and to compare it with existing air quality guidelines. '*Internal pollutant levels were higher in the naturally ventilated building than in the air-conditioned one, while they followed the external variation but at reduced levels. However, there were times when the combustion products from heating boilers entrained into the air-conditioned building via the high-level air inlets of the ventilation system thus,. resulting in higher indoor concentrations of nitrogen oxides, sulphur dioxide and carbon dioxide than in the ambient air'*.

Collignan et al. (2001) have performed an experimental study of ventilation and pollutant measurements (CO, SO_2, NO, NO_2, O_3, VOC, $PM_{2.5}$ particles and black smoke) in a dwelling placed in a polluted area, in Paris, during winter and summer period 2000. The main objective was to analyse the impact of natural and mechanical ventilation strategies, seasons, climate, the presence of absorptive surfaces and physical and chemical reactions on the indoor concentration of pollutants in relation to the outdoor pollution. This study reveals the difficulty in adopting ventilation strategies in order to prevent the transfer of outdoor urban pollution inside buildings. Because of the different pollutant concentrations during the day period, '*a low ventilation strategy during peak hours would result in an under ventilated indoor environment. It is recommended to situate the air inlets on the less exposed facades to outdoor pollutants'*. The authors propose that gaseous filtration and tight building envelopes are effective solutions in order to ensure indoor air quality levels against the outdoor polluted environment.

An experimental investigation of natural ventilation and indoor air quality in urban school buildings was performed by Synnefa et al. (2003) during May 2002 in Athens, Greece. Experiments were performed in fifteen school classrooms where the air-exchange rates and indoor concentration levels of various pollutants such as CO_2, CO, TVOC, HCHO, and radon were measured. Moreover, the experimental investigation included measurements of several environmental parameters such as temperature, relative humidity and air velocity inside each classroom while ventilation was examined by estimating the air changes using the tracer gas technique. From the above investigation it was found that the indoor air quality inside the classrooms is strongly related to the number of occupants and their activities. The pollutant concentrations measured inside the classrooms were lower while the relative limit values did not create any problem for the occupants. Ventilation levels were insufficient and mechanical ventilation was nearly non-existent.

5.1.2 Night Ventilation Experiments

The potential of night ventilation techniques, when applied to real urban buildings, has been investigated experimentally and theoretically by Geros et al. (1999) under different structure, design, ventilation and climatic characteristics. Also, the impact and the limitations of night ventilation techniques regarding the thermal behaviour of various types of buildings were studied. Full-scale measurements were performed in three buildings operating under free-floating and air conditioning conditions in central Athens during the summer of 1995 and 1996. In all buildings, continuous measurements of the indoor temperature distribution, as well as, of the air flow rates were performed, when night ventilation was applied. It was found that night ventilation had a particularly significant impact on the building with the highest thermal mass resulting in daytime temperature reduction up to 2.5ºC under free floating conditions and 1ºC under air conditioned operation. The exact contribution of night ventilation for a specific building is a function of the building structural and design characteristics, the climatic conditions, the site layout, the applied air flow rate, the efficient coupling of air flow with the thermal mass of the building and the assumed operational conditions. Appropriate design of night ventilation systems requires exact consideration of all the above parameters and optimization of the whole procedure by using exact thermal and air flow simulation codes.

5.1.3 Wind Tunnel Studies

Jozwiak et al. (1996) have investigated the influence of wind direction on natural ventilation in apartment buildings in a series of wind tunnel experiments in urban boundary layer. The research was initiated after the fatal accidents of suffocation by carbon monoxide coming from gas heaters which were recorded in eleven-storey apartment buildings which had windows situated on the leeward side, during strong winds in southern Poland. The wind tunnel consisting of six adjacent buildings and on a natural-scale isolated roof ventilation shaft outlet. The wind speed varied between 1m/s and 57m/s, while the boundary layer wind speed profiles were modelled for an urban environment. Walls and roof pressure distribution were obtained and pressure differences between windows and the ventilation shaft outlets on the roof have been calculated. The influence of adjacent buildings on the ventilation performance of the reference building was studied. Significant differences in pressure distributions, with and without modelling the boundary layer, as well as, the neighbouring buildings shows the importance of modelling these two parameters.

Sharples and Bensalem (1998, 2001) report a wind tunnel study which was carried out to investigate the airflow through courtyard and atrium building models located within an urban setting and exposed to an urban atmospheric boundary layer. Ventilation strategies resulting from the use of different courtyard and atrium pressure regimes (positive pressure and suction) were examined. The model buildings were monitored in both isolated and idealized urban environments considering different layout densities. The effect of wind direction was also investigated. The results of the study suggest that the open courtyard in an urban environment had a poor ventilation performance whilst an atrium roof with many openings under a negative (suction) pressure regime was the most effective. For oblique wind incidence angles (45°) relative to the building facades, then smaller airflow rates were observed in all model studies in comparison with perpendicular wind directions.

5.2 Theoretical Studies of Natural Ventilation

5.2.1 Based on Field Measurements

Estimations of the real potential of natural ventilation techniques when applied to buildings located in urban canyons have been reported by Santamouris et al. (2001). Simulations of the air flow processes were carried out and reported for ten different canyons in which wind speed and temperature data were collected in a number of field measurements in the framework of POLIS European research project. Single-sided and cross-ventilation configurations were considered for a typical building zone with a window opening in each canyon facade. Two types of simulations have been performed for each configuration using the AIOLOS natural ventilation program (Allard, 1998) validated within the framework of the PASCOOL research project (Limam et al., 1997). The first was based on the wind and temperature data measured inside the canyon, while the second one was based on the undisturbed

temperature and wind speed measured above the buildings. It has been found that the potential of natural ventilation techniques when applied to buildings located in urban canyons is seriously reduced because of the important reduction of the wind speed inside the canyon. Air flow reduction may be up to 10 times than the flow that corresponds to undisturbed ambient wind conditions. Efficient integration of natural and night ventilation techniques in dense urban areas requires detailed knowledge of wind and airflow characteristics, as well as, adaptation of the ventilation components to the local conditions.

Geros et al.(1999, 2001) have calculated the reduction of the performance of night-ventilation techniques when applied to naturally ventilated buildings located in urban canyons. The study was performed for the same reference building, as described above, for all ten canyons in Athens for which experimental data were available. The application of night ventilation techniques has been studied in a typical single zone room and various simulations have been performed under controlled and free-floating operation, when single-sided and cross ventilation are considered, during night period. The influence of the urban microclimate on the efficiency of the technique has been studied by considering the examined zone inside and outside the experimental urban canyons. The comparison of the results permits to evaluate the impact of the urban canyons on the effectiveness of night ventilation techniques. The performed analysis shows that due to the increase of air temperature and the decrease of wind velocity inside canyons, the potential of night techniques can be significantly reduced.

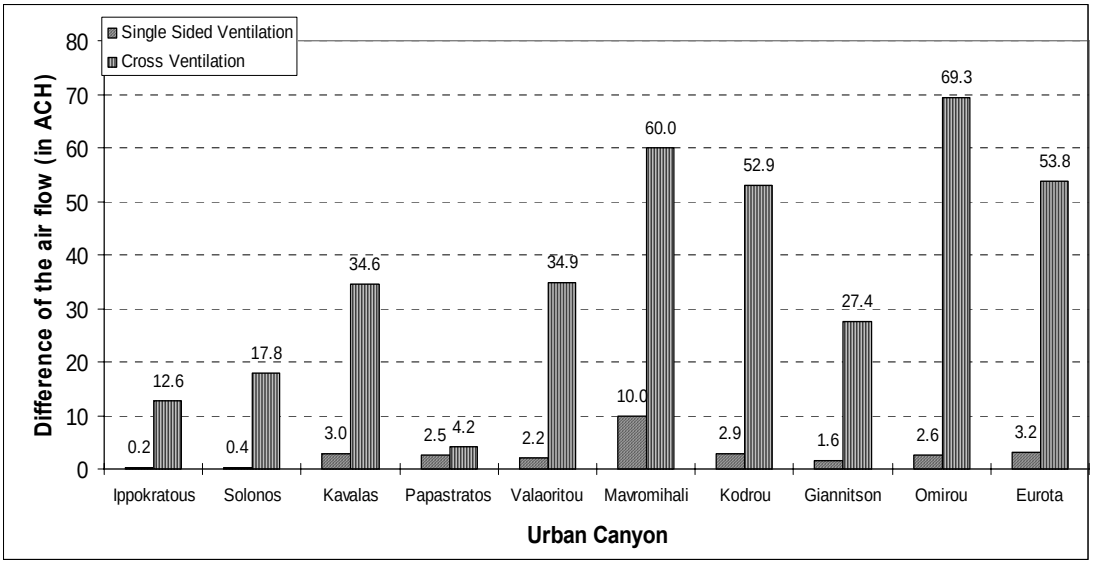

Figure 5.1 : Reduction of Air Change Rate for Single Sided and Cross Ventilated Buildings in Ten Urban Canyons (Geros et al., 2001)

Kolokotroni et al. (2001) used monitoring results of air and slab temperatures, during summer 1997, in order to investigate passive ventilation cooling for an educational building which houses the Faculty of the Built Environment of Portsmouth University (UK). Based on the monitored conditions, a simplified thermal and ventilation model was calibrated and simulations were carried out to quantify the effect of external weather in relation to provided ventilation and shading. It was shown that by using simple controls based on external temperature, radiation and internal gains, it is possible to improve the performance of the building, so that periods of uncomfortable conditions are avoided under certain conditions.

In another study, Kolokotroni et al. (2006) investigated the effect of increased air temperatures, due to the London urban heat island, on the effectiveness of stack night ventilation strategies for office buildings. Real air temperature measurements, carried out in London in 1999/2000 to quantify the London Urban Heat Island Intensity, were used to perform a parametric analysis on the cooling demand and potential for night cooling ventilation for typical offices. The study was applied by using

a thermal and air flow simulation tool specifically designed for London office in SE England. Two representative weeks were studied, one with extreme hot weather and one with typical hot weather in the centre of the London heat island as well as in a rural reference site. Results indicated that increased urban temperatures should be taken into account as they resulted in significant deviations rather than when using standard meteorological weather data.

5.2.2 Based on Parametric Models

Moeseke et al. (2005) investigated the potential of wind driven ventilation in urban areas. A number of dynamic simulations were performed, using the TAS program, for a standard office building using pressure coefficients obtained from a parametrical model. A sensitivity analysis was carried out considering two major parameters: wind incidence (0°, 45°, 90°) and environment density. Three terrain configurations were studied: open, suburban and urban. It is shown that for the study of natural ventilation it is necessary to estimate the horizontal pressure gradients. It was found that different wind incidence angles induce different air movements, while the environment density affects the estimated air changes per hour (ACH).

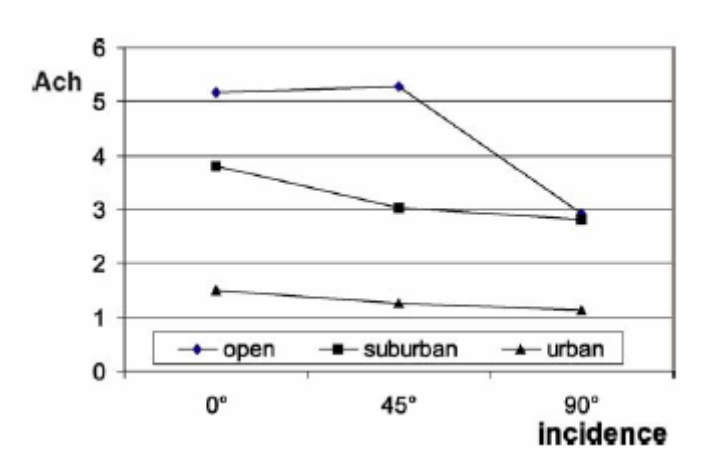

Figure 5.2: Mean ACH Values (h^{-1}) on Windward Side of an Office Building for Different Environmental Densities (Moeseke et al., 2005)

5.2.3 Based on Empirical Models

A number of simplified or detailed methods have been developed for the design of natural ventilation in urban buildings, considering realistic wind speeds. The proposed methods calculate the impact of the building location on the effectiveness of natural ventilation. The existing methods focus on the estimation of wind speeds or air flow rates due to building location and shielding effects.

A simplified but quite comprehensive method has been deployed by the Florida Solar Energy Center. In order to take into account for the effects related with the reduction of the wind speed because of building location, a 'Terrain Correction Factor', TCF, has been proposed for the estimation of air change rates. The proposed values are given in Table 5.1 for day and night period.

The same method proposes a reduction coefficient in order to compensate for the shielding effect from adjacent buildings. The coefficient is a function of the wall height of the upwind building, h, and of the distance between the studied building and the adjacent upwind building, g. The values of the Neighbourhood Correction Factor, as a function of the ratio g/h, are given in Table 5.2.

Finally, the real air flow rate is estimated from the design air flow rate multiplied by the Neighbourhood Correction Factor and the Terrain Correction Factor.

Table 5.1: Terrain Correction Factor (Vollebregt and Boonstra, 1998)

Terrain Type	TCF, 24 hours ventilation	TCF, Night only ventilation
Oceanfront or > 3 miles water in front	1.30	0.98
Airports or flatlands with isolated-wall separated buildings	1.00	0.75
Rural	0.85	0.64
Suburban or Industrial	0.67	0.50
Centre of Large City	0.47	0.35

Table 5.2: Neighbourhood Correction Factor (Vollebregt and Boonstra, 1998)

Ratio g/h	Neighbourhood Correction Factor
0	0.00
1	0.41
2	0.63
3	0.77
4	0.85
5	0.93
6	1.00

5.3 Methodologies/Techniques to Assess Potential of Natural Ventilation

Roulet et al. (2002) mention that *'natural ventilation potential (NVP) is defined as the ability to ensure at a given urban site, an acceptable indoor air quality by natural ventilation only. Passive cooling potential (PCP) is the possibility to ensure an acceptable summer comfort using natural ventilation.*' Additionally, they have developed a method to assess the site natural ventilation potential. This is defined as '*the potential of the site of having good ventilation, provided that an appropriate building is or will be built on'*. A multicriteria evaluation is applied consisting of meteorological (macroscale wind speed and temperature distribution, solar radiation and air moisture) and urban criteria (microscale wind speed and temperature distribution, building layout and height, outdoor noise and pollution levels, indicators of the urban context, etc). Then, the geographic information system (GIS) is used to represent the NVP at each location as a new GIS layer. This methodology constitutes a necessary tool for the designer to choose an appropriate location to construct a well ventilated building or the location of an old building having the possibility, after refurbishment, to be well ventilated. However, the lack of GIS data on a global basis constitutes a major disadvantage for the wide application of this methodology.

Germano et al. (2004) have developed a tool to estimate natural ventilation potential, as well as, the passive cooling potential of urban buildings. First, natural ventilation driving forces and constraints are assessed using comfort criteria, statistical meteorological data and user-provided information. Then, the site of interest is compared with other well known sites using criteria related to both natural ventilation driving forces and constraints. This method compares and ranks the site using a qualitative multicriteria procedure. The result of the comparison shows if the assessed site has higher potential of natural ventilation than a set of other known sites.

In another study, Yang et al. (2005) have proposed a simple prediction model to estimate the potential of natural driving forces in Chinese residential buildings. In the research study it is clarified that '*the potential of natural driving forces is a much narrower concept than the potential of natural ventilation. It depends on the indoor and outdoor air temperature differences, the wind conditions, as well as, the building terrain and surrounding conditions'*. The authors have introduced the concept of the pressure difference Pascal hours (PDPH) for natural ventilation, in accordance with degree-days method. A high PDPH value means a great potential for application of natural ventilation. In addition,

hourly effective pressure differences can be obtained and analyzed statistically. This method requires only the hourly weather data (including air temperature, wind speed and direction) and basic parameters such as building height, wall areas, opening ratio, number of people, floor areas and terrain conditions. The concept of pressure difference Pascal hours itself, cannot be used directly for design purposes, but provides guidance on the availability of natural driving forces. This information can help the designers to determine the building opening size, or to assess whether or when mechanical ventilation is necessary. The application of the model can be a simple design tool at preliminary design stage especially in urban areas where the potential of natural driving forces is expected to be limited due to low wind speeds.

As it concerns methodologies to assess the potential of direct ventilative cooling techniques, important tools have been developed in the frame of the URBVENT research project of the European Commission. Ghiaus and Allard (2002) have developed a method to assess the potential of direct natural ventilative cooling using degree hours data.

Axley and Emmerich (2002) have developed a method to evaluate the climate suitability of a given location for direct ventilative cooling and complimentary nighttime ventilative cooling of a building. This method allows the building designer to evaluate the feasibility and potential effectiveness of ventilative cooling strategies, by estimating the required ventilation rates given knowledge of the possible internal gains of the building. On the whole, the proposed methodology can be applied to ventilative cooling implemented by natural, mechanical, or mechanically assisted driving forces.

5.4 Experimental Studies of Hybrid Ventilation

Only a minor number of real urban buildings with hybrid ventilation systems were found in the literature. An extended review of hybrid ventilation systems, as well as, of the existing applications is provided by (Delsante and Vik, 2002) in the framework of Annex 35 (Hybrid Ventilation in New and Retrofitted Office Buildings, IEA). A number of 22 buildings are presented which are low to medium-rise buildings, located in areas with little or moderate dust and noise pollution. Some of them are office (etc. Pihl & Son HQ, Fujita Technology Development Division, NIWI Amsterdam) or educational (Egebjergskolen) buildings located in urban terrain, where the main ventilation principle is stack effect with fan assistance and the main control strategy is temperature control. Results from the first generation hybrid ventilated buildings, show that such a technique has a very high cooling potential.

