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Design of Natural and Hybrid Ventilation

by

Per Heiselberg

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Natural and Hybrid ventilation

1 INTRODUCTION

The effectiveness of natural ventilation, i.e. its ability to ensure indoor air quality and passive cooling in a building, depends greatly on the design process. Mechanical ventilation systems can be designed separately from the design of the building in which they are installed. They can also be installed in existing buildings after a few modifications. In contrast, ventilation systems using only natural forces such as wind and thermal buoyancy need to be designed together with the building, since the building itself and its components are the elements that can reduce or increase air movement as well as influence the air content (dust, pollution etc.). Architects and engineers need to acquire qualitative and quantitative information about the interactions between building characteristics and natural ventilation in order to design buildings and systems consistent with a passive low-energy approach.

Natural ventilation can be used to provide fresh air for the occupants, necessary to maintain acceptable air quality levels, and to cool buildings in cases where the climatic conditions allow it. Natural ventilation is caused by pressure differences at the inlets and outlets of a building envelope, as a result of wind velocity and/or stack effect. Natural ventilation can be achieved by infiltration and/or by allowing air to flow in and out of a building by opening windows and doors.

The term infiltration is used to describe the random flow of outdoor air through leakage paths in the building's envelope. The presence of cracks and a variety of unintentional openings, their sizes and distribution determine the leakage characteristics of a building and its potential for air infiltration. Modern architecture tends to minimize air infiltration by introducing "air-tight" buildings, where the cracks in the structure are sealed. Infiltration rates vary seasonally in response to outdoor temperature and wind conditions. Infiltration associated air-change rates may vary from a low of 0.1-0.2 air changes pr hour in tight, energy efficient houses to 2-3 air changes per hour (ACH) in leaky houses under high-infiltration conditions, while, with the windows wide open during summer, it is possible to achieve 15-20 ACH. Even larger air changes, around 30 ACH, can be achieved by natural means, but there is a need for large number of window openings and careful placement within the space. It is important to link the necessary number of windows and their placement with the requirements for natural lighting purposes.

The effectiveness of natural ventilation is determined by the prevailing outdoor conditions – microclimate (wind speed, temperature, humidity and surrounding topography) and the building itself (orientation, number of windows or openings, size and location). In addition to the use of windows and other openings for natural ventilation, there are some additional means of enhancing the air movement. Wind towers utilise the kinetic energy of wind, which is properly channelled within the building in order to generate air movement within a space. They have been successfully integrated in many architectural designs. Solar chimneys are constructions used to promote air movement throughout the building using solar gains. They are positioned on the sunward side of the building to make the best possible use of direct solar gains.

Natural ventilation is used to create a volumetric flow, for renewal of indoor air and transfer of heat, resulting from the outdoor wind speed and/or stack effects in order to remove heat stored into the building materials and to enhance heat dissipation from the human body to the environment. The savings from natural ventilation depend on the number of air changes, the construction of the building (heavy or light construction), the microclimate and the temperature and humidity in the space.

Outdoor temperature, humidity and wind velocity are determinant factors for the successful application of natural ventilation techniques. For cooling purposes, the incoming air should be at a lower temperature that the indoor air temperature. However, even at higher temperatures, the resulting air flow inside the space can cause a positive effect on the thermal comfort conditions of the occupants, since it increases heat dissipation from the human body end enhances evaporative and convective heat losses. Natural ventilation techniques for cooling purposes are also very effective during the night hours, when outdoor air temperatures are usually lower than the indoor ones. As a result the cooling load is reduced and the peak indoor air temperatures can be reduced by 1 to 3 °C.

Air humidity is the most important limiting factor for the application of natural ventilation techniques. High levels of humidity have a negative influence on thermal comfort. As a result, in regions with high relative humidity levels during summer, the use of conventional air-conditioning systems is necessary in order to remove water vapour from indoor air. Under such circumstances, natural ventilation during the day- or night-time hours should be avoided.

