NATURAL VENTILATION FOR HEALTH, COMFORT AND ENERGY EFFICIENCY

F. Allard, C. Ghiaus, Y. Mansouri
LEPTAB
Université de La Rochelle
Ave. M. Crépeau F-17042La Rochelle cedex 01
francis.allard@univ-lr.fr

ABSTRACT

The aim of the present paper is at first to define the different ventilation strategies, to present briefly the physical phenomena involved in the natural ventilation processes and the control strategies. Then, a typology of natural ventilation scenarios is given as well as a short review of natural ventilation components and some examples of innovative solutions. Finally we discuss the various steps of a design process from the conceptual stage to the final application.

1. INTRODUCTION

Ventilation is essential for supporting life by maintaining acceptable levels of breathable air, to remove all kinds of pollutants, moisture, and odours generated inside the buildings, and guarantee healthy conditions. Awareness of this physiological necessity has been developed since the 18th and 19th centuries and it became consistent at the end of the 19th century with the industrial revolution and the development of social housing (Awbi, 1998) At the end of the 19th century, it became clear for scholars and medical professionals that it was absolutely necessary to provide fresh air to indoor spaces. The first guidelines based on CO_2 concentrations appeared at this time in Western Europe defining a ventilation need about 7 litres of fresh air per second and per person (Figure 1). In most cases, this health requirement has been assessed by natural ventilation until the second half of the 20th century.

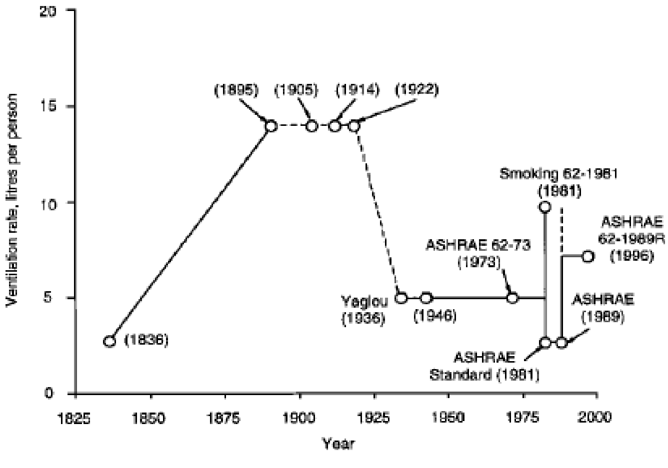


Figure 1: Changes in the minimum ventilation rates in USA (Awbi 1998)

Furthermore, until few decades, natural ventilation has also been the most effective and very often the unique way to reduce the effect of internal heating loads and to improve comfort conditions inside buildings during hot seasons or in warmer climate regions like the Mediterranean zone or in the Middle East. Usually coupled with evaporative cooling strategies for the hotter regions, many architectural strategies have been developed in order to improve the use of dominant winds or generate stack effects between zones of a building maintained at different temperatures. The wind catchers of the Middle East regions or the "patio andaluz" are some of the more representative figures in this domain.

A third element that became more sensitive recently is the energy efficiency of buildings. After the oil crisis of the seventies, most countries developed standards and codes to reduce the energy demand of the building sector. The first task was to reduce the heat losses by insulating the building envelopes, making ventilation to be usually in the range between 30 and 60% of the building energy demand. This large proportion of ventilation energy demand, due to the good thermal insulation level of modern or retrofitted buildings, represents the thermal energy necessary for heating or cooling the fresh air introduced for ventilation and the mechanical energy necessary for moving the air (Liddament, 1996). In this respect, natural ventilation appears more and more frequently as a sustainable solution to maintain good indoor environment and reduce energy demand of buildings (Blondeau et al, 2002).

In the present paper we propose to analyse the real targets of ventilation and the strategies we can develop to reach these targets. In a second part we give some examples of recent developments in natural ventilation systems and applications. Finally, we discuss new trends in developing natural ventilation in urban areas.

2. VENTILATION STRATEGIES

2.1 Ventilation Strategies Characteristics:

Their aim, the used means and the way they are controlled can characterize ventilation strategies (Roulet, 2002).

Table 1: Sorting ventilation strategies

	Aim	Means	Control
1	Hygiene, IAQ	Mechanical ventilation	Constant flow rate
2	Heating or cooling	Natural, stack effect	Clock control
3	Free cooling	Natural, wind induced	Demand control
4	Night cooling	Natural hybrid	Temperature controlled
5		Hybrid	Offer dominated

2.2 Aims of Ventilation

2.2.1 Indoor air quality

The aim of ventilation is to ensure acceptable or good indoor air quality, which is to keep all contaminants concentration below a given limit. The required airflow rate hence depends on the intensity of indoor pollution source I_k of contaminant k, its limit concentration C_{kmax} and the outdoor concentration of that contaminant, $C_{k,o}$:

$$\dot{V} = \max\left(\frac{1}{\varepsilon_k}\frac{I_k}{\overline{C}_{k,\max} - C_{k,o}}\right) \quad \text{(Eq. 01)}$$

Where ε is the removal effectiveness of the ventilation system for contaminant k, i.e. the effectiveness in diluting the pollutants in the occupied zone:

$$_{\varepsilon}k = \frac{C_{k,e} - C_{k,s}}{\overline{C}_{ki} - C_{k,s}} \qquad \text{(Eq. 02)}$$

where $C_{k,e}$ is the concentration in exhaust air (or in the air leaving the space), $C_{k,s}$ is the concentration in supply air (or in the air entering the space, e.g. outdoor air in case of natural ventilation), and $\overline{C}_{ki}$ is the average concentration in the occupied space. Note that the effectiveness depends more on the location of the pollutant sources than on the pollutant species.

In systems performing full mixing, $\overline{C}_{ki} = C_{k,e}$, hence $\varepsilon_k=1$ for any pollutant. If there are shortcuts and dead zones, $\varepsilon<1$, while it could be larger in displacement ventilation, since $\overline{C}_{ki}$ could then be smaller than $C_{k,e}$. If the building is clean, i.e. if the occupants are the only source of pollution, the required airflow rate is in the range of 20 to 40 m^3/h according to the literature.(Fanger, Melikov et al. 1988; 1989; Awbi 1998)

Basic principles to ensure good indoor air quality are:

- Avoid as far as possible internal sources of pollution
- Extract air close (in space and time) to remaining contaminant sources and bring new air into the occupied area
- Control airflow rate according to (Eq. 01)

2.2.2 Heating and cooling

The objective is to bring enough air at warmer, respectively colder temperature θ_a, in order to maintain a comfortable temperature θ_i, despite a heat load Φ (which is negative if it is a heat loss). The required airflow rate is then:

$$\dot{V}_H = \frac{\Phi_l}{\rho\, c(\theta_i - \theta_o)} \qquad \text{(Eq. 03)}$$

where ρ is the air density of air, c its thermal capacity at constant pressure (1004 J/(kg.K)).