Niachou et al. (2005a, 2007) performed an experimental campaign, in the frame of RESHYVENT European project in two urban street canyons in Athens in order to investigate the impact of the urban environment on natural and hybrid ventilation. Natural ventilation experiments consisted of single-sided and cross ventilation. Hybrid ventilation was focused on fan-assisted natural ventilation, where supply and extract fans were used to enhance pressure differences by mechanical fan assistance. 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. From the number of ventilation experiments performed under calm conditions (wind speed lower than 0.2m/s), it has been found that hybrid ventilation has a small advantage over natural ventilation with regard to ACH values.

Other research studies of real non-urban buildings with hybrid ventilation systems have been reported by Arnold (2000), Braham (2000), Ring and Brager (2000), Aggerholm (2001 and 2002), Schild (2001), Wahlstrom and Nielsen (2001), Hendriksen (2001 and 2002), Van der Aa (2002), Yoshino et al. (2002), Brohus et al. (2003), Principi et al. (2003) and Rowe (2003). Most of these buildings are office or educational buildings, which are mostly found on a European level, however very few studies provide real monitored data.

5.5 Theoretical Studies of Hybrid Ventilation

5.5.1 Based on Parametric Models

Jreijiry et al. (2005) compared the performance of a reference mechanical exhaust and a hybrid ventilation system developed in the framework of the European project RESHYVENT. Two demand control strategies were developed for the hybrid ventilation system, where the first one was based on occupant detection and the second one was based on indoor CO_2 levels. The performance of the two ventilation systems was studied through a number of yearly simulations which were performed for four European climates (Athens, Nice, Stokholm and Trappes) using SIMBAD building and HVAC toolbox. The hybrid ventilation system was found to have a better performance with respect to indoor air quality and electrical consumptions of the fan, compared with the reference mechanical exhaust ventilation system because it optimized the use of natural ventilation mode.

5.5.2 Based on Design Methods

Fracastoro et al. (2001) have developed a simple tool to assess the feasibility of hybrid ventilation systems at the early design stages. It is a simplified method which enables the designer to determine the permeability of the building envelope in order to ensure the required ACH. This method requires information about building typology and surrounding terrain, together with the test reference year of the location. The effective pressure difference across the envelope is determined as a function of outdoor-indoor temperature difference and wind velocity. A graphical procedure is then used, given the overall permeability of the building envelope, to estimate the time period during the heating season when natural ventilation exceeds the required air change rate. Then, the designer can decide either the increase of building permeability using natural airing devices, or to determine the necessary time period for mechanical ventilation.

In a further study Axley et al. (2002) have presented a methodology for the design of natural and hybrid ventilation systems that accounts for specific climatic and operational conditions. The proposed methodology is based on: a) the climate suitability analysis method b) the loop equation design method to estimate preliminary sizes of system components and control and operational strategies and c) the multizone coupled thermal-airflow analysis, using CONTAM97R, for design development and, ultimately, system performance evaluation. The authors report that *'research efforts must be applied to enhance reliability of these computational tools, while the highest priority must be given to multizone coupled thermal-airflow analysis which is very important for the design of natural and hybrid ventilation systems'*.

Dorer et al. (2005) and Dorer and Weber (2005) have investigated the criteria and design parameters of demand controlled hybrid ventilation systems for residential buildings in the framework of RESHYVENT project. The survey is focused on design parameters, sensitivity analyses and design constrains on essential elements like wind effects in the built environment and modelling air flows in spaces. A very detailed background has been prepared on topics which are not sufficiently covered by existing literature (e.g. wind pressures or thermal comfort evaluation by CFD simulation). Besides, detailed information on input data necessary to perform computer simulations for the performance analysis of these systems.

6 Natural Ventilation in Urban Environment

6.1 Development of a Methodology to Calculate the Optimum Openings for Naturally Ventilated Buildings Located in Urban Canyons

6.1.1 Introduction

In the framework of URBVENT European project (2001) a methodology to calculate the optimum opening of naturally ventilated buildings located in urban canyons has been developed. The overall work is based on the development of a recurrent neural network model that calculates the air flow in natural ventilated apartments in buildings located in urban canyons under:

- specific climatic conditions
- specific canyon characteristics
- specific openings of a building
- specific building geometrical and operational characteristics

The methodology followed is consisted of three main parts:

1. Detailed experiments have been carried out in five urban canyons in Athens where the ambient conditions inside and outside the street have been measured. In parallel, tracer gas experiments have been carried out is buildings located in each canyon where the air flow rate has been measured both for single and cross flow configurations. The experimental data have been analyzed and the exact air flow rate has been calculated for each case.
2. Simulations have been carried using the AIOLOS network software tool to calculate the flow rate in naturally ventilated buildings located in urban canyons. About 150 000 scenarios have been defined and a similar simulation number has been performed. Calculations have been performed for different climatic and geometrical characteristics as defined by the architectural scenarios. In total, 1.5 million values of air changes (and flow rates) are available. Calculation cover single side ventilation configurations as well as stack effect natural ventilation. The results of the simulations have been used to train a neural network to calculate the air flow in naturally ventilated buildings located in urban canyons.
3. The experimental results have been compared with the corresponding theoretical data in order to assess the accuracy of the developed model.

6.1.2 Data and Architecture Scenario

Two types of data were used to accomplish this work, that were supplied by the “Instituto de Engeharia Mecânica” and obtained from simulations on AIOLOS and COMIS softwares.

6.1.2.1 Single Sided Ventilation

A matrix of 15 million values formed the database for single sided ventilated rooms. The results came from single sided ventilation scenarios which were studied. A study that was held for a small room (Figure 6.1) with only one external opening located in one façade with the following dimensions:

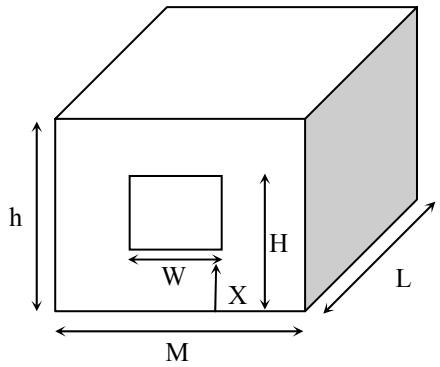

Figure 6.1 : Single-sided ventilation room (Allard and Ghiaus, 2005)

M	-Width of zone	[3.0 ↔ 5.0m]
L	-Length of zone	[3.0 ↔ 5.0m]
h	-Height of zone	[2.8 ↔ 5.0m]
X	-Height of the opening bottom of the bottom	[0.1 ↔ 2.4m]
H	-Height of the opening top of the window	[0.6 ↔ 3.0m]
W	-Width of the window	[0.2 ↔ 4.0m]

6.1.2.2 Stack Induced Ventilation

A matrix containing 2.6 million values is used as the database for stack induced ventilated rooms. It is the result of stack induced ventilation scenarios which were studied. A study that was held for the same small room shown in Figure 6.1 but it was inserted into a multi-storey building and the stack effect was induced by a single external opening in the façade and a chimney linking the room the roof of the building (Figure 6.2).

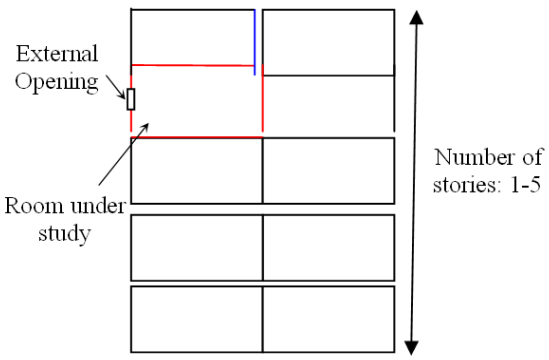

Figure 6.2 : Multistory building with stack induced ventilated rooms (Allard and Ghiaus, 2005)

The dimensions used were:

M	-Width of the zone	[5.0 ↔ 5.0m]
L	-Length of zone	[3.0 ↔ 5.0m]
hpq	-Height of zone	[2.8 ↔ 5.0m]
X	-Height of the opening bottom of the window	[0.1 ↔ 1.8m]
Hgr	-Height of the opening top of the window	[2.0 ↔ 2.3m]
W	-Width of the window	[1.0 ↔ 2.0m]
Dch	-Diameter of the chimney	[0.1 ↔ 0.5m]
Sc	-Useful area	(%)
F	-Floor	[1 ↔ 5]

6.1.3 Methodology of Developing the Model

A neural network model (Figure 6.3) which is based on establishment of empirical laws obtained starting from an experimental data base. Practically this model can be seen as a black box establishing the link between input variables which influence the studied phenomenon and an output variable corresponding to the value that we seek to predict.

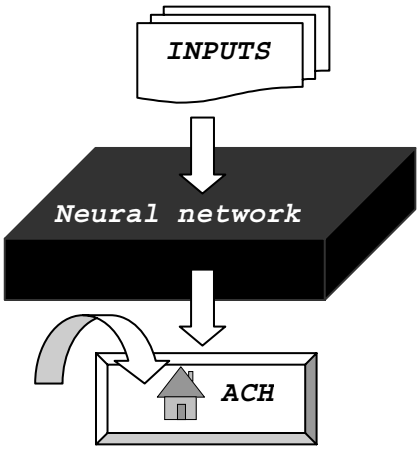

Figure 6.3 : General outline of the model (Allard and Ghiaus, 2005)

6.1.4 Development of Neural Networks

A neural network model that take all the variables (inputs and outputs) and give functions which can be used to reproduce correctly the same phenomenon, has been developed. A feed-forward back propagation network with two layers, a tan-Sigmoid Transfer Function (Tansig) for the first layer and a Linear Transfer function (Purelin) for the second layer (Figure 6.4) was used.

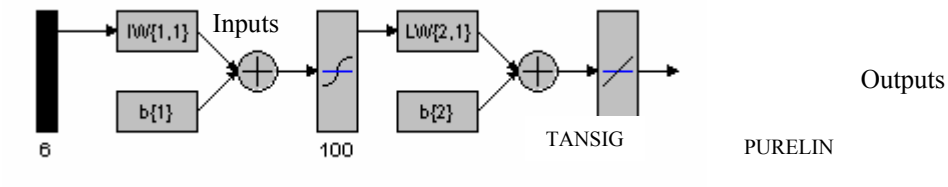

Figure 6.4 : Feed-forward network (Allard and Ghiaus, 2005)

Input arrays and the corresponding output vectors are used to train a network until the approximation of a function with associates input vector with specific output vectors. Four neural network models have been built, two treating the single sided ventilation case and the other two treating the stack induced ventilation case.

6.1.4.1 Tool for Single Sided Ventilated Room

A) Calculation of ACH

Each network “networkx” is a feed-forward back propagation network that has as inputs the values of external temperature, the wind velocity, the room volume, the height of the opening top of the window, the height of the opening bottom of the window and the width of the window, and that after been trained according to corresponding values of air change per hour for the rooms, can simulate new inputs and predict the ACH for single sided ventilated room (Figure 6.5).

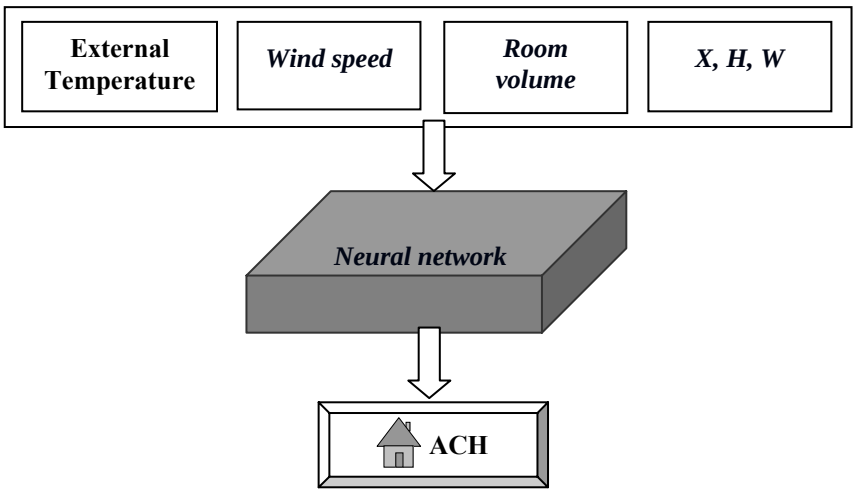

Figure 6.5 : Architecture of the model of calculation of ACH for single sided ventilation (Allard and Ghiaus, 2005)

A network for each couple of temperature and wind velocity was built and trained. In total we have 336 neural networks. Then a graphical interface was developed in order to make it easy for users to use the model (Figure 6.6).

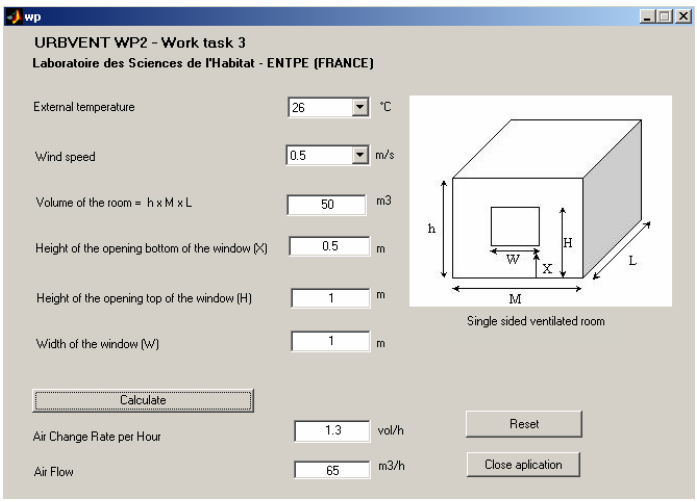

Figure 6.6 : Graphical interface to calculate ACH (Allard and Ghiaus, 2005)

B) Calculation of the optimal opening

Each network "netx" is a feed-forward backpropagation network that has as inputs the values of external temperature, the wind velocity, the room volume, the height of the opening bottom of the window, the height of the opening top of the window and the ACH. The network model is trained according to corresponding values of air change per hour for the rooms and can simulate new inputs and predict the width of the window for the single sided ventilated room (Figure 6.7).

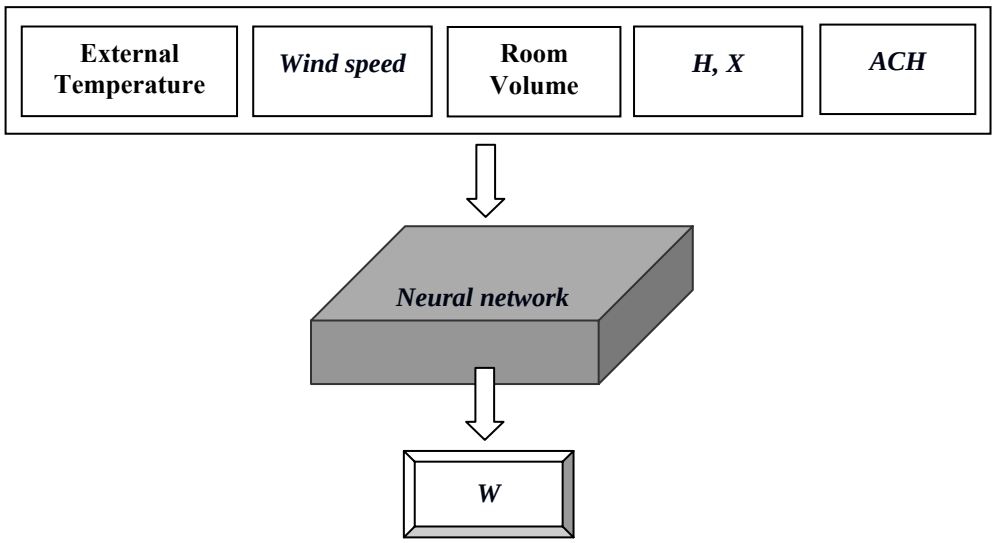

Figure 6.7 : Architecture of the model of calculation of W for single sided ventilation (Allard and Ghiaus, 2005)

A network for each couple of temperature and wind velocity was built and trained. In total we have 336 neural networks. Then a graphical interface was made to use the networks (Figure 6.8).

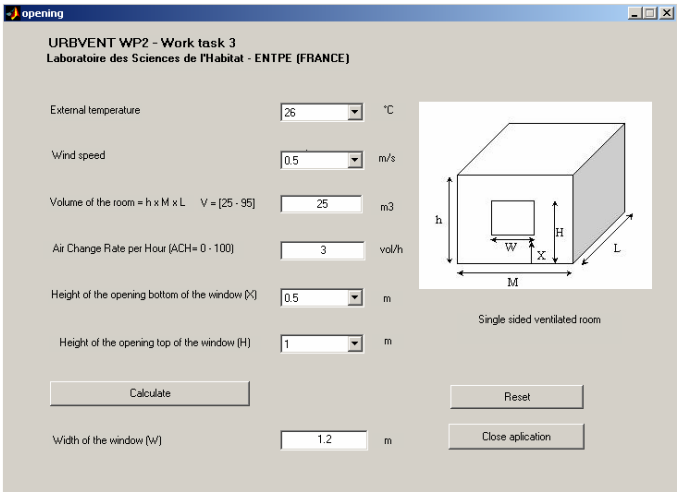

Figure 6.8 : Graphical interface to optimize the opening (Allard and Ghiaus, 2005)

6.1.4.2 Tool for Ventilated Room With Stack Effect

A) Calculation of ACH

Each network "networkx" is a feed-forward backpropagation network that has as inputs the values of external temperature, the room volume, the height of the opening top, the height of the opening bottom of the window and the width of the window, the diameter of the chimney, the useful area and the floor level of the room in the building, and that after been trained according to correspondent values of air change per hour for the rooms, can simulate new inputs and predict the ACH values for the natural ventilated room with stack effect (Figure 6.9).