Hybrid ventilation systems can be described as systems that provide a comfortable internal environment using both natural ventilation and mechanical systems, but using different features of these systems at different times of the day or season of the year. In hybrid ventilation mechanical and natural forces are combined in a two-mode system where the operating mode varies according to the season, and within individual days. Thus the active mode reflects the external environment and takes maximum advantage of ambient conditions at any point in time. The main difference between a conventional ventilation system and a hybrid system is the fact that the latter has an intelligent control system that can switch automatically between natural and mechanical modes in order to minimize energy consumption.

There are multiple motivations for the interest in hybrid ventilation. The most obvious are:

- Hybrid ventilation has access to both ventilation modes in one system, exploits the benefits of each mode and creates new opportunities for further optimisation and improvement of the overall quality of ventilation.
- Advanced hybrid ventilation technology fulfils the high requirements on indoor environmental performance and the increasing need for energy savings and sustainable development by optimising the balance between indoor air quality, thermal comfort, energy use and environmental impact.
- Hybrid ventilation results in high user satisfaction because of the use of natural ventilation, the high degree of individual control of the indoor climate

(including the possibility of varying the indoor climate - adaptive comfort) as well as a direct and visible response to user interventions.

- Hybrid ventilation technology offers an intelligent and advanced ventilation solution for the complex building developments of today, that is user transparent and sustainable.

Naturally, expectations of hybrid ventilation performance will vary between different countries because of climate variations, energy prices and other factors. In countries with cold climates, hybrid ventilation can avoid the trend to use mechanical air conditioning in new buildings, which has occurred in response to higher occupant expectations, the requirements of codes and standards, and in some cases higher internal gains and changes in building design. In countries with warm climates, it can reduce the reliance on air conditioning and reduce the cost, energy penalty and consequential environmental effects of full year-round air conditioning.

Both natural and mechanical ventilation have advantages and disadvantages. For natural ventilation systems one of the major disadvantages is the uncertainty in performance, which results in an increased risk of draught problems and/or low indoor air quality in cold climates and a risk of unacceptable thermal comfort conditions during summer periods. On the other hand, air conditioning systems often lead to complaints from the occupants, especially in cases where individual control is not possible. Hybrid ventilation systems have access to both ventilation modes and therefore allow the best ventilation mode to be chosen depending on the circumstances.

The focus on the environmental impacts of energy production and consumption has provided an increased awareness of the energy used by fans, heating/cooling coils and other equipment in ventilation and air conditioning systems. An expectation of a reduction in annual energy costs has also been an important driving force for the development of hybrid ventilation strategies. Available data from case studies provided in the international project IEA ECBCS-Annex 35 (Heiselberg 2002) show that a substantial energy saving has been achieved in a number of buildings, mainly because of a very substantial reduction in energy use for fans and a reduced energy use for cooling.

Buildings with natural ventilation are associated with less SBS-symptoms, than buildings with traditional ventilation systems, (Seppänen and Fisk, 2002). Natural ventilation is well accepted by occupants and the natural ventilation mode should therefore be used, when the climatic conditions allow it. In addition the high degree of user control in hybrid ventilation systems has an influence on the perceived indoor environmental quality. Another aspect is that hybrid ventilation implies less noise (provided that there are no outdoor sources of heavy noise), which may also improve the perceived quality. In ECBCS-Annex 35 the high degree of user control in the investigated buildings was greatly appreciated by the occupants. In one of the cases (Rowe 2002) investigations via occupant questionnaires showed that the perceived performance increased as a function of perceived indoor air quality and thermal comfort.

Estimating the initial cost of hybrid ventilation systems in buildings can be quite difficult as the installation often consists of both mechanical installations and of building elements. Part of the investment in mechanical equipment is often shifted towards a larger investment in the building itself: increased room air volume per person, a shape favourable to air movement, a more intelligent facade/window system, etc. On the other hand the building might provide more useable (rentable) space, as space for plant rooms, stacks for ventilation channels, etc., is not needed. Recently a method for calculation of Life Cycle Costs (LCC) of natural ventilation systems have been developed, (Vik, 2003), which takes all these issues into consideration. This method can as well be applied on buildings with hybrid ventilation systems.