Basic principles to ensure efficient heating are:

- Avoid heat loss as far as possible by appropriate thermal insulation and controlled ventilation.
- Take profit of solar gains as far as possible.
- Use preferably hydraulic heating, since water is several thousands more efficient than air to transport heat
- If air heating is nevertheless used:
  1. Control airflow rate according to (Eq. 03),
  2. Arrange airflow pattern in order to distribute heat in an appropriate manner to compensate the loss, and avoid shortcuts between supply and extract air.
  3. Take advantage of heat recovery from exhaust air wherever possible.

Basic principles to ensure efficient cooling are:

- Avoid heat gains as far as possible by appropriate thermal insulation and controlled solar protection.
- Take profit of free- or night cooling as far as possible.
- Use preferably hydraulic cooling (cold ceilings), since water is several thousands more efficient than air to transport heat
- If air cooling is nevertheless used:
  1. Control airflow rate according to equation (Eq. 03),
  2. Arrange airflow pattern in order to distribute cold air in an appropriate manner to compensate the gains, avoid cold drafts, and avoid shortcuts between supply and extract air.
  3. Take advantage of heat recovery from exhaust air wherever possible.

2.2.3 Free cooling

The aim is to save energy and to improve comfort by bringing outdoor air colder than indoors to cool down immediately the indoor air loaded by internal heat load. The airflow rate needed for this is:

$$\dot{V}_{FC} = \frac{\Phi_l}{\rho\, c\, (\theta_i - \theta_o)} \qquad \text{(Eq. 04)}$$

where θ_o is the outdoor temperature, which should of course be colder than internal temperature θ_i.

Basic principles to ensure efficient free cooling are:

- Avoid heat gains as far as possible by appropriate thermal insulation and controlled solar protection.
- Extract air close to remaining heat sources.
- If mechanical "free" cooling, oversize air ducts, to be able to have large airflow rates without too large pressure drop.
- If natural free cooling, place an opening as high as possible in the cooled zone, and another one in a lower place.
- Control airflow rate according to (Eq. 04), when outdoor temperature is colder than indoor temperature, and according to (Eq. 01) otherwise.

2.2.4 Night cooling

The objective is to save energy and to improve comfort by bringing outdoor air, when it is colder than the indoor environment, to cool down the internal building mass that was heated beforehand by internal and solar load. The relationship between airflow rate and heat load is then:

$$\int_{t_1}^{t_2} \dot{V}_{NC}\, \rho\, c\, (\theta_i - \theta_o)\, dt = \int_{t_1}^{t_2} \Phi_l\, dt \qquad \text{(Eq. 05)}$$

Where t_1 and t_2 are the begin and end times of the considered time period, typically one or a few days. Φ_l does include heat gains by transmission through the building envelope as well as internal and solar gains, but not heat gains by ventilation during the day, which is included in the left term of the above equation.

The amount of heat that can be stored during the day depends on the allowed internal temperature swing, and on the internal thermal inertia. This technique can be applied only in climates where the outdoor temperature is below comfort temperature during several hours per night, and the outdoor air dew point is always below comfort temperature.

Basic principles to ensure efficient night cooling are (Roulet, Van der Maas et al. 1996):

- Avoid heat gains as far as possible by appropriate thermal insulation and controlled solar protection.
- The building should have a large internal thermal inertia: The building time constant defined by the ratio of the heat loss coefficient[1] by the thermal capacity[2] should be larger than 100 hours. This thermal inertia should be in direct contact with indoor air.
- If natural night cooling, place at least one opening as high as possible in the cooled zone, and at least another one in a lower place. These openings should be safe (for weather, insects, stealers, etc.) even when opened.
- If mechanical night cooling, largely oversize air ducts and fans, to be able to have very large outdoor airflow rates (about 10 building volumes per hour) without too large pressure drop.
- Airflow rate should be as large as possible when outdoor temperature is colder than internal temperature, and adjusted according to (Eq. 01) otherwise.

2.2.5 Several aims

If there are several simultaneous aims (e.g. heating and hygienic requirements), the required airflow rate is the largest of the flow required for each aim:

$$\dot{V} = \max\left(\dot{V}_{IAQ}; \dot{V}_H; \dot{V}_{FC}; \dot{V}_{NC}\right) \qquad \text{(Eq. 06)}$$

2.3 Means for Ventilation

2. 3.1 Mechanical ventilation

Fans and ducts are used to bring air at the right place and at an appropriate airflow rate, and to extract contaminated air from the building. The supply air can be conditioned (either heated or cooled, dried or moistened) to improve comfort.

The mechanical power provided by the fans is:

$$\Phi = \dot{V}\ \Delta p \qquad \text{(Eq. 07)}$$

---

[1] According to EN 832, it is the heat flow rate required to maintain, on the average, an internal temperature 1 K higher than the outdoor temperature.

[2] According to EN 832, the thermal capacity used here is the amount of heat that can be stored and recovered in the building structure when the internal temperature swings periodically with an amplitude of 1 K.

where Δp is the pressure drop across the fan, which equals the pressure drop along the ducts network. Since the pressure drop is proportional to the square of the airflow rate, the mechanical power is proportional to the cube of the airflow rate, for a given network.

Efficiency η of fans depends not only of its quality, but also on the nominal power ($). The total power delivered to the fan is then:

$$\Phi_T = \frac{\dot{V}\,\Delta p}{\eta} \qquad \text{(Eq. 08)}$$

All this power ends soon or later in heat delivered to the air. The supply fan therefore heats the air with the power Φ_T. This is convenient during the heating period, but not during cooling.

Mechanical ventilation is appropriate for IAQ control. It is often used for artificial heating and cooling, in many cases together with re-circulation of a part of the extract air to supply air. The free cooling strategy can be applied to save cooling energy, simply by switching off the cooling coil when outdoor air is cold enough to refresh the building alone, and use fans at high speed even when outdoor air is not required for IAQ control.

Mechanical ventilation is not well adapted to night cooling, since airflow rates required for this application are in most cases much larger than the airflow rates needed for IAQ control. In addition, the supply fans heat the airflow by several degree, especially in high pressure systems.

2.3.2 Natural stack effect ventilation

Stack pressure depends on air density differences and height of the opening above or below the neutral level. Assuming that the air has the same composition indoors and outdoors, the density depends on air temperature only. The pressure difference resulting from stack effect is then:

$$\Delta p_s = -g(z - z_0)(\rho_o - \overline{\rho}_i) \qquad \text{(Eq. 09)}$$

where ρ is the density, z the height of the opening and z_0 that of the neutral level. Suffixes i and o are for indoor and outdoor respectively.