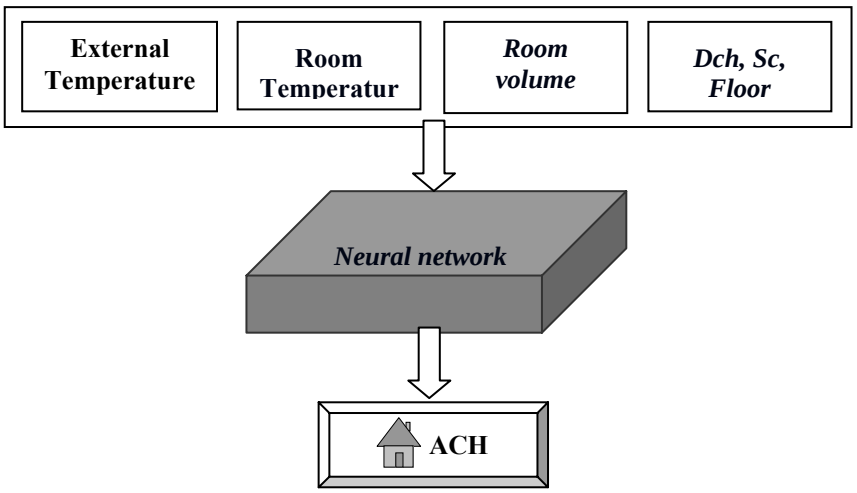

Figure 6.9 : Architecture of the Model of Calculation of ACH for Single Sided Ventilation (Allard and Ghiaus, 2005)

A network for each couple of temperature and wind velocity was built and trained. In total there are 16 neural networks. Then a graphical interface was developed with Matlab (Figure 6.10).

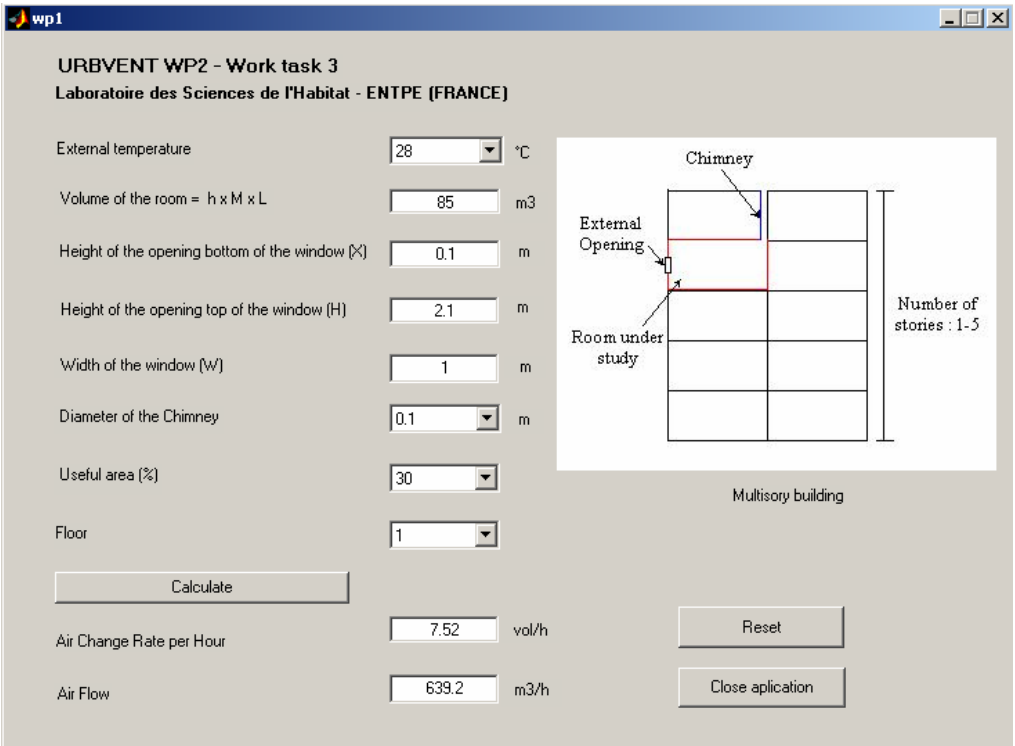

Figure 6.10 : Graphical interface to calculate ACH (Allard and Ghiaus, 2005)

B) Calculation of the optimal opening

Each network "netx" is a feed-forward backpropagation network with input values the external temperature, wind velocity, room volume, the height of the opening bottom, the height of the opening top of the window, the ACH, the diameter of the chimney, the useful area and the floor level of the room in the building. Then it is trained according to correspondent values of air change per hour for the rooms and can simulate new inputs and predict the width of the window for the natural ventilated room with stack effect (Figure 6.11).

A network for each couple of temperature and wind velocity was built and trained. In total we have 16 neural networks. Then a graphical interface was developed with Matlab (Figure 6.12).

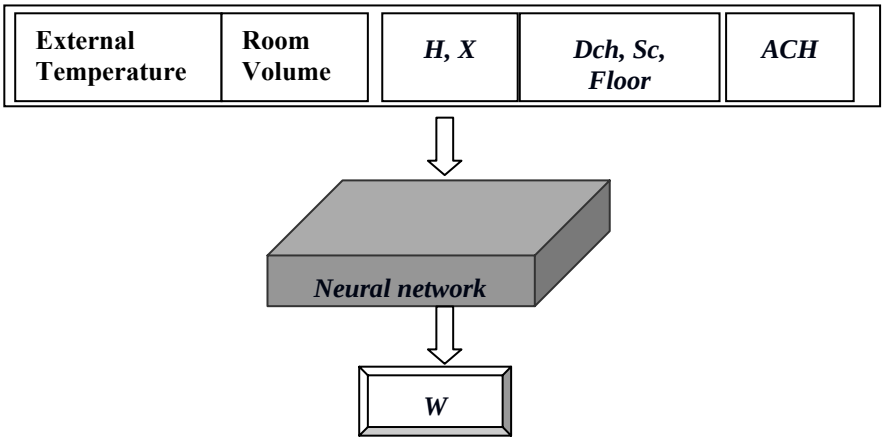

Figure 6.11 : Architecture of the model for the calculation of W for single sided ventilation (Allard and Ghiaus, 2005)

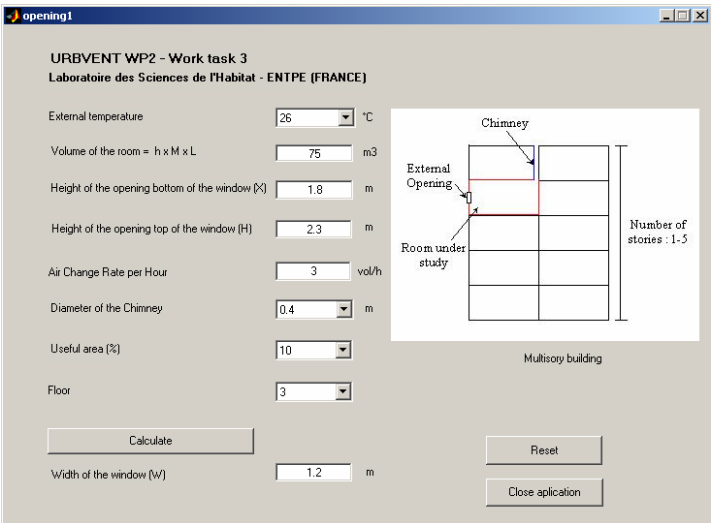

Figure 6.12 : Graphical interface to optimise the opening (Allard and Ghiaus, 2005)

6.2 Comparison of Theoretical with Experimental Values

Using the AIOLOS software calculations have been performed for each measured configuration. In total ten different case studies have been calculated for single-sided and cross ventilation. The results of the comparison are given in Table 6.1 and Table 6.2. As shown, the calculated values are for almost all cases very close to the experimental values.

Table 6.1: Comparison of experimental and theoretical air changes per hour for single ventilation in the five measured canyons (Allard and Ghiaus, 2005)

Single Ventilation Experimental ACH (Air Changes per Hour)				
Ermou	Miltiadou	Voukourestiou	Kaniggos	Dervenion
0.2-0.8	0.4-1.1	0.8-1.2	0.2-1	0.4-1.5
Single Ventilation Mean Theoretical ACH (Air Changes per Hour)				
Ermou	**MILTIADOU**	Voukourestiou	Kaniggos	Dervenion
0.65	1.5	1	1.3	1.35

Table 6.2: Comparison of experimental and theoretical air changes per hour for cross ventilation in the five measured canyons (Allard and Ghiaus, 2005)

Cross Ventilation Experimental ACH (Air Changes per Hour)				
Ermou	Miltiadou	Voukourestiou	Kaniggos	Dervenion
0.5-1.5	0.7-1.4	2.-3.0	0.6-1.5	1.8-3
Cross Ventilation Theoretical ACH (Air Changes per Hour)				
Ermou	Miltiadou	Voukourestiou	Kaniggos	Dervenion
1.3	2.1	2.6	1	3.2

6.3 Conclusions

In the context of URBVENT project, a methodology to calculate the air flow rate in naturally ventilated buildings located in urban canyons has been developed. A numerical model has been developed to estimate the air change rates in a small single sided ventilated room based on neural networks modelling. This model has the power of reproducing correctly a phenomenon hard to interpret. It will give in all circumstances a result whose relevance will depend on the choice of the variables of entry and the quality of available information to define the configuration simulated starting from these variables.

The predictions of the model developed to calculate the air flow rate in naturally ventilated buildings located in urban canyons, have been compared against experimental data. The comparison has shown that there is a very good agreement between the experimental and the theoretical data for both studied configurations.

7 Hybrid Ventilation in urban environment

Hybrid ventilation in urban areas is highly affected by a number of urban parameters. Effective design of hybrid ventilation in urban buildings requires a good understanding of the urban climate characteristics. The most important parameters (canyon geometry and layout, wind and temperature distribution inside canyons, pollutant concentrations, external noise, solar/daylight access, humidity and wind pressure on building facades) have been identified and analyzed through experimental and computational procedures in the framework of WP10 of the RESHYVENT Project (2001), entitled 'Urban Impact in EU'. This chapter summarises the main results of the experimental and theoretical investigation (Niachou and Santamouris, 2005) in order to study the impact of the urban environment on hybrid ventilation airflow process.

7.1 Experimental Research of Hybrid Ventilation in Urban Canyons

The total experimental campaign was based on field and indoor experiments aiming at the investigation of the impact of the various urban features on the efficiency of the applied ventilation system. Full-scale measurements have been performed in two urban canyons and three building apartments near the centre of Athens during summer 2002.

Table 7.1: Characteristics of urban canyons and building apartments measured during summer 2002 (Niachou and Santamouris, 2005)

Experiment/ Apartment	Area (m^2)	Volume (m^3)	Canyon	Orientation from North	H/W	L/W
Gizi/ A_1	65	112	Ragavi	100^0	1.7	3.8
Pagrati/ A_2	78	130	Ag. Fanouriou	137^0	2.6	9.5
Pagrati/ A_3	50	120				

The geometrical characteristics of the two studied canyons indicate typical urban canyon configurations with H/W>1. The L/W ratios for both canyons are less than 20 and "end effects" were observed by Niachou et al. (2005b). The mean measured wind speeds were lower than 1m/s, either in the centre of canyon or rear the external openings of the studied apartments, while the air temperature differences between inside and outside were up to 6°C. As it will be discussed in the next paragraphs, the thermal forces, due to the temperature differences between inside and outside, were found to compensate for the reduced wind effect in natural ventilation experiments, during the periods of low wind speeds (<0.2m/s) or calms.

7.2 Description of Ventilation Systems

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. In A_1 apartment, N_2O was used as a tracer, while in A_2 and A_3 apartments two tracer gasses (N_2O, SF_6) were used.

Natural ventilation experiments were performed in single-sided and cross ventilation configurations. In case of single-sided ventilation, openings were considered either, from the canyon or, from the rear canyon facade. Cross ventilation experiments were studied with two or more openings placed at the front and back canyon walls.

Mechanical ventilation was tested experimentally with one or two T-series window fans, which are designed to be mounted on single and double-glazing, or any type of glass or material. The fans were appended vertically on wooden patents attached to openings adjacent to the canyon and rear canyon.

They had a relative performance of 795m^3/h and operated either in inlet or extract modes in order to investigate the best ventilation performance.

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 at openings adjacent to the canyon and rear canyon façades operating in inlet or extract modes together with natural ventilation through one or two openings. The hybrid ventilation systems measured in the three building apartments (A_1, A_2, A_3) during summer 2002 are depicted in Figure 7.1.

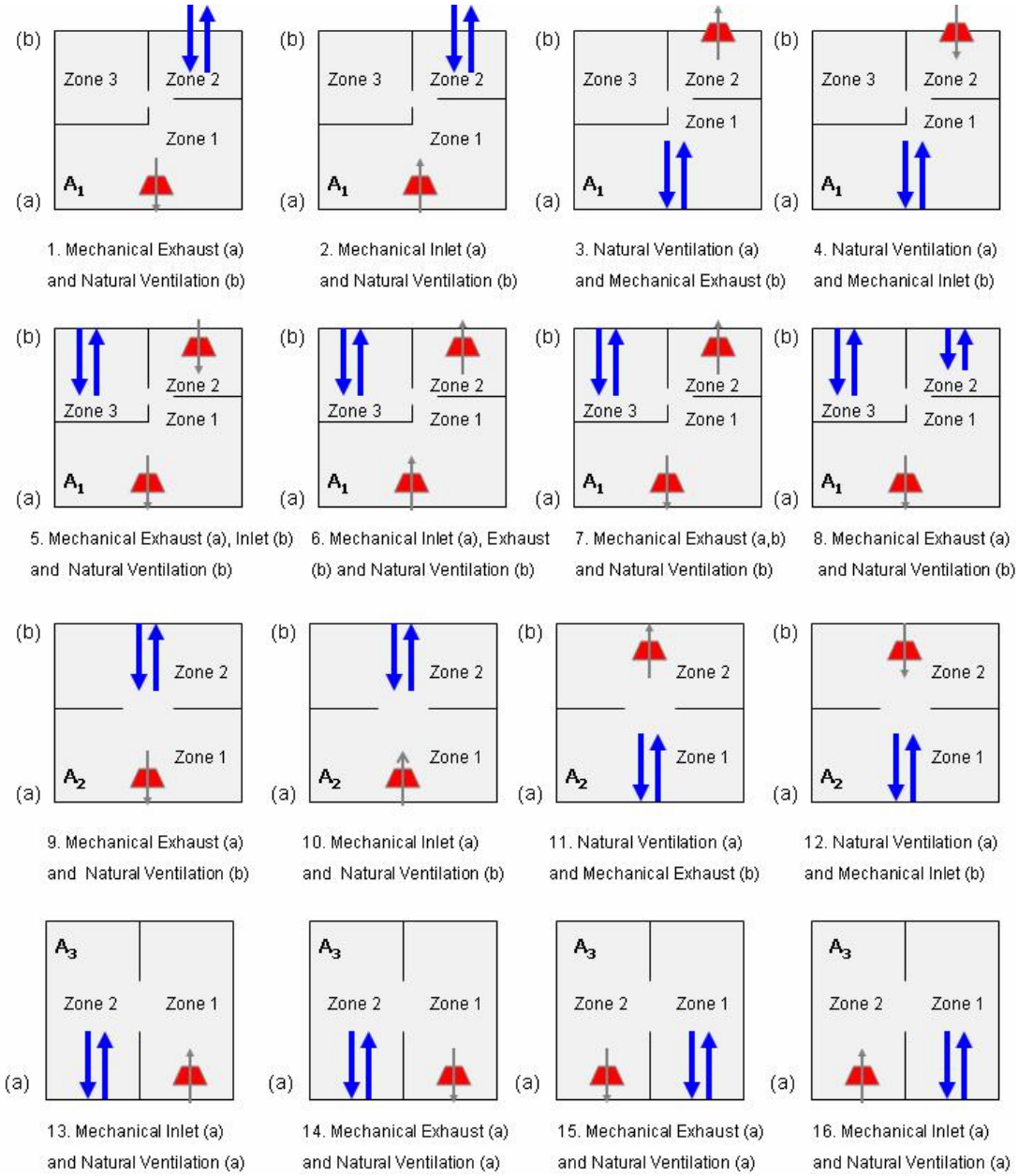

Figure 7.1 : Hybrid Ventilation systems measured in the three building apartments (A_1, A_2, A_3), where (a) refers to canyon façade and (b) to rear canyon façade

7.3 Evaluation of the Experimental Results in Urban Canyons

7.3.1 Field Measurements

In order to investigate the impact of the urban environment on the potential of natural and hybrid ventilation, a detailed analysis of air and surface temperature distribution and of the observed airflow characteristics inside the two studied street canyons has been performed. The observed wind and temperature distributions are discussed in order to get a better sight of the urban canyon microenvironment, which has been shown to have a direct impact on the ventilation performance in urban buildings (Niachou et al., 2005b).

7.3.2 Ventilation Measurements

The results obtained from the experimental procedures were analyzed in order to evaluate the impact of the urban parameters on the performance of natural and hybrid ventilation. A comparison analysis, taking into account air-exchange rates was performed for different ventilation systems under specific outdoor conditions in the two urban street canyons. For the estimation of air-exchange rates, different theoretical approaches have been proposed by Niachou et al. (2005a), based on single-zone and multizone methods.