(Eq. 10)

where T is for the absolute temperature, T_0 being the reference temperature at which the air density is ρ_0. If T_i is constant inside, this becomes simply:

$$\overline{\rho}_i = \frac{\rho_0 T_0}{T_i} = \frac{358}{T_i} \qquad \text{(Eq. 11)}$$

at 1013 mBar, if 0°C (273 K) is taken as a reference temperature. Hence:

$$\Delta p_s = -g\rho_0 T_0 (z - z_0)\left(\frac{1}{T_o} - \frac{1}{T_i}\right) \qquad \text{(Eq. 12)}$$

It can easily be calculated from this equation that a pressure differential large enough to move significant air flow, say 2 Pa, arises with 5 K temperature difference at $\Delta z = 9$ m or with only 2 K temperature difference at $\Delta z = 22$ m.

Large airflow rates occur through large openings at much smaller pressure differentials. For example, 525 m³/h flow both ways through a single opening 1 m wide and 2 m high with only 1 K temperature difference, at a pressure differential of 0.02 Pa only.

The airflow rate is related to the pressure differential by the empirical equation:

$$\dot{V} = D \cdot (\Delta p)^n \qquad \text{(Eq. 13)}$$

Where:

D is the airflow coefficient in $m^3/(h\ Pa^n)$

n is an exponent, which lies between 0,5 (full turbulent flow) and 1 (laminar flow).

The height of the neutral level is determined by the balance of in-going and out-going air flow rates. If there are two openings, (Figure 2), this balance is:

$$A_1\, u_{d1}\, \rho_e = A_2\, u_{d2}\, \rho_i \qquad \text{(Eq. 14)}$$

Where u_d is the air velocity determining the airflow rate..

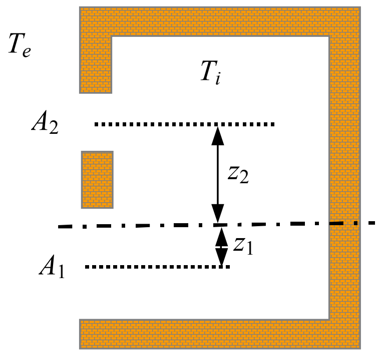


Figure 2: Location of the neutral level in case of two openings.

Using the Bernoulli equation and introducing a discharge coefficient C_d to take account of not modeled phenomena, the airflow rate through an opening of area A is:

$$\dot{V} = C_d A u = C_d A \sqrt{\frac{2\Delta p}{\rho}} \qquad \text{(Eq. 15)}$$

The discharge coefficient is determined from experiments. Its value is about 0,6 for sharp edges openings.

If the neutral level is between openings, all of them have a single way flow and combining equations (Eq. 09), (Eq. 13), and (Eq. 14):

$$\frac{z_1}{z_2} = \frac{\rho_i}{\rho_e}\left(\frac{A_2}{A_1}\right)^2 = \frac{T_e}{T_i}\left(\frac{A_2}{A_1}\right)^2 \qquad \text{(Eq. 16)}$$

The neutral level tends to get closer to the largest opening.

The position of the neutral level being known, combining equation (Eq. 13) with (Eq. 09) gives the airflow rate through two openings separated by height H:

$$\dot{m} = \rho_i A_2 C_d \sqrt{\frac{2gH\left(\overline{T_i} - T_e\right)}{T_i\left[1 + \frac{T_e}{T_i}\left(\frac{A_2}{A_1}\right)^2\right]}} \qquad \text{(Eq. 17)}$$

T_i is the temperature of the outgoing air, while $\overline{T_i}$ the average indoor temperature.

If there are more than two openings, they could be sorted in two groups: the openings (or opening parts) located below and above the neutral level. The effective area of each group is the sum of the area of the openings belonging to each group.

If there are several areas in series, the effective area is calculated with:

$$\frac{1}{A_{eff}^2} = \sum_j \frac{1}{A_j^2} \qquad \text{(Eq. 18)}$$

If there is only one opening, the neutral level is located approximately at mid-height. If H is the height of the opening and W its width, the airflow rate is:

$$\dot{V} = \frac{1}{3} HWC_d \sqrt{\frac{gH\left(\overline{T_a} - T_e\right)}{T_e}} \qquad \text{(Eq. 19)}$$

2.3.3 Solar induced ventilation

This is a natural ventilation system in which the stack effect is reinforced by the use of solar heating. The exhaust air is driven into the bottom of a solar collector and leaves it at the top. The walls of this collector heat it, themselves heated by the solar radiation. Increasing the temperature of the air increases the stack effect. More information is given in (Awbi 1998).

This technique is appropriate at insolated locations, and in buildings requiring ventilation when the sun shines. It is therefore not appropriate for night cooling.

2.3.4 Natural, wind driven ventilation

The kinetic energy of the wind is changed into potential energy (pressure) against obstacles such as buildings. Here again, simply applying the Bernoulli equation, it can be seen that, for an insulated building, the windward facades will be submitted to a positive outdoor-indoor pressure differential, while the roof and the leeward façade will get a negative pressure differential. Airflow through cracks can be modeled using equation (Eq. 13) with this pressure differential.

A well known method for predicting air flow rates in buildings is to use nodal network models, each node representing a zone characterized by its pressure, and each link representing a flow path modeled by a relationship between flow rate and pressure differential. The pressures at boundary nodes being given, the airflow rates are obtained by solving a set of non linear equations. The pressures at boundary nodes result of the effect of wind and temperature differences. The pressure resulting from the wind is given by:

$$\Delta p_W = \tfrac{1}{2}\, C_p\, \rho_o\, u_W^2 \qquad \text{(Eq. 20)}$$

Where u_W is the wind velocity at a reference location and *Cp* is the so-called pressure coefficient, which should be determined either experimentally in a wind tunnel or numerically using CFD. Important is to remember that pressure coefficients were invented to compute wind forces on buildings for structural design. For this, peak values and safety factors are of common use. The use of C_p's for the prediction of infiltration was proposed later. Their use to calculate airflows through large opening was, and still is contested.

Also important is to remember that p_W from (Eq. 20) is the pressure on a closed surface. If there is an opening through which air may flow, the pressure strongly drops, and the C_p has no meaning anymore.

These pressure coefficients are strongly influenced by the wind direction and the surroundings of the addressed building. They can take any value between -1 and +1 (Orme, Liddament et al. 1994), depending on the shape, dimension, and location of surrounding buildings. In addition, their value also changes with the location on the building envelope. and may even depend on details that are not modeled in the scale model placed in the wind tunnel or in the computer model.

To summarize: pressure coefficients are not known at all in most cases, and especially in urban climates. This does however not hamper the possibility of determining natural ventilation potential.

2.3.5 Mixed natural ventilation

Most of the time, wind and stack effect are both active in moving the air through the buildings. The pressure differential to be used in equation (Eq. 13) is the algebraic sum of the pressure differentials resulting from stack, wind and fans:

$$\Delta p = \Delta p_s + \Delta p_w + \Delta p_f \qquad \text{(Eq. 21)}$$

In mechanical ventilation systems, the effect of the fans should outdo the other effects. In case of natural ventilation, the Archimedes number determines the relative importance of wind and stack:

$$Ar = \frac{\Delta T\, g\, h}{T_i\, u_v^2} \qquad \text{(Eq. 22)}$$

Ar is proportional to the ratio of the stack pressure differential to the wind pressure differential. If *Ar* is large, the stack effect dominates, while the wind dominates if *Ar* is much smaller than 1.

Depending on the position of the ventilation openings, wind and stack effect may co-operate or counter-operate (Figure 3). In this last case, the airflow rate resulting from stack effect may be reduced for some wind directions and velocities. It is however possible to design the building and the openings in such a way that the frequency of such an event is small.

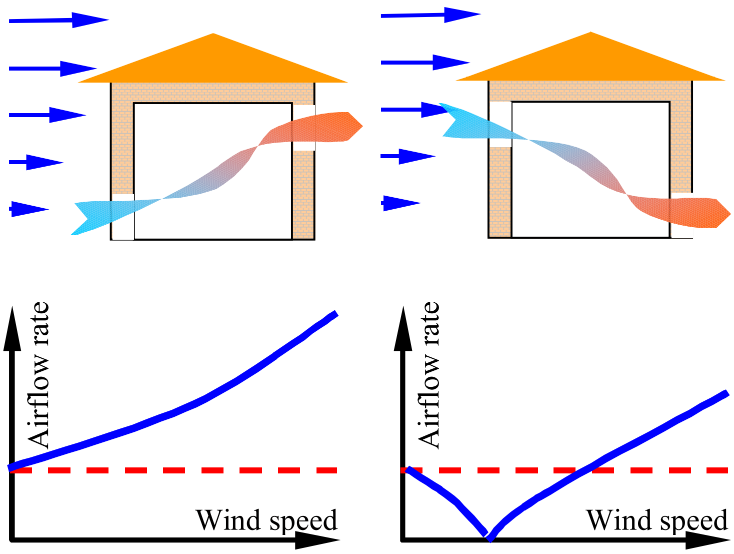


Figure 3: Co-operation (left) and counter-operation (right) of wind and stack effects.

2.3.6 Hybrid ventilation

Hybrid ventilation is a strategy in which natural ventilation is used as far as possible and mechanical ventilation is switched on when necessary. A good example of such a strategy is to use passive cooling strategy in the warm season, while very large airflow rates can easily be provided through cheap, large openings, and to use the mechanical ventilation system in winter, to recover ventilation heat losses related to the relatively smaller hygienic airflow rate. Buildings using this strategy should be located in a place having reasonable passive ventilation potential

2.4 Control Strategies

In order to ensure both good indoor air quality and a reasonable energy use, the airflow rate shall be controlled. There are several ways to perform such a control. All these strategies can be applied a priori with mechanical or natural ventilation systems, but appropriate devices may not yet be available for both systems in some cases.

2.4.1 Constant flow rate

The air is delivered at a quasi-constant flow rate either by a mechanical system or by so-called "constant flow rate" openings. This control strategy can be recommended only if the demand is actually constant (e.g. in case of constant pollutant source intensity and constant air quality requirement.)

2.4.2 Clock control

The fans and the ventilation openings can be controlled by a clock that switches them (or switches the various fan speeds) on and off according to a pre-determined schedule. This control strategy is appropriate where the demand schedule is well known (e.g. schools and office buildings).

2.4.3 Demand control

The fan speed or the size of the ventilation opening is controlled by a system in such a way that the concentration of a given pollutant is always smaller than a set-point value. In this case, it is important that the monitored pollutant is indeed the principal one, i.e. the one requiring the largest airflow rate during the occupation periods. Most used indicators are air moisture in dwellings and carbon dioxide in offices and assembly rooms. So-called "multigas" sensors, in fact sensitive to oxidizing compounds such as CO and most VOC's, are also used in office buildings.

2.4.4 Temperature controlled

The temperature control is a kind of demand control, which is appropriate when the principal pollutant is heat. Temperature control is recommended for free- and night cooling, to ensure that the outdoor air is actually colder than the building structure.

2.4.5 Offer dominated

This corresponds to the absence of control. In this case, the airflow rate is actually controlled by the wind and stack effects, and has in most cases no relation with the actual demand. For example, the demand is small to limit the indoor air humidity during a cold winter, while the offer may be large (blizzard!). At the contrary, the demand is very large in mid-season, while the outdoor air is mild and moist, and approximately at the same temperature as indoors.

3. TOPOLOGY Of ARCHITECTURAL SCENARIO

A building that uses natural ventilation requires the integration of the strategy of ventilation in the architectural design. The main physical effects which will produce natural ventilation are the dynamical effect of the wind and the stack effect due to the thermal buoyancy of air inside the building generated by the temperature differences between different zones and between indoor and outdoor air (Allard, 1998). In this respect, various architectural scenarios can be found in order to improve the efficiency of this basic physical principles and integrate them in the architectural design of the building. Figure 4 gives the basic elements of a typological classification of these solutions (Mansouri et al. 2002).

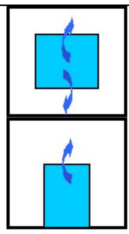
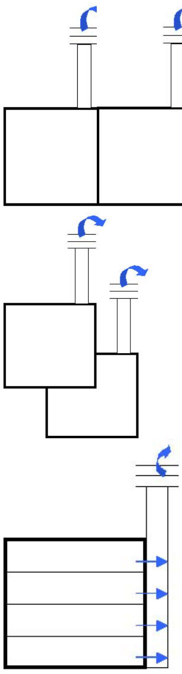
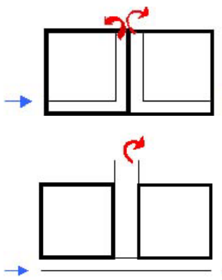
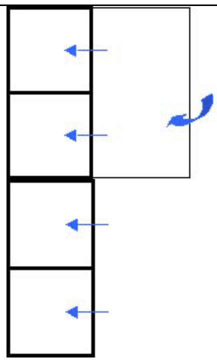
<u>Transition space</u> This strategy of ventilation is based on the use of the distribution space such as the atrium or the stairwell atrium. Besides Its function of distribution, the transition space permits the ventilation of the spaces It serves.		- Total inclusion with a central position - Side inclusion with a lateral position.
<u>Stack devices</u> The most common system is the chimney formal aspect, which differs from a building to another. The building design is then independent of the natural ventilation strategy. Actually, each space is ventilated by a natural ventilation device. The most important is the space allocation and partitioning within the building.		- An adjacency structure: each space is ventilated individually. Basic units of spaces form the plan of the building. - An overlapping structure: all spaces are partially superposed. However, each space has a specific ventilation strategy. - A parallel structure: similar spaces are superposed.
<u>Ventilation shaft</u> The ventilation shafts are integrated in the building envelope. From the architectural point of view, the building space composition can be different in function of the ducts integration mode.		- An adjacency structure: each space contains separately the ventilation shafts. - A parallel structure: the spaces are ventilated using one single duct and the stale air is rejected by another common duct.
<u>Front opening</u> The ventilation of the spaces is essentially based on the building external envelope design and the opening allocation on the façades. The variations concern the linkage between the ventilated spaces and outdoor. This could lead to two main strategies, single sided or cross ventilation.		- In total inclusion, what leads to an indirect communication. - In side inclusion, what leads to a direct communication.