7.3.2.1 Theoretical Analysis for the Estimation of Air-Exchange Rates

The equations for interpreting tracer gas measurements are based on the conservation of mass of the tracer and the mass of air. In a zone i, the rate of change of a tracer concentration at any time, t, is given by the continuity equation:

$$V_i \frac{dC_i(t)}{dt} = F(t) + \sum(Q_{ji}C_j(t)) + Q_{oi}C_o - (Q_{io} + \sum Q_{ij})C_i(t) \quad (12)$$

Rate of change in the amount of tracer inside a zone i	Amount of tracer introduced into the zone i	Amount of tracer which has left zone i

where V_i is the effective volume of zone i, $C_i(t)$, Cj(t), Co are respectively the mean concentrations of the tracer inside zones i, j and outdoors, Q_{ij} is the air flow from zone i to zone j, Q_{io} and Q_{oi} is the air flow from zone i to outside air and reversely and F(t) is the tracer gas injection rate.

In the decay method used during the ventilation experiments, the concentration of the tracer gas concentrations in the ambient, C_o and its injection rate, F(t), inside the ventilated space are considered zero.

A. Single-Zone Methods

In case of a single zone, where the injection of the tracer gas has stopped (F=0) and its outdoor concentration is zero (Co=0), then Eq. (12) becomes:

$$V_i \frac{dC_i(t)}{dt} = -Q_{io}C_i(t) \quad (13)$$

For the estimation of air-exchange rates (h^{-1}) based on single-zone methods, two theoretical approaches are proposed which are described in the following paragraphs.

i) The zone average concentration C_a

In this methodology, the ventilated space is considered as one zone and an average tracer gas concentration is calculated for the whole apartment. The concentration is the volume weighted average of the concentrations in different rooms:

$$C_a(t) = \frac{\sum_{i=1}^{i=k} V_i C_i(t)}{V_{tot}} \tag{14}$$

where k is the number of rooms and V_{tot} is the total effective volume of the ventilated space.

Once the average concentration $C_a(t)$ is calculated, one can find the air-exchange rate from the tracer balance Eq. (13) between t=0 and t=e (when $C_a(e) \approx 10\% C_a(0)$):

$$V_{tot}(C_a(0) - C_a(e)) = Q_{tot1} \int_0^e C_a(t)dt \tag{15}$$

Where Q_{tot1} is the total outflow rate, natural or mechanical, through all openings. The air-exchange rate (N_1) can also be expressed in air changes per hour (h^{-1}), which can be found by dividing Q_{tot1} by V_{tot}.

When two tracer gasses are used, it is possible to derive a dimensionless average concentration for each room $C_{ai}^*(t)$ by dividing the average concentration of the tracer in a room $C_{ai}(t)$ with the initial value of the concentration of the gas injected in each space.

$$C_{ai}^*(t) = \frac{C_{ai}(t)}{C_i(0)} \tag{16}$$

Similarly, it is possible to define the non-dimensional version of the volume weighted average concentration method of the apartment, $C_a^*(t)$, with the two tracer gasses.

$$C_a^*(t) = \frac{\sum_{i=1}^{i=k} V_i C_{ai}^*(t)}{V_{tot}} \tag{17}$$

In this case, Equation (15) is replaced by:

$$V_{tot}(1 - C_a^*(e)) = Q^*_{tot1} \int_0^e C_a^*(t)dt \tag{18}$$

The air-exchange rate N_1^* is based on the single-zone methodology but with two tracer gasses.

ii) Zero Interzonal Flows

This methodology consists in considering zero interzonal flows between the different rooms. For each room, the ventilation rate towards the surroundings is calculated from the room average concentration $C_{ai}(t)$:

$$V_i(C_{ai}(0) - C_{ai}(e)) = Q_{io} \int_0^e C_{ai}(t)dt \tag{19}$$

From the ventilation rate of each room, the total air ventilation rate can be calculated:

$$Q_{tot2} = \sum_{i=1}^{i=k} Q_{io} \tag{20}$$

The air-exchange rate (N_2) can then be calculated from Q_{tot2} by dividing by the total volume V_{tot}. Note that the summing is only for the rooms which have a connection to outside whereas, V_{tot} includes all spaces participating in the ventilation process, even if they have or no external openings (like halls or corridors).

In case of two tracer gasses, then the Q^*_{tot2} is based on the dimensionless average concentration, $C_{ai}^*(t)$, of rooms with external openings. N_2^* corresponds to air changes per hour (h^{-1}) of the apartment when two tracers are used.

One might of course question the meaning of using single zone methods in the case of a two-tracer experiment. The justification might be that since there are more rooms than tracers, the single-zone methods are necessary to complement the multizone methodology described below.

B. Multizone Methods

i) Single Tracer Gas

The multizone methodology in single-tracer gas experiments is found in the works of Sinden (1978) and Afonso and Maldonado (1986). The basic equation for determining the time evolution of the tracer gas is:

$$V_{tot}\frac{dC_a(t)}{dt} = \sum_{i=1}^{i=N} Q_{io}C_{ai}(t) \tag{21}$$

where N is the number of zones, $C_{ai}(t)$ is the average concentration of tracer in zone i.
Also the average concentration C_a of the total ventilated space has been defined in Eq. (14).

The above equation can be integrated between t=0 and t=e:

$$V_{tot}(C_a(0) - C_a(e)) = \sum_{i=1}^{i=N} Q_{io}\int_0^e C_{ai}(t)dt \tag{22}$$

To find the actual Q_{io} -assuming that the experiment is short enough so that Q_{io} does not appreciably change during the experiment, the tracer mass balance Eq. (22) has to be integrated for more than one time intervals. Afonso and Maldonado (1986) showed that even for the same concentration variations, the calculated values of the exchange rates are dependent on the times chosen for the balance. It must be stated that although individual outflow rates, Q_{io}, of each room are strongly dependent on the choice of the integration time intervals (and the interzonal flows are often negative), the total exchange rate for the two-zone building is much less dependent on that choice.

In order to avoid making a choice of the times to be used for the integration, the different air outflow rates Q_{io} have been determined using a least square method, namely, minimizing the total square deviation between the experimental and theoretical values of C_a, as calculated from Eq. (20). Thus, one does not use two times to estimate the variation of C_a as for instance the beginning and the end of the experiment, but he tries to minimize the total square deviation for all times. The solution of the least square equations is straightforward, but the result is unacceptable if any of the calculated outflow rates is negative. In such cases one should repeat the determination of the values of the different outflow rates by assuming that some of them are zero and the least square minimization is done with the rest of the flows only. Thus, the estimated total exchange rate, N_3, equals to Q_{tot-3}/V_{tot} and it is the one corresponding to the minimum square deviation, with no negative outflows. For example, in case of a mechanical exhaust experiment through one of two openings, it is possible to have a solution with a non-zero outflow and a solution with a zero outflow but with minimum square deviation. Then the second solution with the zero-flow through that opening is rejected, regardless of the square deviation.

ii) Two Tracer Gasses

According to Afonso and Maldonado (1986), the air exchange rates from multi-room configurations can only be estimated using a multi-tracer gas experiment. In a two-tracer gas experiment, it is possible to start with different initial concentrations of each gas in two zones of the building and obtain reasonably accurate values of the outflow rates from each zone. This was the reason that a two-tracer experiment was used in the case of the two apartments, A_2 and A_3, in the second street canyon. The two apartment buildings were considered as two-zone buildings, where N_2O was injected in the

first zone and SF_6 in the second one. The equations for the time evolution of N_2O and SF_6 between the beginning and the end of each ventilation experiment are:

$$V_{tot}(C_{SF_6}(0) - C_{SF_6}(e)) = Q^*_{1o}\int_0^e C_{SF_6,1}(t)\,dt + Q^*_{2o}\int_0^e C_{SF_6,2}(t)\,dt \quad (23a)$$

$$V_{tot}(C_{N_2O}(0) - C_{N_2O}(e)) = Q^*_{1o}\int_0^e C_{N_2O,1}(t)\,dt + Q^*_{2o}\int_0^e C_{N_2O,2}(t)\,dt \quad (23b)$$

where subscripts 1 and 2 refer to the two zones and Q^*_{1o} , Q^*_{2o} account for the air flow rates from zones 1,2 to outside air when two tracers are used.

Thus, the total airflow rate for a two-zone apartment is:

$$Q^*_{tot3} = Q^*_{1o} + Q^*_{2o} \quad (24)$$

The total air changes per hour (h^{-1}) are denoted by N_3* and they are based on the multizone method with the two-tracer gas experiments.

7.3.2.2 Experimental Results

Based on single-zone and multizone approaches, it was possible to consider different ways of estimating air-exchange rates from the measurements of the tracer gas concentrations. A detailed discussion of the advantages and disadvantages of the single and multizone methods is presented by Niachou et al. (2005a, 2005c). It is shown that for a multizone experiment, a multi-tracer gas is necessary. When a single tracer is used then the multizone analysis is inaccurate and in this case the use of single-zone methods is preferable. Single-zone methods can also be adapted to analyze multi-tracer experiments. Despite the fact that the multizone methods are theoretically more appropriate, single-zone methodologies are less sensitive to the accuracy of the measured data.

The calculated air-exchange rates for the three building apartments are summarized in Table 7.2 to Table 7.4 and they are divided into relevant categories according to the studied ventilation system.

A comparative analysis between the three methodologies has been performed using the statistical t-test of the differences of the mean air-exchange rates (Niachou et al., 2005α). The t-test values, together with the critical $t_{0.05}$ value, are given in Table 7.5, where it is shown that the estimated air-exchange rates, based on the single and multizone methodologies are statistically equal at a confidence interval of 95%.

Table 7.2: Estimated mean air-exchange rates (h^{-1}) for all ventilation systems in A_1 apartment, based on single-zone (N_1, N_2) and multizone (N_3) methods

Ventilation	Description	No	N_1 (h^{-1})	N_2 (h^{-1})	N_3 (h^{-1})
	Infiltration	1	0.25	0.25	0.25
Natural	Single-Sided with one window	3	2.6	2.8	3.1
	Cross Ventilation with two windows	4	12.9	15.4	15.2
	Cross Ventilation with more than two windows	4	10.2	11.3	11.0
Mechanical	One supply/exhaust fan	4	5.7	5.9	5.7
	Two supply/exhaust fans	6	7.4	8.0	6.6
Hybrid	One supply/exhaust fan and natural ventilation with one window	7	7.3	8.4	7.4
	One supply/exhaust fan and natural ventilation with more than one windows	3	11.3	12.6	13.2
	Two supply/exhaust fans and natural ventilation with more than one windows	2	14.2	16.3	15.4

Table 7.3: Estimated mean air-exchange rates (h^{-1}) for all ventilation systems in A_2 apartment, based on single-zone (N_1^*, N_2^*) and multizone (N_3^*) methods

Ventilation	Description	No	N_1^* (h^{-1})	N_2^* (h^{-1})	N_3^* (h^{-1})
	Infiltration	1	0.4	0.4	0.3
Natural	Single-Sided with one window	7	4.1	4.2	4.5
	Cross Ventilation with two windows	3	10	10.1	9.8
Mechanical	One supply/exhaust fan	5	5.4	5.5	3.8
	Two supply/exhaust fans	5	5.9	6.1	4.5
Hybrid	One supply/exhaust fan and natural ventilation with one window	10	6.1	6.2	5.6
	One supply/exhaust fan and natural ventilation with more than one windows	5	6.9	7.1	5.9
	Two supply/exhaust fans and natural ventilation with one window	6	7.9	8.0	6.3

Table 7.4: Estimated mean air-exchange rates (h^{-1}) for all ventilation systems in A_3 apartment, based on single-zone (N_1^*, N_2^*) and multizone (N_3^*) methods

Ventilation	Description	No	N_1^* (h^{-1})	N_2^* (h^{-1})	N_3^* (h^{-1})
	Infiltration	1	0.5	0.5	0.5
Natural	Single-Sided with one window	6	3.9	4.1	4.2
	Single-Sided with two windows	3	5.8	5.8	5.2
Mechanical	One supply/exhaust fan	6	3.9	4.1	4.9
	Two supply/exhaust fans	8	5.0	5.1	5.4
Hybrid	One supply/exhaust fan and natural ventilation with one window	14	5.8	6.0	7.4

Table 7.5: The t-test values of the statistical test for the comparison of the mean air-exchange rates based on the single (1, 2) and multizone (3) methods at a confidence interval of 95%

Apartment	Ventilation	t-values	Methods (1)-(2)	Methods (2)-(3)	Methods (3)-(1)
A_1	Concentration decay method with one tracer N_2O	$\|t\|$	0.97	0.39	0.48
		$t_{0.05}$	2.04	2.04	2.04
A_2	Concentration decay method with two tracers N_2O and SF_6	$\|t\|$	0.26	1.65	1.40
		$t_{0.05}$	2.02	2.02	2.02
A_3	Concentration decay method with two tracers N_2O and SF_6	$\|t\|$	0.42	1.47	1.83
		$t_{0.05}$	2.03	2.03	2.03

Due to the better theoretical basis of the multizone approach, the estimated air- exchange rates based on this method, for the three building apartments in the two urban canyons, are depicted in Figure 7.2.

Natural cross ventilation was proven to very effective in spite of the reduced wind speeds inside the urban canyons. 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 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 (Figure 7.2) in the studied apartments in the two urban canyons is greater in A_1 apartment in comparison with the other two, due to implementation of cross ventilation experiments between more than two windows.

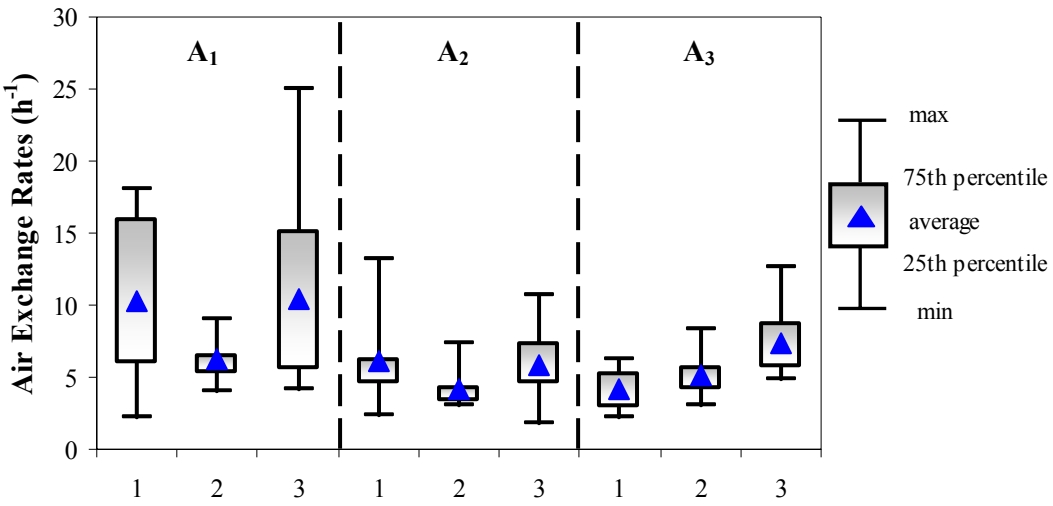

Figure 7.2 : Estimated Air-exchange rates based on multizone method (h^{-1}) for natural (1), mechanical (2) and hybrid (3) ventilation experiments in apartments A_1, A_2 and A_3 under different ambient weather conditions (Niachou et al., 2005c)

The lowest air-exchange rates were measured in the A_3 apartment where natural ventilation was only single-sided (since external openings exist only from the building façade adjacent to canyon) and because of the existence of windless ambient conditions. However, even under low wind speeds (<0.2m/s) or calms outside A_3 apartment in Ag. Fanouriou canyon, natural ventilation is not eliminated. In fact, the thermal forces due to the temperature differences between inside and outside compensated for the reduced wind effect. The air temperature differences between inside and outside ranged from 0.5°C up to 5°C during the conditions of low wind speeds.

Contrary to natural ventilation, mechanical ventilation led to constant flow rates, irrespectively of the climatic conditions. The observed variability in the mechanical ventilation experiments (Figure 7.2) is mainly attributed to the different combinations of inlet/exhaust fans.

Hybrid ventilation has been shown to be associated with rather lower air-exchange rates than natural cross-ventilation, but with relatively higher values in comparison with single-sided ventilation especially under calm conditions. The estimated airflow rates varied according to the position of mechanical inlet/exhaust fans and the external openings. In general, they presented a smaller variability than the natural air-exchanges but greater than the mechanical ones. In A_1 experiment, higher air-exchange rates are calculated, when natural ventilation from one opening is combined with an exhaust fan rather than with an inlet fan. When two fans (a supply and an exhaust) are combined with natural ventilation then higher air-exchange rates are measured in comparison with ventilation experiments with one exhaust fan and natural ventilation though more than one openings. In A_2 experiment, when a supply or an exhaust fan is applied with natural ventilation (through one or more openings), then the mean air-exchange values are lower in comparison with the hybrid systems where with two mechanical fans and natural ventilation are combined (Table 7.3). Hybrid ventilation, in A_3 experiment, was shown to perform better than natural ventilation, especially during periods of low (<0.2m/s) ambient wind speeds (Figure 7.3).

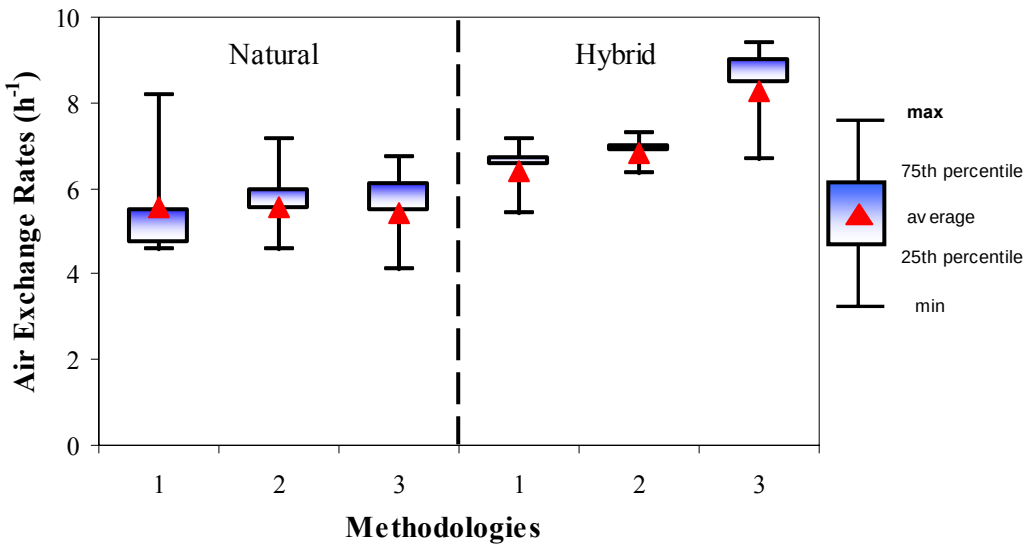

Figure 7.3 : Estimated air-exchange rates (h^{-1}) for natural (single-sided) and hybrid ventilation experiments in A_3 apartment under low wind speeds or calms based on single-zone (1,2) and multizone (3) methods

The main result is that under the conditions experiments were performed (all internal doors open) there is little advantage to be gained in those apartments by using hybrid in place of natural ventilation. Of course, this is not to assert that hybrid ventilation has little use. There is definitely an advantage for hybrid ventilation when one is forced to have doors closed in an apartment and thus, making natural ventilation much less effective. Besides, there is also an advantage when one needs hybrid ventilation to vent a bathroom, a toilet or a kitchen, in that case natural ventilation may be both insufficient and counter-productive (when there are flows in the wrong direction). Although the small number of experiments performed under low wind speeds or calms, the existing results confirm that hybrid ventilation has an advantage over temperature driven single-sided ventilation (Niachou et al., 2005a, 2005c).

7.4 Computational Calculations of Airflow Characteristics in Urban Canyons

In order to complete the work on the parameters that influence hybrid ventilation in urban environment, computational calculations of airflow characteristics were performed, using the multizone airflow and thermal model COMIS/TRNSYS (Dorer and Weber, 2001). These airflow characteristics helped to get a better insight of the impact of the urban environment on the ventilation effectiveness.

Advanced hybrid ventilation systems have been studied, based on RESHYVENT concept and on RESHYVENT consortiums. Five different canyon configurations have been studied, having an aspect ratio (H/W) equal to 1, 1.5, 2, 2.5 and 3. Weather data of eleven European cities representing different climatic conditions were used in the simulations. The undisturbed wind speed data has been translated into canyon data based on the developed research methodology within URBVENT European Project.
A detailed sensitivity analysis has been performed considering all the following parameters:

- Canyon Geometry
- Canyon Layout
- Outdoor Urban Air Characteristics
- Indoor Pollutant Emissions
- Building Leakage
- Demand Control

A set of simulations under dynamic conditions have been performed. The dynamic simulations were performed on an hourly basis within a year period for eleven European climates. A full data basis with all simulation scenarios and results are given in final report of WP10 of RESHYVENT project (Niachou and Santamouris, 2005).

7.4.1 Description of Studied Canyons

Five different canyon configurations have been studied, having an aspect ratio (H/W) equal to 1, 1.5, 2, 2.5 and 3.

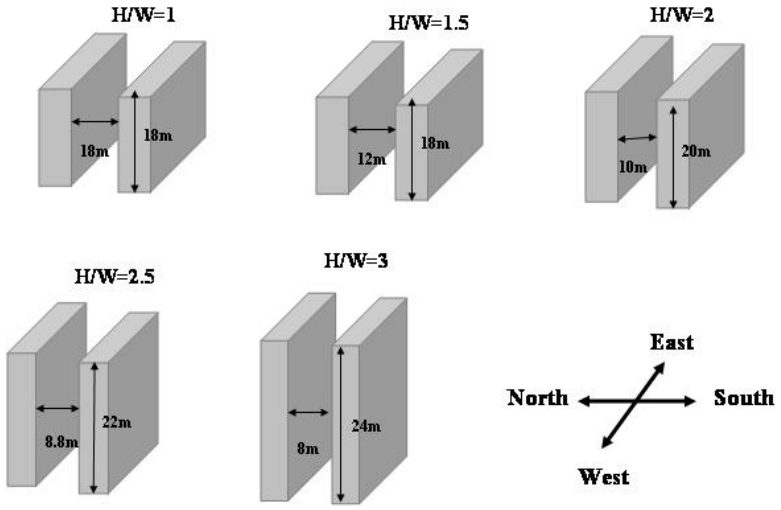

Figure 7.4 : Five canyon geometries with different aspect (H/W) ratios (Niachou and Santamouris, 2005)

The rear canyon facades were studied either with local or with no local obstructions. Namely, when considering local obstructions a similar canyon geometry is assumed at the rear canyon side (Figure 7.5a), whereas without local obstructions an open configuration exists (Figure 7.5b). The long canyon axis has an orientation from East to West, namely 100 degrees from the North. A typical roughness length, z_0, for high-density urban terrain equal with 5 was considered (Oke, 1987).

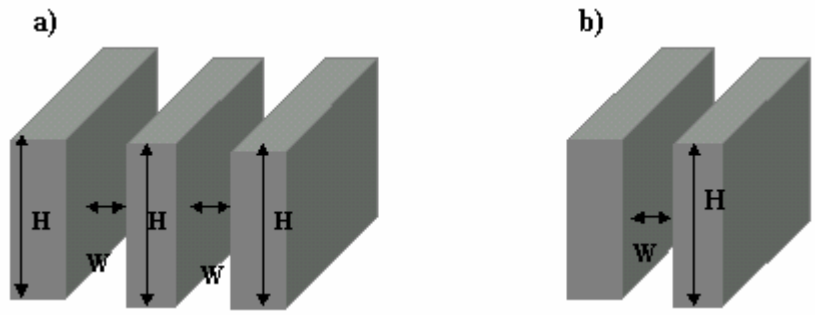

Figure 7.5 : Canyon geometries a) with and b) without local obstructions (Niachou and Santamouris, 2005)

7.4.2 Description of Reference Building

The reference building is a single-family house, namely an apartment, located inside an urban street canyon. The apartment is modelled as a single zone with dimensions width x length x height =10m x 10m x 2.7m. The apartment had two external walls, one facing the canyon and the other one facing the rear canyon side. The glazing areas are respectively 3 m^2 and 2.5 m^2 for canyon and rear canyon facades.

7.4.3 Occupation Scheme

A standard family consisting of four people occupies the dwelling. The occupation schedule on a daily basis is illustrated in Figure 7.6.

TIME	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Home partner																								
Working partner																								
Schoolchild																								
Home child																								

Figure 7.6 : Occupation Scheme during the 24-hour Period (Niachou and Santamouris, 2005)

Two air pollutants (CO_2 and TVOC's) were taken into account in the simulations. Occupants were the only source of CO_2 in the apartment. The source strength of CO_2 was considered for both adults and children and equal with 6.6 10^{-6} kg s^{-1} for each person. This source changed with time according to the occupancy scheme. With regard to TVOC's, a constant emission of 3.1 10^{-8} kg s^{-1} (or 1.1mgh^{-1}m^2, Gustafsson and Jonsson, 1993) was considered for the whole apartment.

7.4.4 Building Leakage

Three leakage scenarios have been considered, namely, a tight, an average and a leak. Table 7.6 presents the overall leakages (n, ACH@50Pa) with the total air mass flow coefficients (C_{total}, Kg/s@1Pa). The flow exponent is equal with 0.66.

Table 7.6: Definition of overall leakages (n and corresponding C_{total}) for different leakage classes (Niachou and Santamouris, 2005)

Leakage classes	n (ACH@50Pa)	C_{total} (Kg/s@1Pa)
Tight	0.6	0.00408
Average	2.5	0.017017
Leak	5	0.034034

The air leakage is modelled by means of a crack in each of the external walls (facades). The cracks are positioned in the middle of the apartment height (1.35 m above the zone floor). The mass flow rate characteristic for each of two cracks is:

$$Q_1 = K_1\ \Delta P^n = 0.002042\ \Delta P^{0.66} \quad [kg\ s^{-1}] \text{ for tight leakage}$$

$$Q_2 = K_2\ \Delta P^n = 0.008508\ \Delta P^{0.66} \quad [kg\ s^{-1}] \text{ for average leakage}$$

$$Q_3 = K_3\ \Delta P^n = 0.017016\ \Delta P^{0.66} \quad [kg\ s^{-1}] \text{ for leak leakage}$$

where Q_i (kg s^{-1}) is the mass flow rate, K_i (kg s^{-1} @ 1 Pa) is the mass flow coefficient through each crack and ΔP (Pa) is the pressure difference across building facades, at the position of links (fans or inlet grilles).

7.4.5 Wind Pressure Coefficients

Two levels of shielding conditions were considered for the rear canyon facade:

- Exposed
- Shielded – surrounded by obstructions equal to the height of canyon buildings.

The Cp-values for the two building facades and for the five canyon geometries are given in Table 7.7. Façade (1) refers to front and façade (2) to rear canyon wall. The Cp-values for the roof are considered equal for all canyon geometries and they have been estimated by 'CP-generator' (Knoll et al., 1995).

*Table 7.7: Cp-values for each wind incidence angle (*Knoll et al., 1995*)*

Canyon	Shielding	Facade	Wind Angle							
			0°	45°	90°	135°	180°	225°	270°	315°
1	shielded	1	-0.273	-0.207	-0.301	-0.045	0.056	0.637	-0.281	-0.37
	exposed	2	0.548	0.307	-0.133	-0.215	-0.186	-0.302	-0.479	0.253
2	shielded	1	-0.306	-0.236	-0.429	-0.109	-0.138	0.523	-0.412	-0.422
	exposed	2	0.627	0.35	-0.151	-0.233	-0.22	-0.347	-0.539	0.286
3	shielded	1	-0.329	-0.255	-0.48	-0.125	-0.17	0.567	-0.453	-0.457
	exposed	2	0.679	0.379	-0.162	-0.253	-0.244	-0.375	-0.578	-0.309
4	shielded	1	-0.35	-0.273	-0.56	-0.179	-0.231	0.514	-0.597	-0.489
	exposed	2	0.73	0.407	-0.173	-0.268	-0.274	-0.4	-0.617	0.331
5	shielded	1	-0.371	-0.292	-0.63	-0.216	-0.282	0.47	-0.715	-0.521
	exposed	2	0.78	0.435	-0.185	-0.286	-0.304	-0.424	-0.657	0.353
1	shielded	1	-0.131	-0.212	-0.399	-0.106	-0.042	0.124	-0.426	-0.398
	shielded	2	0.051	-0.085	-0.183	-0.35	-0.19	-0.073	-0.836	0.073
2	shielded	1	-0.134	-0.281	-0.418	-0.221	-0.22	-0.025	-0.414	-0.59
	shielded	2	-0.126	-0.237	-0.176	-0.41	-0.196	-0.083	-0.88	-0.038
3	shielded	1	-0.149	-0.327	-0.469	-0.251	-0.262	-0.046	-0.453	-0.7
	shielded	2	-0.16	-0.275	-0.191	-0.465	-0.218	-0.095	-0.986	-0.053
4	shielded	1	-0.166	-0.392	-0.521	-0.298	-0.325	-0.086	-0.489	-0.848
	shielded	2	-0.215	-0.333	-0.206	-0.532	-0.246	-.132	-1.097	-0.084
5	shielded	1	-0.183	-0.436	-0.58	-0.315	-0.365	-.124	-0.515	-0.984
	shielded	2	-0.256	-0.361	-0.223	-0.59	-0.27	-0.212	-1.189	-0.124
1,2,3,4,5	Shielded/exposed	Roof	-0.36	-0.417	-0.473	-0.782	-0.361	-0.417	-0.473	-0.772

7.4.6 Weather Data

Weather data of eleven European cities representing different climatic conditions were studied in the simulations. The weather data, except for Athens climatic data, were obtained by means of the METEONORM software.

Table 7.8: European cities involved in simulations (Niachou and Santamouris, 2005)

City	Longitude	Latitude
Athens	22.72°E	37.58°N
Amsterdam	4.54°E	52.21°N
Berlin	13.25°E	52.32°N
Brno	16.40°E	49.13°N
Copenhagen	12.34°E	55.43°N
Glasgow	4.15°W	55.53°N
Madrid	3.43°W	40.25°N
Oslo	10.45°E	59.56°N
Paris	2.20°E	48.52°N
Stockholm	18.05°E	59.21°N
Zurich	8.33°E	47.23°N

The undisturbed wind speed data was translated into canyon data inside the five canyon geometries based on the methodology depicted in Figure 4.3 and related calculation methods. The cumulative frequency distributions of the wind speed outside and inside the studied canyons for Athens climatic data are shown in *Figure 7.7*.

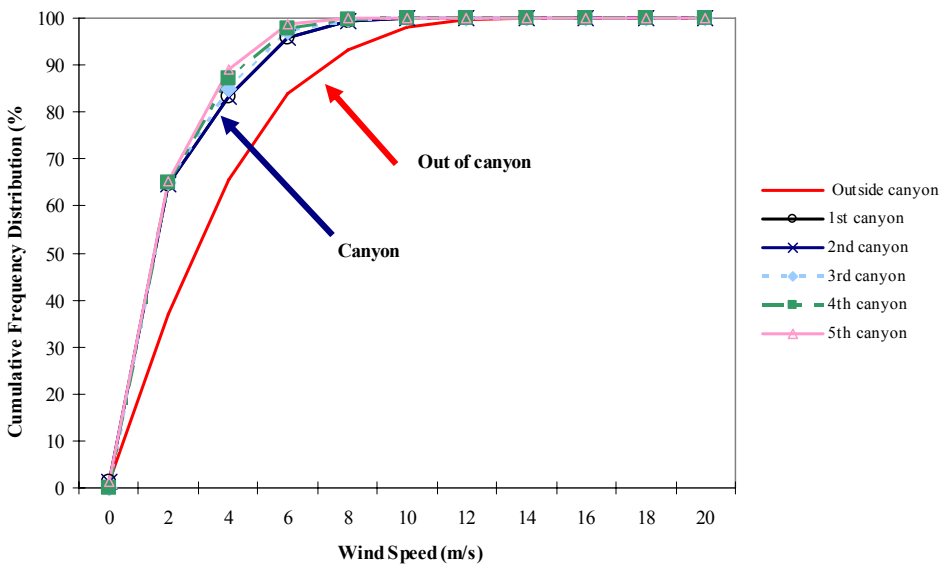

Figure 7.7 : Cumulative frequency distributions of the wind speed outside and inside the five canyon geometries for Athens reference year (Niachou and Santamouris, 2005)

The two studied hybrid ventilation systems consisted of demand control and a balancing supply and exhaust system.

7.4.6.1 Pilot Ventilation System

The first studied hybrid ventilation system (*Figure 7.8*) is a pilot ventilation system, consisting of the following technical components:

I. Demand Control

The demand control system was applied through an on/off control strategy based on the indoor CO_2 or TVOC's concentrations. When indoor CO_2 levels exceeded the threshold value of 1000ppm or when indoor TVOC's concentrations were higher than 3mgr/m^3, above which discomfort is expected (Molhave and Nielsen, 1992), then a balancing supply and exhaust system (Figure 7.8) was activated with a relative performance which is described in Table 7.9, otherwise the system was closed.

II. Balancing Supply and Exhaust

Two supply/exhaust fans have been used with a corresponding performance of 795m^3/h. The fans are installed on the external building walls at canyon and rear canyon façades. The fans are reversible and they operate on both extract and intake modes according to the specific case study.

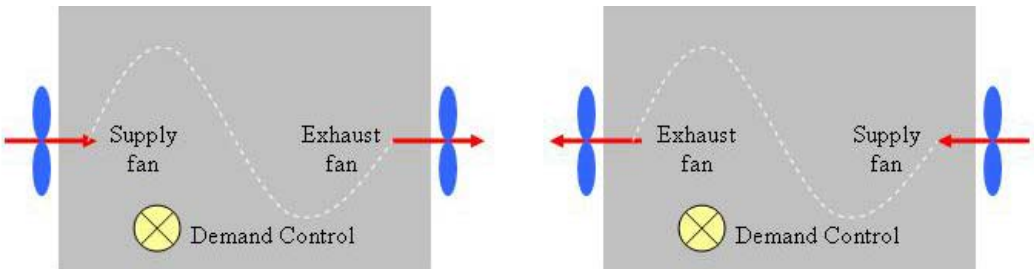

Figure 7.8 : A representation of the pilot hybrid ventilation system with two inlet/extract fans Installed At the two external building walls. An inverse operation of the fans is considered on the right photo.

Table 7.9: Characteristic of inlet-exhaust fans

ΔP [Pa]	Flow rate [$m^3 s^{-1}$]
0	0.22
15	8.2
30	11.6
45	14.2
50	16.4
70	0

7.4.6.2 RESHYVENT Hybrid Ventilation System

The second studied ventilation system is one of the four RESHYVENT ventilation systems, IC2, which was developed for moderate climates and employed natural air supply and natural or mechanical duct air exhaust. The system consists of self-regulating air inlets, DC fan, motorized damper, flow meter, central control unit, CO_2 sensors and ductwork (Figure 7.9). The demand control of the ventilation system is based on monitoring of CO_2 in rooms (Jacobs and de Gids, 2003). There is a CO_2 sensor and a self-regulating air inlet in each room. The self-regulating inlets are positioned above windows. These inlets are able to maintain a constant flow rate for the pressure difference across the facade higher than 1 Pa. The hybrid ventilation system was simulated either with self-regulating or with pressure-dependent inlets, which opened when CO_2 concentration exceeded 1200 ppm. The exhaust fan is used when the air exhaust through the duct is lower than the demanded flow and the inlet grilles are activated. The efficiency of the IC2 system in the five canyon geometries was studied with the pressure-dependent grilles in order to realize better the canyon effect.