Figure 4 : Topology of natural ventilation scenarios

4. SHORT REVIEW OF NATURAL VENTILATION COMPONENTS

A research carried out on natural ventilation components proposed by European industry allows us to give a short summary of the most important components available on the market.

Concerning the air inlets, the components vary from the simple grille to the controlled air inlet. Several types of controllers are available on the market:

- Pressure control
- Humidity control
- Pollutant control
- Temperature control.

At the same time, to improve their acoustic performance, some natural ventilation openings are combined with reduction of sound transmission into or out of buildings.

Another component has been more and more developed recently. Less widespread, roof mounted terminals like wind catcher systems provide natural ventilation by encapsulating the prevailing wind from any direction. Clean, fresh air, relatively free from contamination or traffic pollution, is taken at roof level and is carried down to the rooms.

On the other hand, the wind-driven exhausts hot, extract air from the buildings by taking advantage of the wind to create a positive flow through the throat of the wind driven exhaust system. Figure 5 presents one example of an integrated wind driven component.

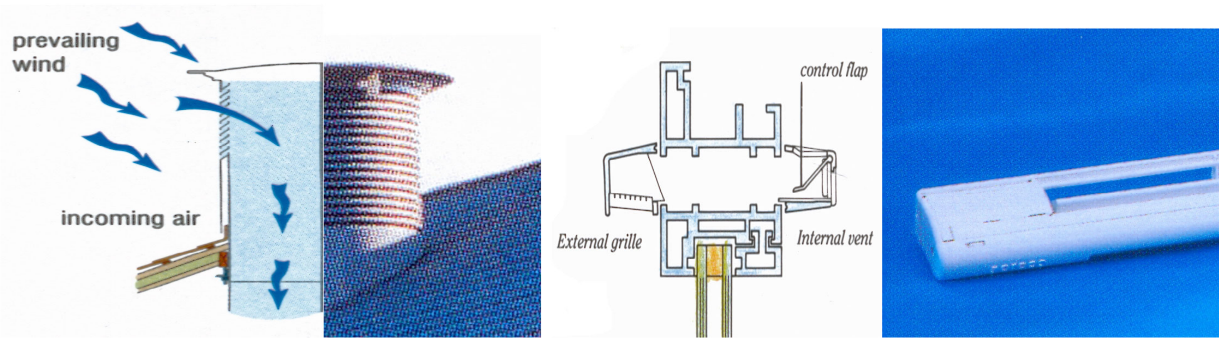


Figure 5: Examples of technical solutions

A good control of ventilation systems is also an important issue to ensure an optimal efficiency and provide the correct level of ventilation at a minimum energy cost. Available control methods vary from simple occupant control devices to intelligent systems triggered by sensors, which detect occupancy, temperature, and humidity or air quality, matching ventilation demand. Usually, these control components are integrated to an overall building management system.

5. EXAMPLES OF INNOVATIVE SOLUTIONS

Through the selection of three examples of naturally ventilated buildings, we are not pretending to give an exhaustive list of innovative solutions of integration of natural ventilation concepts in the architectural design; we propose only to highlight innovative solutions of natural ventilation.

5.1 Flow Control

The aim of the Commerzbank's internal environmental control systems (Architectural review, 1997) is to reduce the use of energy while giving the ocupants healthy conditions over which they can have a degree of personal control (Figure 6). Natural ventilation is expected to save

60% of the energy demand for conditioning during the running hours. A building management system (BMS) controls the windows (Figure 7). Small weather stations, distributed around the building, gather solar radiation, dry bulb and wet bulb air temperature, air pressure, wind speed and wind direction data. Based on this information, the building management system (BMS) makes a decision whether or not to allow the operation of the natural ventilation system. The original energy consumption estimate was 13 million kWh per year, while actual energy consumption has been measured around 10 million kWh per year.

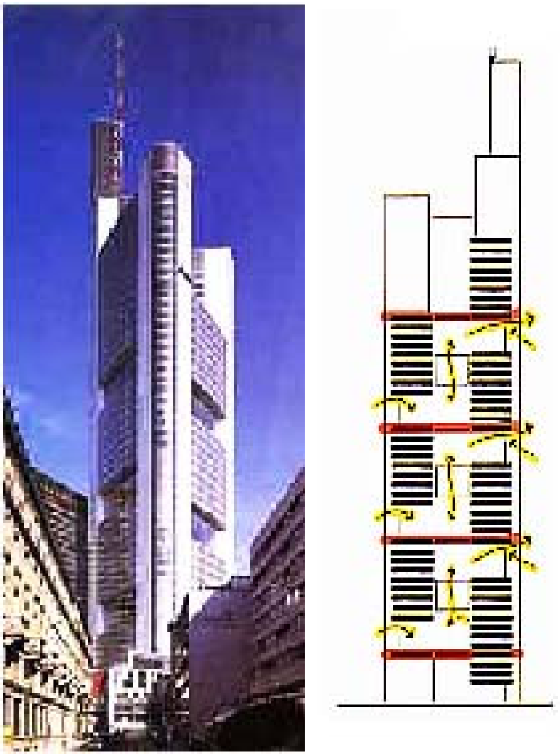


Figure 6: Commerzbank Building in Frankfurt

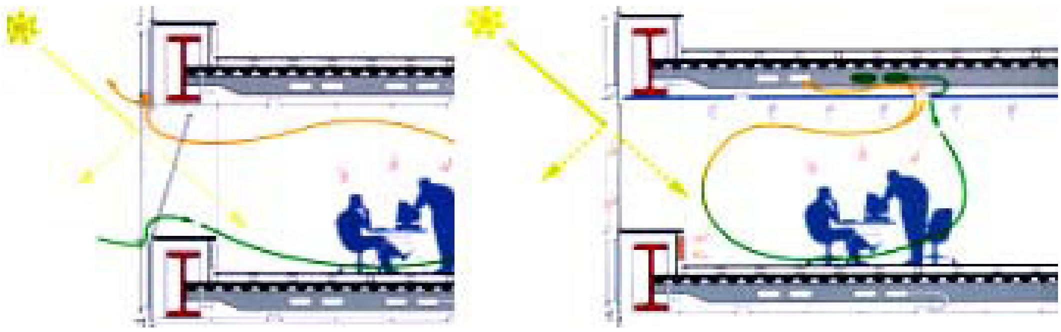


Figure 7: Details of the ventilation control principles in offices

5.2 Heat Recovery

The central position of the atrium, in the administrative building of Wurzbürg (Detail, 1997), contributes mainly to the natural ventilation concept (Figures 8 and 9). The other key element of the design concept is the double glazed facade (Figure 10). On sunny winter days, the absorptive side of the aluminium slats is turned outwards. The dark coating and the penetration of sunlight heat the air in the facade space, which creates an additional thermal buffer zone. The axial air circulation fans in the corners of the building convey the solar heated air horizontally all around the building. Those sides of the building that are shadowed, therefore, also profit from the solar heat. Despite its higher building costs the, sol-skin building still achieves the 8-10 year breakeven point of conventional buildings, thanks to its much lower energy consumption.