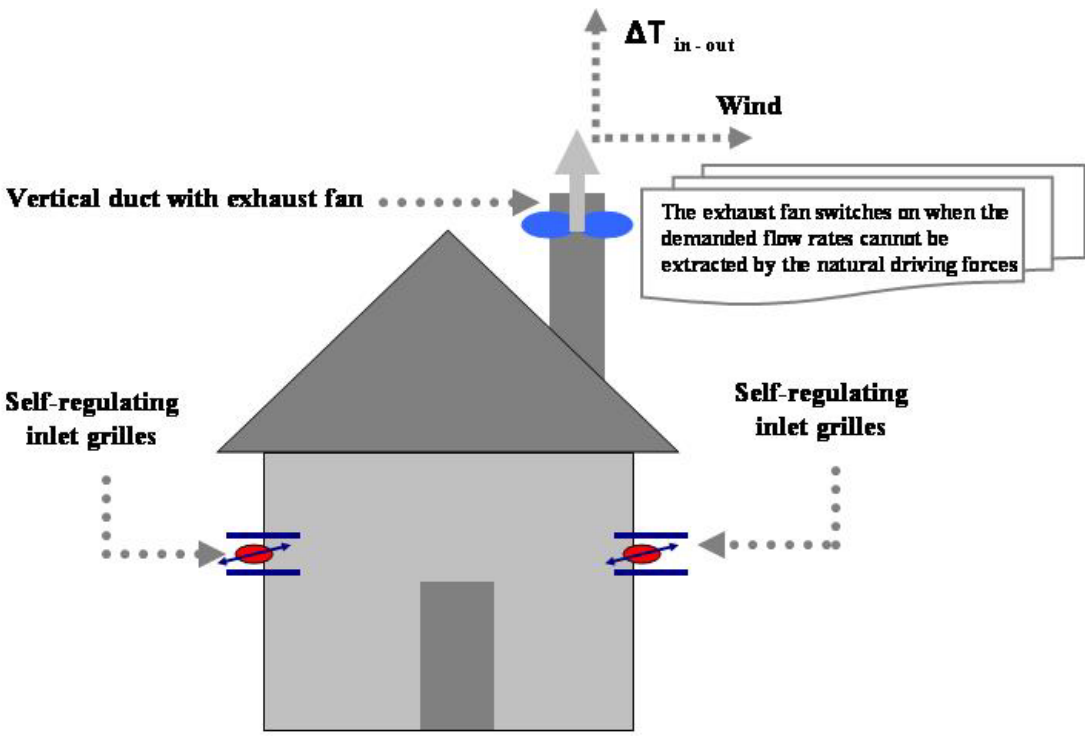

Figure 7.9 : Representation of the RESHYVENT hybrid ventilation system for moderate climates (Niachou and Santamouris, 2005)

For pressure differences above 1Pa, the pressure-dependent inlet grilles have the following characteristics:

$Q = K\ \Delta P^n$ and $K=25.96 dm^3/s$ per 1 Pa , n=0.50

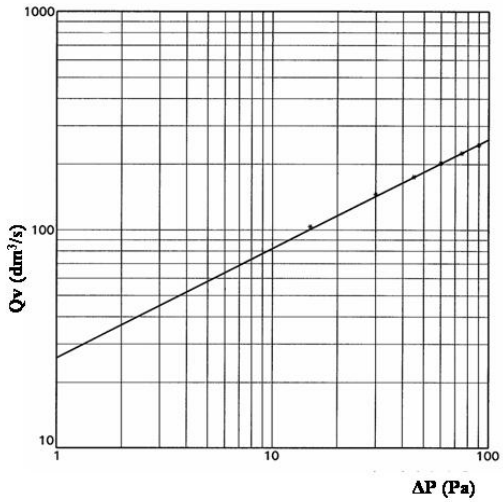

Figure 7.10 : Characteristic of pressure dependent inlet grilles for pressure differences above 1 Pa (Niachou and Santamouris, 2005)

The inlet grilles are considered fully open between 0Pa and 0.5 Pa. Above 0.5 Pa the inlet grilles start to control and the airflow admission (dm^3/s) in relation to the pressure difference for self-regulating and pressure-dependent air inlets is given respectively in Table 7.10 and Table 7.11.

Table 7.10: Characteristics of self-regulating inlet grilles (Niachou and Santamouris, 2005)

ΔP [Pa]	Flow rate [dm^3/s]
0	0
0.1	8.2
0.2	11.6
0.3	14.2
0.4	16.4
0.5	18.4
0.6	19.0
0.7	21.7
0.8	22.5
0.9	24.0
1	26.0
5	26.0
10	26.0
20	26.0
50	26.0

Table 7.11: Characteristics of pressure-dependent inlet grilles (Niachou and Santamouris, 2005)

ΔP (Pa)	Flow rate (dm^3/s)	ΔP (Pa)	Flow rate (dm^3/s)
0	0	1	26
0.1	8.2	2	36.7
0.2	11.6	5	58.0
0.3	14.2	10	82.1
0.4	16.4	20	116.1
0.5	18.4	40	164.2
0.6	19.0	50	183.6
0.7	21.7	60	201.1
0.8	22.5	75	224.8
0.9	24.0	100	259.6

The RESHYVENT ventilation system is examined either with natural or with hybrid duct exhaust system. With natural duct exhaust system, the air exhaustion is affected by natural driving forces.

When the exhaust flow rate through the duct is lower than the demanded flow rate, then the fan starts to operate. A minimum airflow rate of 7 dm^3/s is assumed per occupant. However, during the hours of activity (etc. showering, cooking) a standard airflow rate of 42 dm^3/s is considered with the four occupants present. Besides, a minimum value of 21dm^3/s is ensured independently of the number of occupants in the ventilated space. The total demanded flow rates (dm^3/s) based on occupancy and activity schedule within the 24-hour period is given in Table 7.12. In case of the hybrid ventilation system, the exhaust fan will operate during the hours when the exhaust flow rates through the duct are lower than the required values in order to ensure the total demanded airflow rate. Thus, when CO_2 sensor activates the exhaust fan the airflow rate will be kept constant.

Table 7.12: Demanded exhaust flow rates (dm^3/s) (Niachou and Santamouris, 2005)

Time	Demanded flow (dm^3/s)
0-6h	28
6-8h	42
8-17h	21
17-19h	42
19-22h	28
22-23h	42
23-24h	28

7.5 Computational Results

A detailed analysis of the efficiency of the pilot and RESHYVENT ventilation systems has been performed in various urban canyon configurations and under different climatic conditions. The main concluding results regarding the performance of these ventilation systems will be discussed in the following paragraphs.

7.5.1 Performance of the Pilot RESHYVENT Ventilation System

The efficiency of the pilot hybrid ventilation system, based on the RESHYVENT concept, was studied in a single zone apartment of an average leakage class (2.5 ACH@50Pa) located in different canyons. The simulations were performed on a yearly basis for different European climates and considering various scenarios of ambient TVOC's concentrations.

7.5.1.1 Impact Of Canyon Geometry

A sensitivity analysis has been performed in order to study the performance of the hybrid ventilation system in different canyon geometries (Figure 7.4) with and without local obstructions behind the rear building walls (Figure 7.5). The exhaust fan is considered at the canyon façade and the inlet fan at the rear canyon wall. The applied control strategy is based on demand control (TVOC's<3mgr/m^3 and CO_2<1000ppm). The main goal of the simulations was to estimate the time during which the hybrid ventilation system would operate in the mechanical mode. The ambient TVOC's and CO_2 concentrations are considered respectively equal with 1.5mgr/m^3 and 400ppm. Figure 7.11 illustrates the percentage (%) of hours of fans operation (%) for a year period for Athens climate.

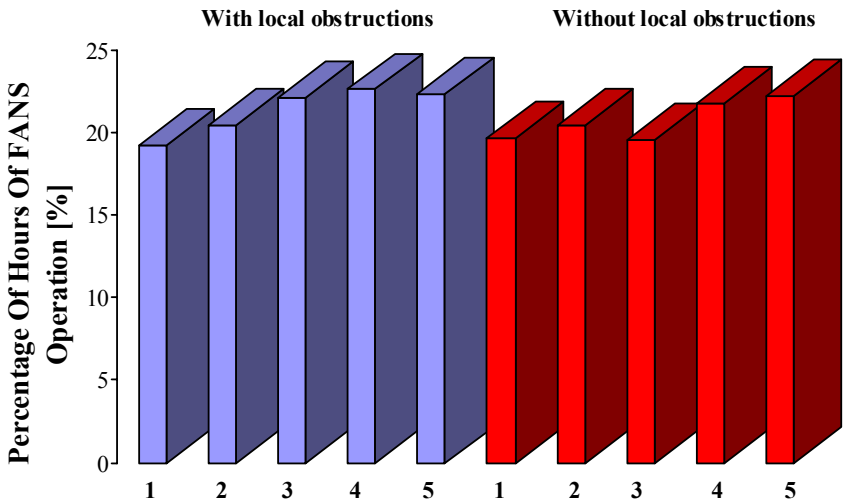

Figure 7.11 :: Percentage of hours (%) of fans operation for the pilot hybrid ventilation system for Athens climate in five canyon geometries 1)H/W=1, 2)H/W=1.5, 3)H/W=2, 4)H/W=2.5, 5)H/W=3 with and without local obstructions behind the rear building walls

As shown the impact of various canyon geometries on the hours of operation of supply/exhaust fans, when the performance of the hybrid ventilation system is based on demand control, is characterized by small absolute differences (up to 3%). This is explained by the relatively similar distribution of pressure differences ($|\Delta P| = |P_{out} - P_{in}|$) across canyon facades (Figure 7.12). The pressure differences are calculated at a height of 1.8m above the zone level, where inlet/exhaust fans are installed. It has been estimated that the majority of the estimated absolute pressure differences for all canyon configurations is less than 1Pa, as a result of wind and pressure distributions.

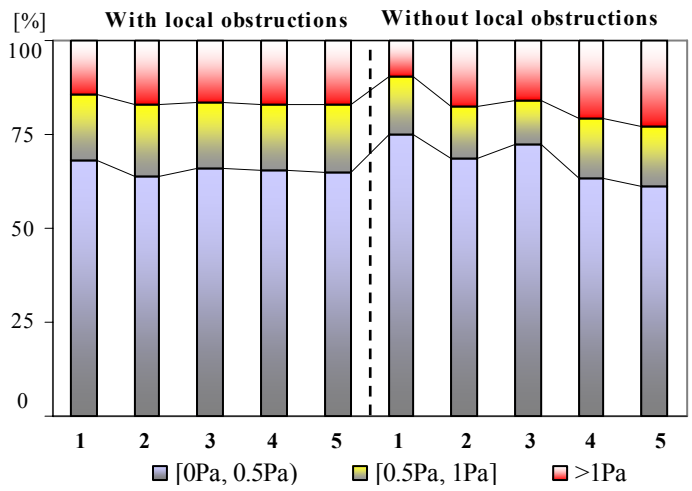

Figure 7.12 : Percentage (%) of various absolute pressure differences, $|\Delta P|$, across canyon facades for Athens climate for five canyon geometries 1)H/W=1, 2)H/W=1.5, 3)H/W=2, 4)H/W=2.5, 5)H/W=3 with and without local obstructions behind the rear canyon façades

7.5.1.2 Impact of Different Climates

In order to show the impact of different climatic conditions on the performance of the pilot hybrid ventilation system, a number of simulations were performed on a yearly basis for a typical urban canyon with H/W equal with 2 (Figure 7.4) and with shielded rear canyon façade. Eleven European climates were simulated, while the majority of them had moderate climate (Table 7.4). One city with the cold/severe climate (Oslo) and one city with the warm climate (Madrid) were included in the list in order to estimate the performance of the hybrid ventilation system under 'extreme' weather conditions. Stockholm represents cold climate and Paris is somewhere in-between the moderate and mild climate.

As shown in Figure 7.13 the observed differences in the hours of operation of the inlet/exhaust fans, when installed at canyon facades, under different climatic conditions are very small (the absolute maximum difference is 3%).

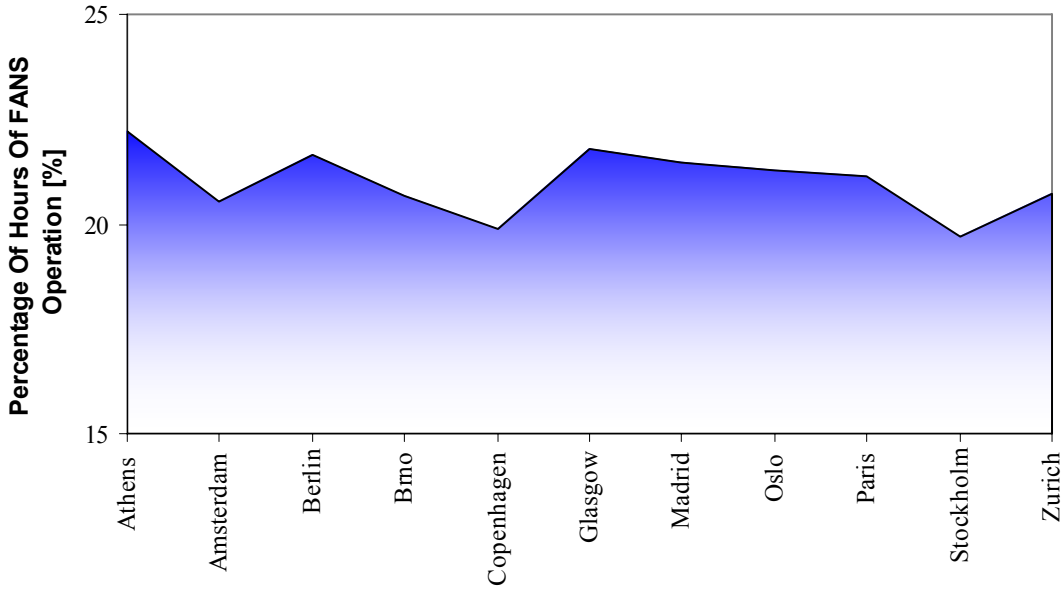

Figure 7.13 : Percentage of hours (%) of fans operation on a yearly basis in an urban canyon with H/W=2 for eleven European climates

The impact of different climates on the hours of operation of the hybrid system in the mechanical mode has been minimized due to the strong canyon effect on the wind and pressure distributions across the building walls. From the estimated values of the absolute pressure differences ($|\Delta P| = |P_{out} - P_{in}|$) across the canyon facades (Figure 7.14), it has been found that for almost all climates, except for Amsterdam, more than 50% are between 0Pa and 1Pa. This is a conclusion which is valid either for regular or deep canyon configurations (Niachou and Santamouris, 2005).

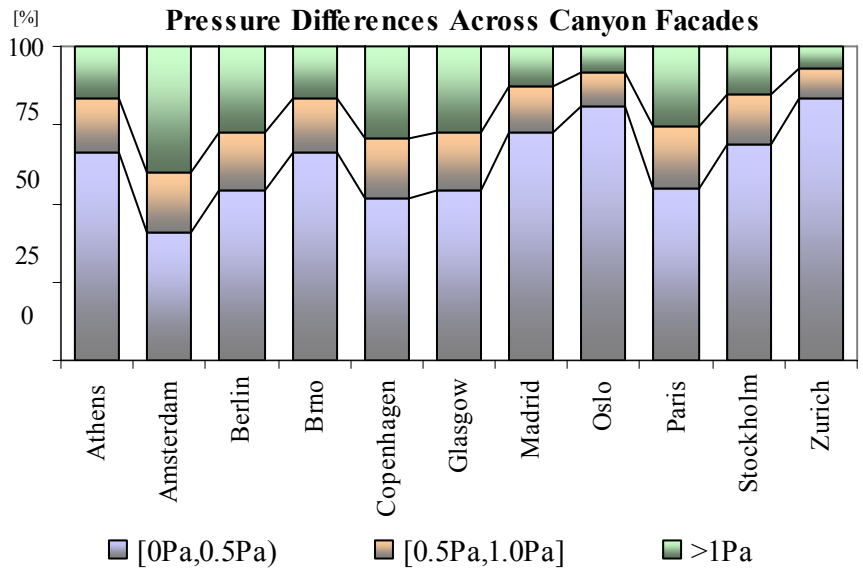

Figure 7.14 :Percentage (%) of absolute pressure differences, $|\Delta P|$, across canyon facades, on a yearly basis for eleven European climates

In case of Amsterdam, 40% of the absolute pressure differences ($|\Delta P| = |P_{out} - P_{in}|$) were above 1 Pa due to higher wind speeds, in comparison with all other European climates (Table 7.13).

Table 7.13: Estimated mean, 50th and 95th percentiles of wind speed values (m/s) inside the canyon with H/W=2 for various European climates

CITY	Wind speeds inside canyon (m/s)		
	mean	50th percentile	95th percentile
Athens	1.8	0.6	5.5
Amsterdam	3.2	3.2	7.2
Berlin	2.4	2.1	6.0
Brno	1.8	0.6	4.9
Copenhague	2.5	2.6	6.1
Glasgow	2.4	2.3	6.0
Madrid	1.4	0.6	4.7
Oslo	1.1	0.6	4.0
Paris	2.4	2.1	5.9
Stockholm	1.7	0.6	4.8
Zurich	1.0	0.6	3.8

7.5.1.3 Impact of Outdoor Urban Air Characteristics

The effect of outdoor air characteristics on the performance of the pilot hybrid ventilation system was shown through the study of TVOC's. Finlayson-Pitts and Pitts (1986) mention that TVOC's (ref. toluene) concentrations vary from 0.24mgr/m^3 in remote areas up to 5.64mgr/m^3 in urban areas in a strong air pollution incident. A sensitivity analysis has been performed considering three different outdoor concentrations, namely, 0.5mgr/m^3, 1mgr/m^3 and 1.5mgr/m^3 which correspond to the range of ambient TVOC's concentrations measured by Ekberg (1994) in urban areas near busy streets. The demand control strategy is based on indoor TVOC's levels which must not exceed the value of 3 mgr/m^3. A typical canyon configuration with H/W=2 and with shielded rear building façade was studied for different European climates.

Figure 7.15 shows that when the ambient TVOC's concentration is doubled (1mgr/m^3), then the estimated percentage of hours (%) of operation of the hybrid ventilation system in the mechanical mode, is increased 1.2 up to 1.4 times, while when the outdoor TVOC's concentration is threefold (1.5mgr/m^3), then the percentage of fans operation becomes 1.5 up to 2 times more (for the different climates) in comparison with the lowest ambient TVOC's concentration (0.5mgr/m^3). A similar performance was observed and for the other canyon configurations.

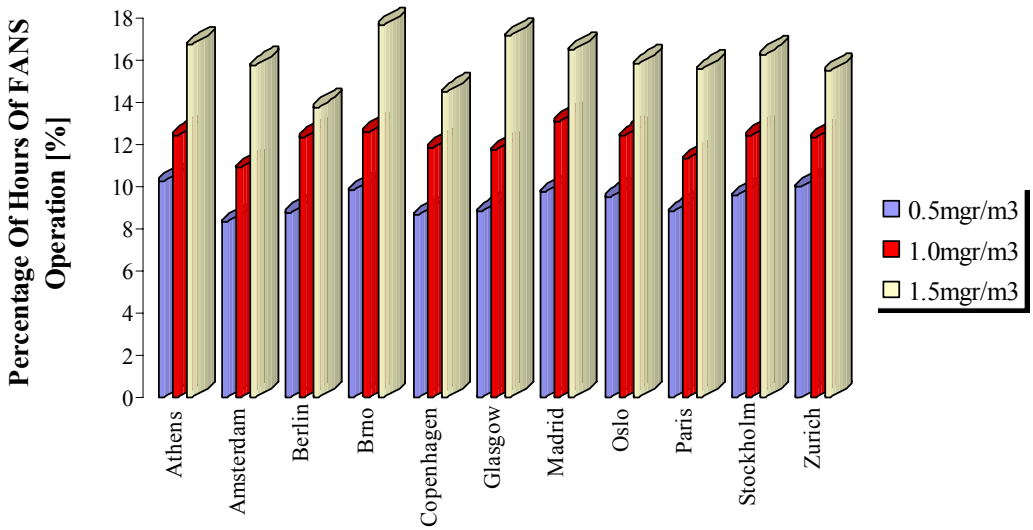

Figure 7.15 : Estimated Percentage (%) of hours of of fans operation on a yearly basis for eleven European climates when ambient TVOC's concentrations are (1) 0.5mgr/m^3, (2) 1mgr/m^3 and (3) 1.5mgr/m^3

7.5.2 Performance of RESHYVENT Hybrid Ventilation System

The performance of the RESHYVENT hybrid ventilation system, with pressure-dependent inlet grilles installed across canyon facades, will be discussed in the following paragraphs.

7.5.2.1 Impact of Canyon Geometry

For each of the five canyon geometries (Figure 7.4), with shielded rear canyon façades, different duct lengths have been considered for the duct ventilation exhaust system, ranging from 2.3m up to 8.3m (Table 7.14), as a function of the building height. In all canyons, the roof outlet is considered 1m above the building roof.

Table 7.14: Geometrical characteristics of studied canyons and length of ducts of the ventilation exhaust system (Niachou and Santamouris, 2005)

Canyon	Height H (m)	Width W (m)	Aspect ratio H/W	Duct Length L (m)
1	18	18	1.0	2.3
2	18	12	1.5	2.3
3	20	10	2.0	4.3
4	22	8.8	2.5	6.3
5	24	8	3	8.3

The impact of different canyon geometries on the performance of RESHYVENT ventilation system for moderate climates has been studied both for steady state and dynamic conditions. It has been resulted that its performance with the natural duct exhaust system is different in the various canyon geometries. Figure 7.16 depicts the estimated airflow rates (m^3/h) through the pressure dependent inlet grilles and vertical ducts in a regular (H/W=1) and a deep canyon (H/W=3), under steady state conditions. Wind effect is the dominant driving force in canyon with the lowest aspect ratio (H/W=1). Stack effect becomes more important in the deep canyon (H/W=3), due to increased pressure differences resulting from the higher duct height (8.3m). Under the combined wind and stack effect, then the air exhaustion through the duct depends on the dominating natural driving force. This is a general conclusion valid for all climates.

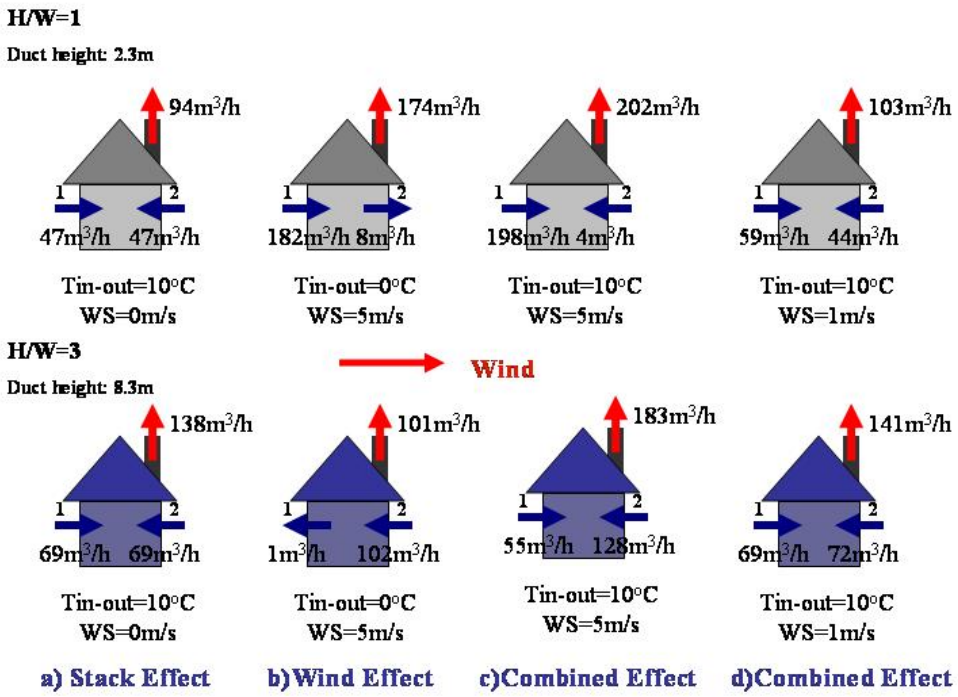

Figure 7.16 : Performance of RESHYVENT ventilation system for moderate climates with the natural duct exhaust system in two canyons with H/W= 1 and 3 under steady state conditions

The present analysis has been further continued with a set of dynamic simulations for Athens reference year. The undisturbed wind speed and wind direction have been translated into canyon data (Georgakis and Santamouris, 2005c). Thus, five wind speed data sets have been estimated for the five canyon geometries. The temperature difference between inside and outside, within the year, is almost the same for all canyon geometries.

The percentage of hours (%), when the air exhaustion through the duct is lower than the demanded flow (Table 7.8), is shown in Figure 7.17. The absolute minimum value, 54%, has been estimated for the deepest canyon with H/W=3. As mentioned above this is explained by the fact that the stack pressure across the vertical duct decreases with height, leading to increased pressure differences across the higher ducts.

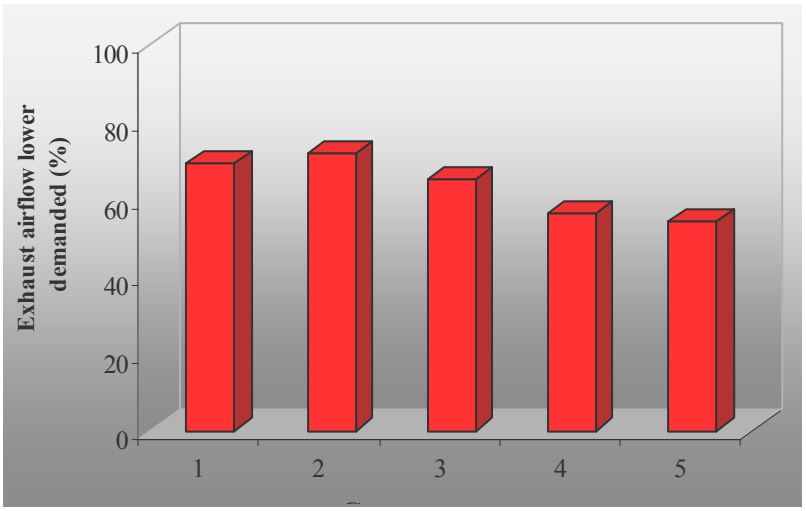

Figure 7.17 : Estimated percentage of hours (%), within a year period, when the exhaust flow rates through the natural duct system is lower than the demanded flow rates, for five canyon geometries 1)H/W=1, 2)H/W=1.5, 3)H/W=2, 4)H/W=2.5 and 5)H/W=3

Figure 7.18 illustrates the estimated percentage (%) of hours for different pressure differences across canyon and rear canyon facades with the natural duct exhaust system. The pressure differences are measured at a height of 1.8m above the floor, where inlet grilles are installed. As it has been already discussed, the majority of pressure differences range between 0-1Pa for all canyon geometries. Thus, the range between 0-1Pa becomes of high interest for pressure-dependent or self-regulated air inlets when installed at canyons facades. This result is not only valid for Athens climate but as it will be shown in the next paragraphs similar conclusions were found for other ten European climates.

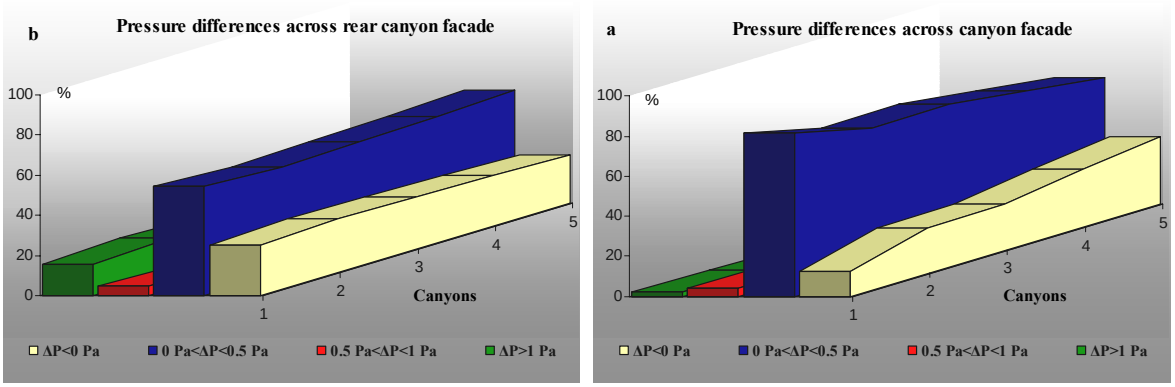

Figure 7.18 : Estimated % of hours for different pressure differences a) across canyon and b) rear canyon facades for natural ventilation exhaust system, for five canyon geometries 1)H/W=1, 2)H/W=1.5, 3)H/W=2, 4)H/W=2.5 and 5)H/W=3 for Athens reference year (Niachou and Santamouris, 2005)

7.5.2.2 Impact of Canyon Layout

The performance of RESHYVENT IC2 ventilation system with the natural duct exhaust system is depicted in Figure 7.19. The inlet and exhaust flows (m^3/h) refer to steady state conditions in a deep canyon with H/W=2, with and without local obstructions opposite rear canyon walls. In case of the canyon without local obstructions then façades 1 and 2 correspond to rear and front canyon walls. It has been estimated that for winds towards the back canyon façades, wind effect is reduced for the shielded facades in comparison with the exposed and thus the air exhaustion through the duct is reduced when local obstructions are considered.

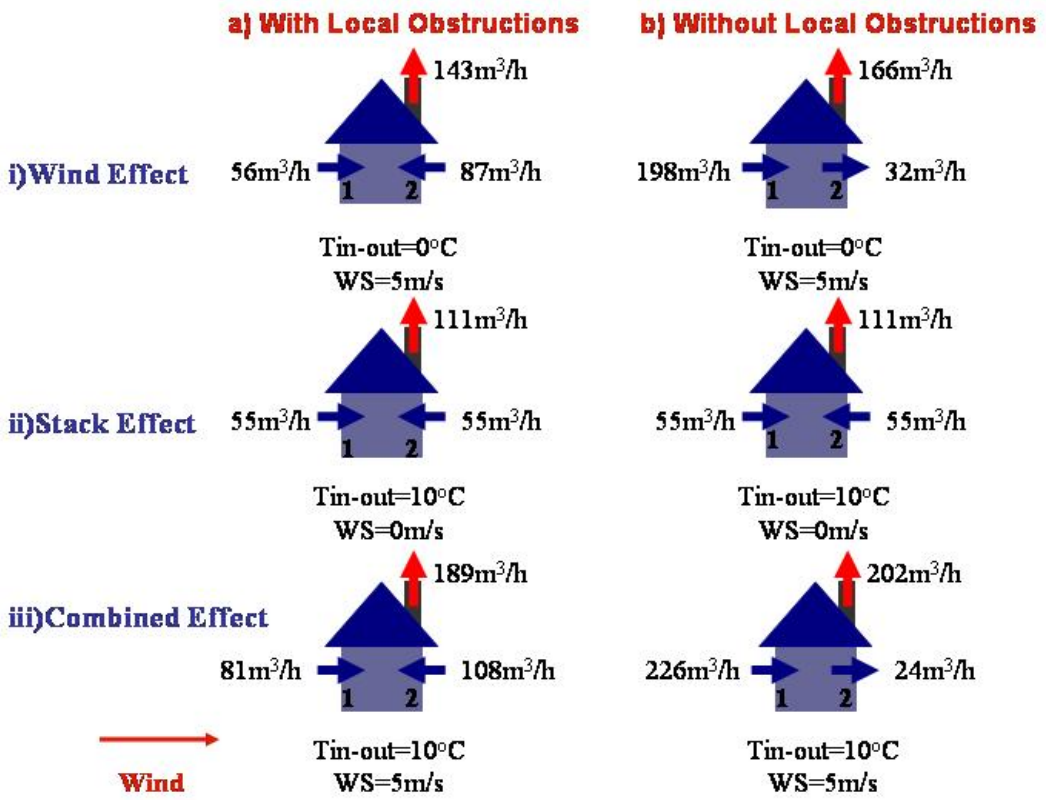

Figure 7.19 : Estimated AirflowRates (m3/h) of RESHYVENT Ventilation System With The Natural Duct Exhaust System In A Canyon (H/W=2) a)With and b)Without Local Obstructions Opposite Rear Canyon Walls For Steady State Conditions

A similar analysis has been performed considering the dynamic conditions for Athens climate based on the following assumptions:

- The average building leakage is $n_{50}=2.5h^{-1}$.
- The control of the pressure-dependent inlet grilles is based on demand control with CO_2.
- The outdoor CO_2 and TVOC's concentrations are respectively 400ppm and $1mgr/m^3$. Half outdoor concentrations are considered at the back canyon facade when an open configuration without local obstructions is considered.
- The indoor TVOC's emission is considered equal with $1.1mgrh^{-1}m^{-2}$.

The present analysis emphasizes on the estimation of indoor air quality levels (IAQ), as a result of different outdoor air characteristics at the front and rear canyon facades. Thus, the estimated percentage (%) of hours when indoor CO_2 levels are lower than 1200ppm and TVOC's levels are lower than $3mgr/m^3$ with the natural ventilation duct exhaust system are shown in Figure 7.20. Better indoor air quality conditions exist in the reference building without local obstructions mainly because

of the better outdoor air characteristics at the rear canyon façade and the stronger wind effect, as it has been explained above.

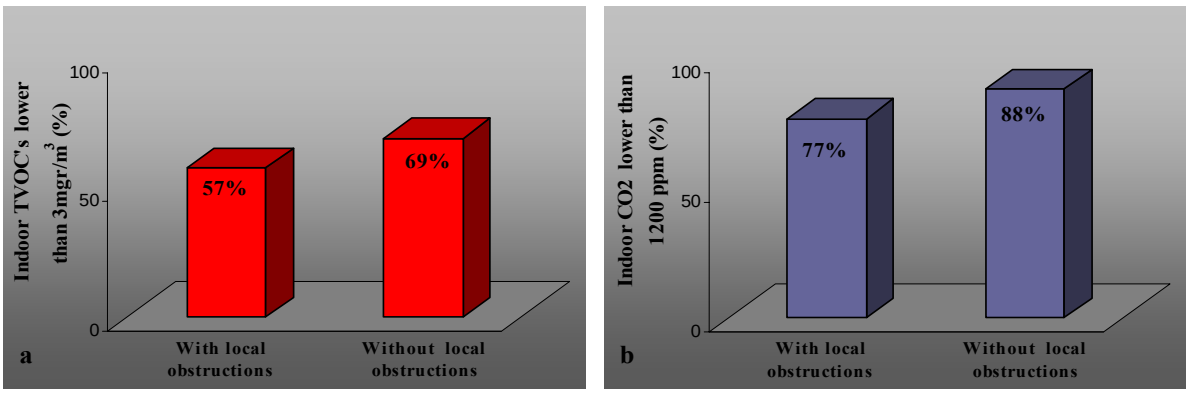

Figure 7.20 : Percentage Of Hours (%) When IAQ Levels Are Fulfilled, With The Natural Duct Exhaust system, In The Canyon With H/W=2 With And Without Local Obstructions Behind Rear Building Walls

It should be mentioned that with the use of the hybrid ventilation system the indoor air quality levels are met in 100% of the hours within the year, for all canyon geometries and studied configurations. Figure 7.21 shows the hours (%) of operation of the exhaust fan. As it has been discussed above, due to the lower exhaust flow rates through the duct in canyons with local obstructions opposite the rear facades, the hours of operation of the exhaust fan become higher.