Figure 8: Administrative building in Wurzbürg

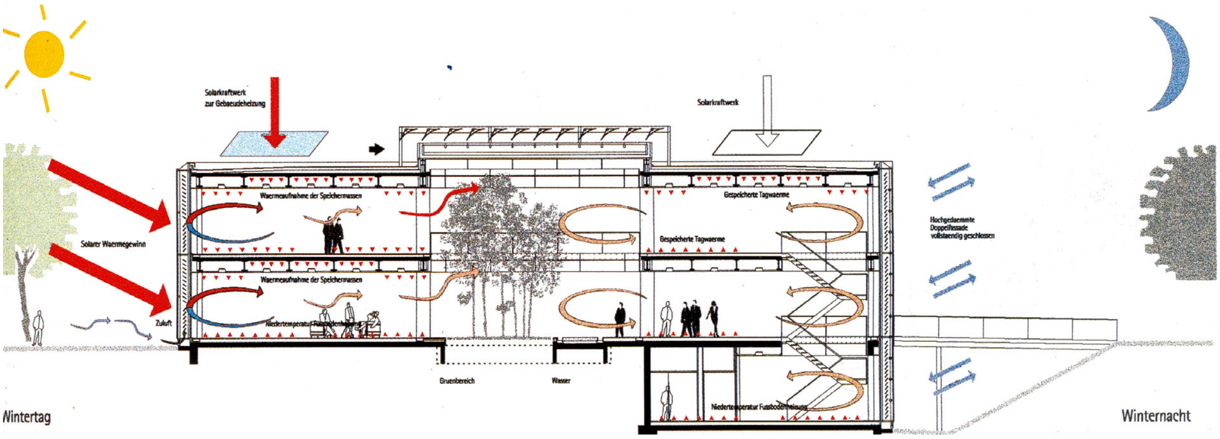


Figure 9: General principle of natural ventilation

Figure 10: Double façade design

5.3 Air Cooling and Coupling with Thermal Mass

The summer monitoring results in the BRE headquarter (Perera, 1999, NATVENT) indicate that the building design provides a generally comfortable indoor environment (Figure 11). The building is thus providing conditions that might be expected in an air-conditioned building but only producing 30% of the CO_2. To maintain cross ventilation of the building while avoiding acoustic problems between offices, a wave form floor slab design was developed to incorporate ventilation routes that pass over the ceiling of cellular spaces. The waveform increases the storage capacity of the slab, increases the exposed surface of concrete and therefore, available thermal mass (Figure 12). Additional cooling can be achieved by circulating cold water through the slab.

Figure 11: The BRE headquarter

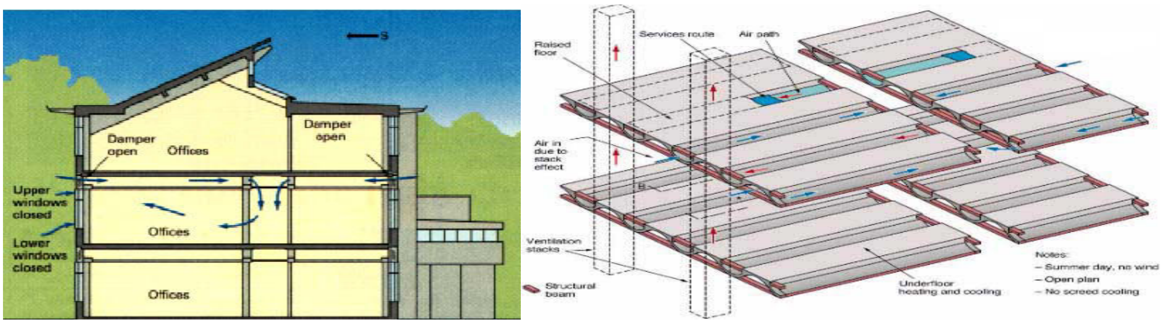


Figure 12: Conditioning concepts in the BRE building

6. INTEGRATION OF NATURAL VENTILATION IN URBAN BUILDINGS

The above mentioned examples show that natural ventilation applied in mild climate can provide effective cooling during day and night while night ventilation is a very effective strategy in hot climates. Nevertheless, these examples represent isolated buildings and their design is quite specific. In an urban environment, appropriate design of a building façade that makes use of natural ventilation requires knowledge of local thermal environment, wind speed and direction. But wind speed in urban environment is seriously reduced compared to the undisturbed synoptic wind and the wind direction inside street canyons differs markedly from routine meteorological stations. Methods to calculate these parameters, as well as the potential for natural ventilation of buildings, are either oversimplified or suffer from high inaccuracies. Preliminary studies of the real potential of natural ventilation techniques applied in buildings located in urban canyons have been carried out recently in the frame of a major European research program (Santamouris, 2001). It is shown that, because of the important decrease of the wind speed, the change of the flow patterns and the important temperature stratification in the canyon streets, the potential for natural ventilation of conventionally designed urban buildings is reduced to a tenth of unobstructed buildings.

Measurements and estimations have confirmed that the adaptation of urban buildings to use efficiently natural ventilation techniques and components, contributes to decrease significantly the cooling needs of urban buildings, enhances thermal comfort and improves indoor air quality. Results of a recent Ph. D. thesis, studying the cooling potential of night ventilation techniques for urban buildings, have shown that for both single and cross natural ventilation configurations, the cooling load of common urban buildings located inside canyons, is much higher than the one calculated for buildings where wind is not obstructed. In particular, the cooling load in single side configuration is 6 to 89 % higher, while in cross ventilation it is from 18 to 72 %. Thus, urban related phenomena, particularly the canyon effect, have a very strong impact on the performance of night ventilation techniques applied to urban buildings.

In Europe, till now, very low attention has been given to the characteristics of urban buildings to better use natural ventilation. Because of low wind speeds inside canyons, pollution and acoustic problems, but mainly because of the lack of appropriate information and design techniques, engineers use air conditioning for both new and retrofitted buildings. Given the already mentioned environmental and energy problems, the development of appropriate natural ventilation components and techniques for the European urban buildings appears to be a first priority for future research. Natural ventilation has to be considered in fact as an active interface between the urban microclimate and the indoor climate of an urban building. A strong effort is needed in order to improve the management of this interface. Due to cross influences of many criteria (air quality, noise, energy, dynamical effects) this optimal management needs strong research efforts in both local micro climate conditions in urban scenarios and the effects on building indoor conditions.

7. WHAT IS THE ROAD AHEAD?

7.1 To Respond to an Open Problem in the Conceptual Stage of Design:

With the rapid advances in computer technology, building simulation tools will be more often and more widely applied in building design and analysis. Several possible R&D trends can be observed.

Most current available building simulation programs can only solve closed problems. They respond to a "*what happens if*" question: what will be the result if this parameter has this value. This is the principle of detailed building simulation programs (Hong et al., 2000), like DOE-2, BLAST, COMIS and TRNSYS, that are useful in the final phase of design when performance has to be evaluated. These programs can help the user either to estimate the annual energy consumption of a building and its HVAC system or to predict the free floating conditions inside the building, but cannot suggest design strategies to improve the building performance.

However, in conceptual and preliminary design stages, the problem is open (Figure 13).

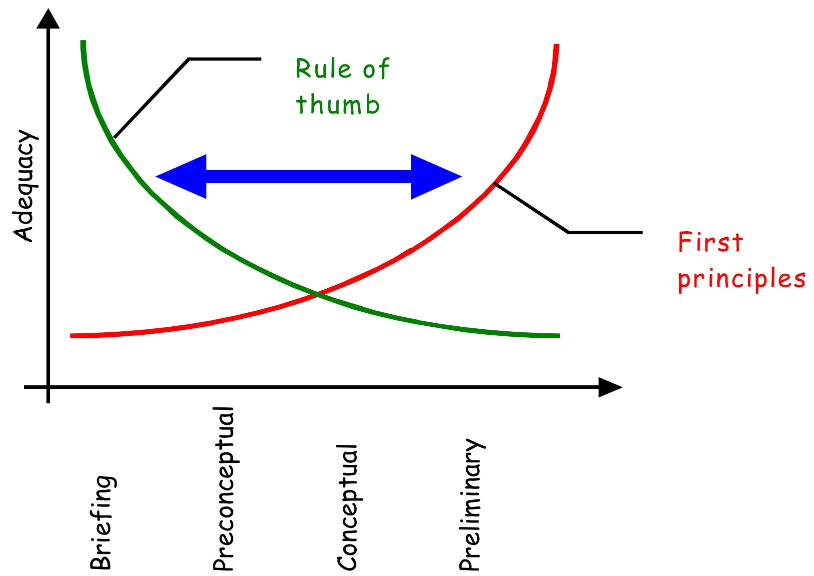


Figure 13 : Design concepts

We need the answer to a "*what to do*" question such as: Should we design the building to use natural ventilation for cooling or should we consider an air-conditioning system? Is it worth to increase the thermal mass? What will be the influence of comfort or IAQ criteria? How to avoid poor energy performance due to excessive part-load operations? In early stages of design, when architects take decisions that implicitly answer these questions, they have usually very little or no support. Engineers are often brought into the project after the building form, fenestration, orientation and construction materials were decided. **It is important to have a tool that can respond to an open problem in the conceptual stage of design.**

One approach for assessing climatic suitability of natural ventilation in office buildings is based on balance point temperature for the class of volume dominated commercial buildings, for which the air change loss dominates over envelope loss (Axley, 2001).

The building energy performance and HVAC solution depends on three factors: thermal characteristics of the building, indoor environment criteria and climate. The first factor may be synthesised by the indoor temperature of the free running building, which is shifted from the value of the outdoor temperature with a difference that depends on heat loss, ventilation rate, solar and internal gains, thermal mass and occupancy. This difference may be easily measured in existing buildings, estimated by rules of thumb or calculated. The second factor, which includes thermal comfort, has a zone that varies with the mean outdoor temperature (Brager and R. De Dear, 2000). This zone is larger in buildings that use natural ventilation as compared with those that have air-conditioning systems installed. Finally, the climate may be characterised by the frequency distribution of the outdoor temperature. Hence, climate suitability of HVAC systems may be assessed as a function of the indoor temperature of the free-running building, thermal comfort and monthly and hourly probabilistic distribution of outdoor temperature. The method can be applied when buildings similar to existing ones are constructed in a new location, when existing buildings are retrofitted or when completely new buildings are designed. This method, which is developed in URBVENT European project, may use public domain global climatic data obtained by satellite measurements (Figure 14).

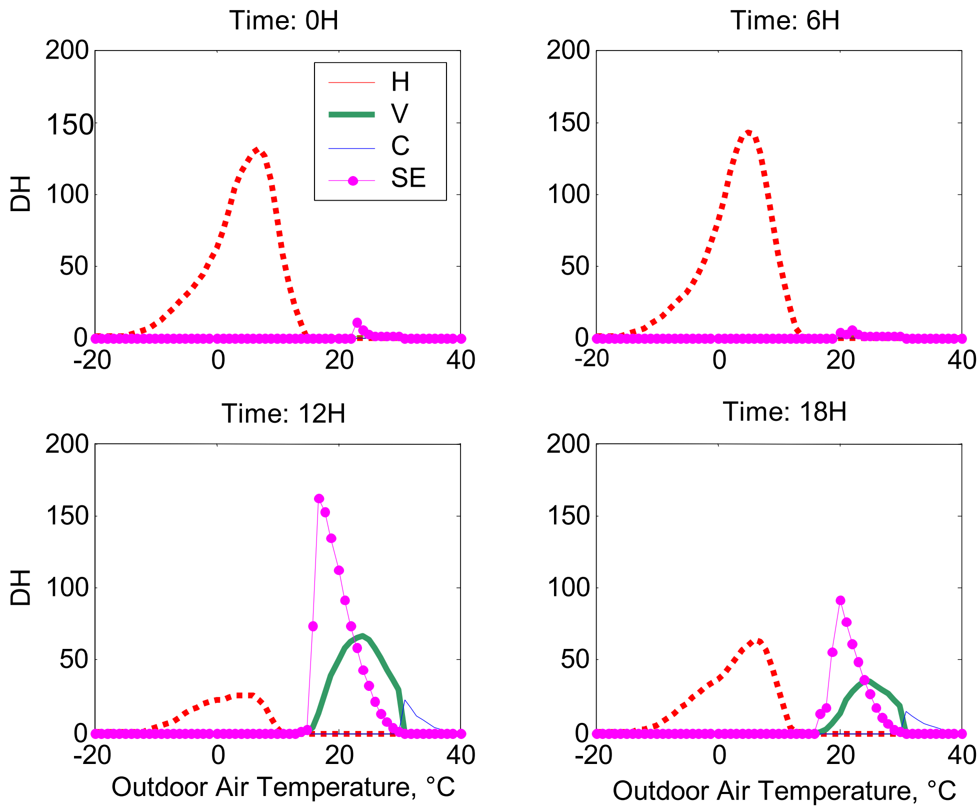


Figure 14: Frequency distribution of degree-hour for heating (H), cooling (C), free-cooling by ventilation (V) and stack effect (SE) for La Rochelle, France.