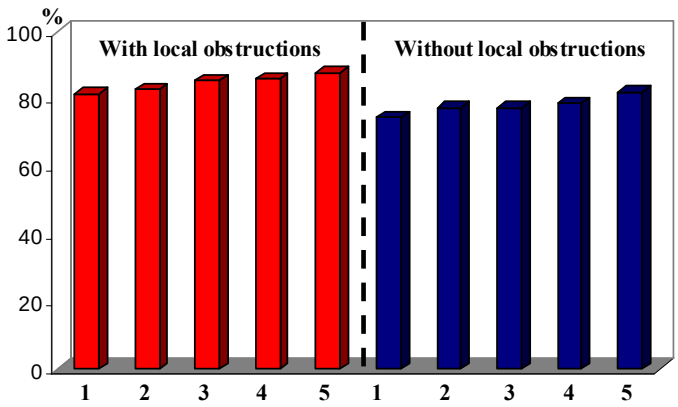

Figure 7.21 : Percentage Hours (%) Of Operation Of The Exhaust Fan For Five Canyon Geometries 1)H/W=1, 2)H/W=1.5, 3)H/W=2, 4)H/W=2.5 and 5)H/W=3 With And Without Local Obstructions, For Athens Reference Year (Niachou and Santamouris, 2005)

7.5.2.3 Impact of Indoor Pollutant Emissions

A parametric study has been performed considering two indoor TVOC's emissions. Namely, an average TVOC's emission equal with 1.1mgh^{-1}m^{-2} (emission factor for 30 vinyl floorings reported by Gustafsson and Jonsson, 1993) and a high emission of 2.2mgh^{-1}m^{-2} (Indoor Air Quality & Its Impact on Man, 1997) were considered in a set of simulations in order to investigate the efficiency of the ventilation system with natural and hybrid exhaust modes. The estimated indoor TVOC's concentrations for the two emission factors for both natural and hybrid ventilation exhaust systems are depicted in Figure 7.22.

It was resulted that when high indoor pollutant emissions are expected in urban buildings, then it is very important to consider effective control strategies in order ensure the required IAQ levels with the minimum demanded flow rates.

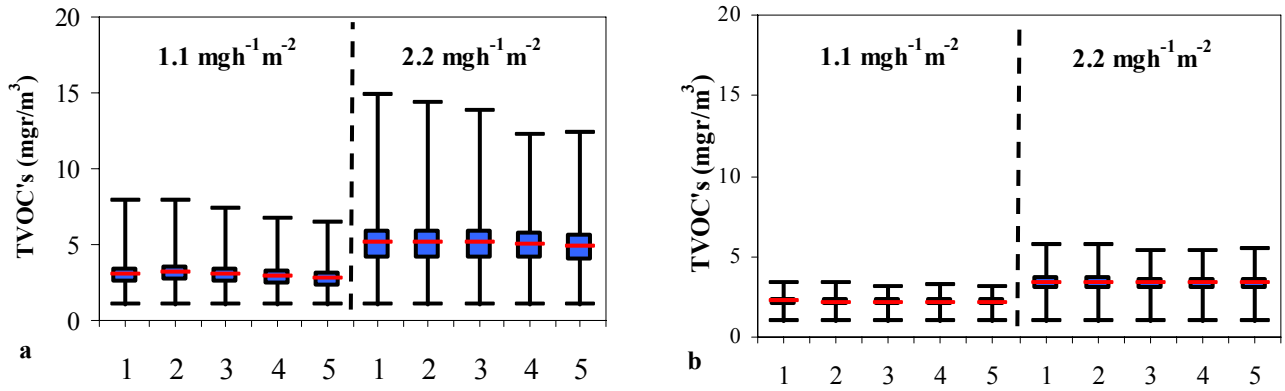

Figure 7.22 : Estimated Indoor TVOC's Concentrations (mgr/m^3) Considering Two Indoor TVOC's Emission Factors for 5 Canyon Configurations for a) Natural and b) Hybrid Ventilation Exhaust systems, for Athens Reference Year (Niachou and Santamouris, 2005)

7.5.2.4 Impact of Building Leakage

The impact of the building leakage on the efficiency of the RESHYVENT ventilation system was studied using three different leakage classes (0.6, 2.5 and 5h^{-1}@50Pa). The demand control strategy of the inlet grilles is based on indoor CO_2 levels which must be lower than 1200ppm, while the outdoor CO_2 concentrations are considered equal with 400ppm.

As it has been expected, when the building leakage is increased, then the introduced airflow through the inlet grilles is reduced, due to increased infiltration rates. Besides, the hours of opening of the exhaust fan is reduced when building leakage is increased (Figure 7.23). It is also interesting that the hybrid ventilation system becomes mechanical (100% operation of the exhaust fan) in very tight buildings (0.6h^{-1}@50Pa).

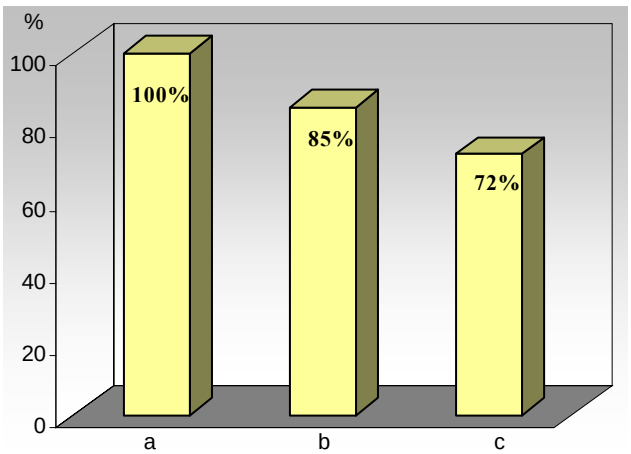

Figure 7.23 : Percentage (%) of Opening of Exhaust Fan for Different Building Leakages (@50Pa): a)0.6h^{-1}, b) 2.5h^{-1} and c) 5h^{-1}

7.5.2.5 Impact of Different Control Strategies

A sensitivity analysis was performed for the study of the IC2 hybrid ventilation system under different control strategies inside the canyon with H/W=2 and with shielded rear canyon facades. The applied control strategies concerning the operation of the inlet grilles were based either on indoor air quality or on thermal comfort requirements:

a. CO_2 control
The inlet grilles open when indoor CO_2 concentration exceeds 1200ppm.

b. TVOC's control
The inlet grilles open, when indoor TVOC's levels exceed 3mgr/m^3.

c. CO_2 & TVOC's control
A combined demand control strategy is considered based on indoor air quality levels. The inlet devices open when CO_2 exceeds 1200ppm or when TVOC's is above 3mgr/m^3.

d. Passive cooling
If indoor air temperature is above 26°C and the ambient air is colder than the indoor air, then the inlet grilles open.

e. Passive cooling & CO_2 control
A combined demand control strategy based on passive cooling (26°C) and on CO_2 control (1200ppm).

f. Passive cooling & TVOC's control
A combined demand control strategy based on passive cooling (26°C) and on TVOC's control (3mgr/m^3).

Figure 7.24 shows the calculated percentage (%) of hours for Athens reference year, when indoor air quality levels are perceived (CO_2 concentration is lower than 1200ppm and TVOC's is less than 3mgr/m^3) for natural and hybrid ventilation exhaust systems and when the operation of the inlet grilles is based on each of the above control strategies.

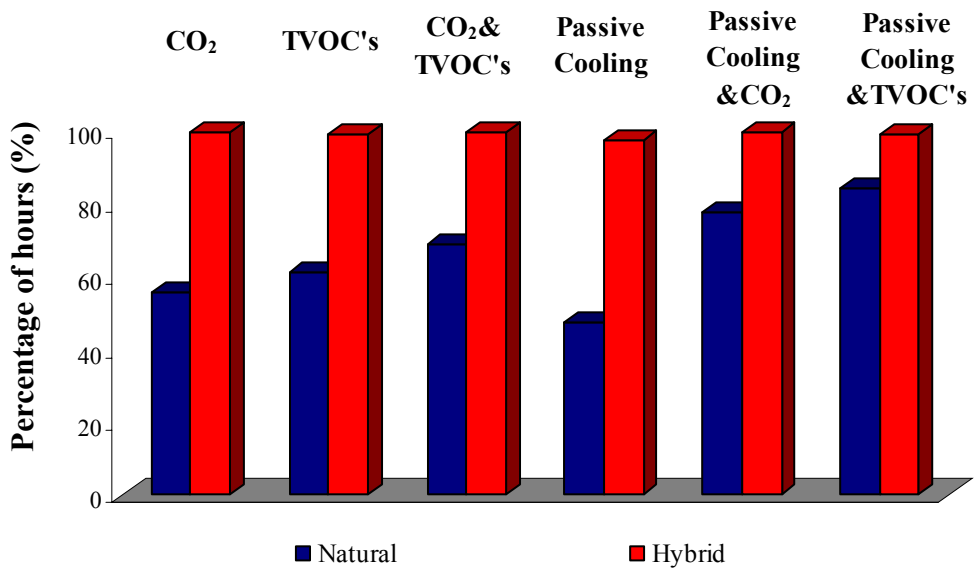

Figure 7.24 : Estimated Percentage (%) Of Hours, When Indoor Air Quality Is Perceived With Different Control Strategies With Natural And Hybrid Ventilation Exhaust Systems, For Athens Reference Year (Niachou and Santamouris, 2005)

Generally speaking, it is very important to apply the most effective control strategy in order to achieve the best performance of the ventilation system with the minimum demanded flow rates. Especially in the urban environment, where the ambient concentration of TVOC's is a very variable parameter and can affect a lot indoor IAQ levels, it is necessary to apply control strategies taking into account both CO_2 and TVOC's.

7.5.2.6 Impact of Different Climates

In order to investigate the impact of different climatic conditions on the performance of the hybrid ventilation system, a number of simulations were performed by means of the TRNSYS with TRNFLOW (Weber et al., 2003), in a typical urban canyon with H/W equal with 2 (Figure 7.4). The main goal of the simulations was to estimate percentage of time (%) during which the hybrid ventilation system would operate in the mechanical mode. The hybrid ventilation system was simulated with the self-regulating inlets, which opened when the CO_2 concentration in the apartment (zone) increased to 800 ppm. The inlets closed when the CO_2 concentration decreased to 600 ppm.

Charvat et al. (2005) have shown that the climatic conditions had a significant impact on the exhaust mode of operation of the hybrid ventilation system. Also, the impact of the climatic conditions on the opening time of the inlets was not as significant as in case of fan running time (Table 7.15). These differences were caused by the pressure difference across the inlets. More time is needed to draw air in when the pressure difference is lower.

Table 7.15: Fan Running Time and Inlet Opening (Charvat et al., 2005)

CITY	FAN switched on [% of hours]	INLETS opened [% of hours]
Amsterdam	44.7	70.8
Berlin	42.3	73.4
Brno	38.6	74.0
Copenhagen	36.5	70.1
Glasgow	40.0	73.1
Madrid	56.8	81.1
Oslo	29.3	71.9
Paris	46.0	74.3
Stockholm	34.5	72.7
Zurich	40.4	77.7

Another outcome of the simulations was the pressure difference across the inlets, while these were opened. The self-regulating inlets are able to control the air flow rate for the pressure difference higher than 1 Pa. Table 7.16 indicates the percentage of time during which the pressure difference across the inlets was higher than 1 Pa. The pressure difference across the facades (inlets) was lower than 1 Pa for a significant amount of time. This is in agreement with the results reported above for Athens climate. Thus, the self-regulating inlets operated most of the time in the regime where flow rate is dependent on pressure difference. As a result, longer time is needed to bring the CO_2 concentration down (since the air flow rate through the inlet is lower than the nominal one).

The average CO_2 concentration was, because of the demand control, very similar in all studied cases. The concentration of CO_2 never exceeded 1200 ppm during simulation period. The average concentration of TVOC's is also very similar in all cases. The concentration of TVOC's exceeded several times 3mgr/m^3 in the simulations. However, the appropriate strategy when dealing with TVOC's in residential buildings is to decrease the source strength and not to increase the ventilation rate.

Table 7.16: Estimated % of Hours During A Year Period With ΔP>1Pa Across Self-Regulating Inlets for Ten Different Climates (Charvat et al., 2005)

CITY	Canyon Facade ΔP>1Pa [% of hours]	Rear-canyon Facade ΔP>1Pa [% of hours]
Amsterdam	39.1	16.0
Berlin	28.6	12.1
Brno	17.6	11.0
Copenhagen	25.0	18.0
Glasgow	28.1	14.8
Madrid	12.4	5.5
Oslo	7.1	6.1
Paris	26.0	14.6
Stockholm	17.5	10.9
Zurich	7.0	3.7

8 Recommendations for the Use of Natural and Hybrid Ventilation Systems in the Urban Environment

Based on the knowledge from the experimental research and computational procedures, in the framework of WP10 of RESHYVENT project, a number of recommendations or guidelines are described for the use of hybrid ventilation systems in different urban situations. The proposed solutions are mostly related to the building and its ventilation relevant characteristics in order to optimize the microclimate of the dwelling. The list of recommendations is summarized in Table 8.1, where a classification is made according to each studied ventilation concept.

Table 8.1: Recommendations For The Use Of Natural And Hybrid Ventilation Systems In The Urban Environment (Niachou and Santamouris, 2005)

Maximize Natural Driving Forces	
i.	Optimize stack effect by using high vertical differences between ventilation supply and extract, especially in canyon configurations, where wind effect is very reduced.
ii.	Locate supply fans or pressure-dependent air inlets at building facades where wind effect is expected to be maximum.
iii.	Use self-regulated grilles at shielded canyon facades in order to ensure a constant flow rate independently of the pressure differences across the facades.
iv.	Optimize wind effect by using effective window airing from the windward facades without causing draught problems to occupants.
v.	When designing inlet grilles for canyons facades, take advantage of small pressure differences, especially between 0Pa-1Pa.
vi.	Use wind and solar technologies in natural and hybrid ventilation systems to enhance wind and stack effect (solar chimneys, wind catchers, etc).
vii.	Ventilation extract should de designed carefully in accordance with air intakes in order to facilitate the recirculation of air inside the building and should exhaust air in places where it is not dispersed easily.
viii.	In case of stack ventilation it must be ensured that the airflow exhausts at high level and thus the risk of downwash is minimized.

	Consider Thermal Comfort
i.	Use natural ventilation as much as possible, but avoid draught and excessive air temperature gradients.
ii.	Use natural ventilation in warm climates mainly for night ventilation during summer period or during intermediate seasons.
iii.	Avoid natural ventilation under excessive ambient temperatures. Instead, think of hybrid ventilation based on temperature control.
iv.	Use self-regulating grilles in order to avoid the draft risk, especially in cold climates.
	Improve IAQ
i.	Consider the most appropriate demand control strategy in order to achieve the best indoor air quality levels with the minimum energy cost.
ii.	Apply source control, when necessary, in order to ensure the indoor air quality without increasing demanded flow rates.
iii.	Ensure that the minimum demanded flow rates will meet IAQ levels, when high indoor pollutant emissions are expected.
iv.	Consider TVOC's control or combined TVOC's with CO_2 control, especially in the urban environment.
v.	Design the position of air inlets near the building facades which are less exposed to outdoor pollution sources in order to enhance the possibility of using outdoor air without filtering.
vi.	Control of ventilation intakes should be applied in order to avoid the ingress of polluted air during periods of peak traffic load.
	Save Energy
i.	Minimize airflow rates and thus the use of cooling/heating, without sacrificing indoor air quality (in terms of CO_2), by designing mechanical exhaust systems with minimum demanded flow rates based on occupancy scheme.
ii.	Exploit natural driving forces, wind and stack effect, especially during the periods when heating or cooling is not needed.
iii.	Use low-energy fans with contemporary control mechanisms (air flow control, pressure drop and frequency control) at canyon facades, where wind effect is seriously reduced, in order to achieve demanded flow rates with minimum energy cost.
iv.	Use hybrid ventilation with heat recovery in cold climates to achieve demanded ventilation rates with the minimum energy cost for heating.
v.	Consider the most appropriate demand control strategy to ensure indoor air quality with minimum use of fan energy and without increasing demanded flow rates.

9 Conclusions

Natural and hybrid ventilation in urban areas are highly affected by a number of urban parameters. Effective design of natural and hybrid ventilation in urban buildings requires a good understanding of the urban climate characteristics. The urban environment has important considerations for the potential of natural and hybrid ventilation systems due to increased ambient temperatures, reduced wind speeds, increased noise and pollution levels. The most important urban parameters (canyon geometry and layout, wind and temperature distribution inside canyons, pollutant concentrations, external noise, solar/daylight access, humidity and wind pressure on building facades) were highlighted and experimental and theoretical investigation was performed. Further experimental or theoretical research will enhance knowledge on the performance of natural and hybrid ventilation in urban environment, thus more efficient ventilation systems will be designed.

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