7.2 To Dimension the Airflow Path

Natural ventilation uses the building for the airflow path. In order to design rigorously natural ventilation strategies, the whole airflow path through and within the building has to be taken account. In a first attempt Dascalaki and Santamouris, (1998) proposed a methodology in order to define an optimal design of openings.

This methodology is limited to a front opening natural ventilation strategy. For more complex configurations, which represent most cases in an urban environment, new methods are being studied. (Axley, 2001, Nitta, 1994), and need to be developed.

They are usually based on the pressure loop concept proposed by Axley (1999) and allow to introduce in the airflow path any kind of singularity like building partition or any specific device or component. (figure 15 gives the principle of the loop equation method).

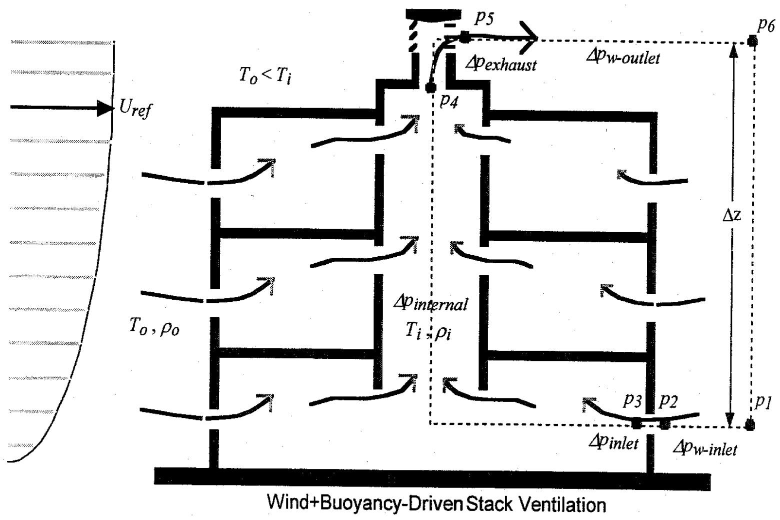


Figure 15: Loop equation principle (Axley, 2001)

7.3 To Control and Predict the Real Behaviour of Naturally Ventilated Buildings

Natural ventilation depends mainly on environmental conditions: wind and temperature. One of the main barriers in the use of natural ventilation is the idea that it is "natural" and then difficult to control. However, some examples (Commerzbank's building) show how a global control of a naturally ventilated building can be efficient. A complementary aspect is that the building regulations in most countries impose ventilation rates, thus building owners, and by consequence designers, need a real prediction of the global behaviour of their buildings in order to get confidence in their design. The way to solve this important problem is to define clearly the probability that such situations occur. URBVENT project will give a measure of the suitability of natural ventilation. This potential is usually larger than needed. In this case, natural ventilation need control, i.e. devices and algorithms to reduce the airflow rate to the value needed.

7.4 To Combine Natural and Mechanical Ventilation

When the driving forces (wind and stack effect) are not available, the control system should start a mechanical system in order to maintain indoor air quality and comfort. In some cases, a combination of natural and mechanical ventilation is then needed and has to be designed. This aspect is studied in Hybvent annex 35 of International Energy Agency. The results of this project have to be analysed and included in the design tools of natural ventilation.

7.5 To Develop Well Documented Innovative Components

During the last decade, various kinds of ventilation components have been developed. These components range from the simple grille, to controlled air inlets or wind-driven exhausts. Most of these components have been designed for specific uses or even for specific buildings. Their technical documentation is usually poor or even not specific enough to be used in a wide range of applications. The specifications are usually not consistent enough to enter these systems in a modelling approach. A reflection is necessary in this aspect and some guides or standards will be really necessary to improve the dissemination and integration of innovative systems.

8. REFERENCES

F. Allard et al., *Natural Ventilation in Buildings, A design Handbook*, James and James Publisher, 1998.

Architectural Review, July 1997, p.26-39

ASHRAE (1989). ASHRAE Standard 62-1989R: Ventilation for Acceptable Indoor Air Quality. Atlanta, ASHRAE.

H. Awbi, (1998). Ventilation. Renewable and Sustainable Energy Reviews, Elsevier Science Ltd. 2**:** 157-188.

H. B. Awbi, *Renewable & sustainable energy review, chapter 7 - Ventilation*, Elsevier Sciences ltd publisher, 1998, 158-188.

J. W. Axley, *Application of Natural Ventilation for U.S. Commercial Buildings*, 2001, NIST. p. 146.

J. W. Axley, *Natural Ventilation Design Using Loop Equations*, Indoor Air 1999, ISIAQ & AIVC

P. Blondeau, M. Spérandio and F. Allard, Multicriteria analysis of ventilation in summer period, Building and Environment 37 (2002), pp; 165-176.

G. S. Brager and R. De Dear, *A Standard for Natural Ventilation*, ASHRAE Journal, October 2000, 21-27.

DETAIL, n° 3, 1997, 343 p.

E. Dascalaki and M. Santamouris, *The AIOLOS Software* in Natural Ventilation in Buildings, A design Handbook, James and James Publisher, 1998.

P.O. Fanger, A. K. Melikov, et al. (1988). “Air turbulence and the sensation of draught.” Energy and Buildings 12: 21-30.

T. Hong, S.K. Chou, T.Y. Bong, *Building simulation: an overview of developments and information sources.* Building and Environment, 2000. 35: p. 347-361.

Li, Y., A. Delsante, Z. Chen, M. Sandberg, A. Andersen, M. Bjerre, P. Heiselberg (2001). “Some examples of solution multiplicity in natural ventilation.” Building and Environment 36: 851-858.

M. Liddament, A Guide to Energy Efficient Ventilation, AIVC 1996, Coventry , (UK)

Y. Mansouri, F. Allard and M. Musy, Building envelope design for natural ventilation, PLEA conférence, Toulouse, 2002.

K. Nitta, *Calculation Method of Multi-room Ventilation,* Memoirs of the Faculty of Engineering and Design, Kyoto Institute of Technology 42, March 1994, 60-94.

M. Orme, M. Liddament, et al. (1994). AIVC technical note 44: Analysis of the AIVC numerical database. Coventry, AIVC.

E. Perera, *Natural Ventilation for Offices*, NATVENT, Building Research Establishment, Garston, Watford WD2 7JR,UK, 1999.

C. A. Roulet, J. Van der Maas, et al. (1996). A Planning Tool for Passive Cooling of Buildings. Indoor Air '96, Nagoya

C. A. Roulet, Ventilation strategies, URVENT Project Internal report, 03/2002.

M. Santamouris, Energy and Climate in the Built Environment, James and James Publisher, 2001, 402 p.