In ECBCS-Annex 35 the reference cost range provided by the participants was used to compare the initial costs of hybrid ventilation systems, and buildings with hybrid ventilation, with the initial cost of traditional systems and buildings, see (van der Aa, 2002). The life cycle costs for hybrid ventilated buildings were often lower than for reference buildings, but the relationship between initial, operating and maintenance costs was different.

These lecture notes includes two main sections. The first section focuses on modelling of natural and hybrid ventilation driven by thermal buoyancy, wind and/or mechanical driving forces for a single zone with one, two or several openings. The second section focuses on design of natural and hybrid ventilation systems describing the design procedure, natural and hybrid ventilation strategies, appropriate site and building design, etc.

2 NATURAL AND HYBRID VENTILATION DESIGN

Today, the construction industry is in the early stages of reinventing the design process that was used before the advent of mechanical systems. Design teams including both architects and engineers are formed and the building design is developed in an iterative process from the conceptual design ideas to the final detailed design.

Building energy use and the sizes of mechanical equipment are reduced without the use of sophisticated technologies, but only through an effective integration of the architectural design and the design of mechanical systems. Buildings with natural ventilation often include other sustainable technologies as e.g. daylight, passive and natural cooling, passive solar heating etc, and an energy optimization requires an integrated approach in the design of the building and its mechanical systems, (Heiselberg 2000 and Tjelflaat 2001). The integrated design approach achieves this due to the close relationships that exist between the building, its surroundings, the architecture and the mechanical systems.

In the integrated design process the expertise of the engineer is available from the very beginning at the conceptual design stage, and the optimization of both the architectural design and the mechanical equipment design can start at the same time as the first design ideas are developed.

2.1 Integrated and Climatic Design

The art and science of using the beneficial elements of nature – sun, wind, earth and air temperatures, plants and moisture – to create comfortable, energy-efficient and environmentally wise buildings are called climatic design. The desirable procedure is to work with, not against, the forces of nature and to make use of their potentialities to create better living conditions. The principles of climatic design derive from the requirement for creating human comfort in buildings using the elements of the natural climate. Perfect balance between natural resources and comfort requirements can scarcely be achieved except under exceptional environmental circumstances and the climatic design will vary throughout the year depending upon whether the prevailing climatic condition is “underheated” compared to what is required for comfort (i.e., like winter) or “overheated” (i.e., like summer).

The integrated design of the heating, cooling, lighting and ventilation of buildings can be accomplished in three separate steps. The first step is the design of the building itself i.e. to minimize heat loss and maximize heat gain in winter, to minimize heat gain in summer and to use daylight and fresh air efficiently. Decisions at this step determine the size of the heating, cooling and lighting loads. Poor decisions at this point can easily double or triple the size of the mechanical equipment eventually needed. The second step involves the climatic design where passive heating, passive and natural cooling, daylight techniques and natural ventilation heat the building in the winter, cool it in the summer and light and ventilate it all year. The proper decisions at this point can greatly reduce the loads created during the first step. The third step consists of designing the mechanical equipment to handle the loads that remain from the combined effect of the first and the second step, see table 1.

The heating, cooling, lighting and ventilation design of buildings always involve all three steps whether consciously considered or not. Minimal demands have in the past been placed on the building itself to affect the indoor environment. It was assumed that it was primarily the engineers at the third step who were responsible for the environmental control of the building. Thus architects, who were often indifferent to the heating and cooling needs of buildings, sometimes designed buildings with large glazed areas for very hot or very cold climates, and the engineers would then be forced to design giant heating and cooling plants to maintain thermal comfort. On the other hand, when it is consciously recognized that each of these steps are an integral part of the heating, cooling, lighting and ventilation design better buildings result. They are often less expensive because of reduced mechanical equipment and energy needs. Frequently they are also more comfortable because the mechanical equipment does not have to fight giant loads.

The principles of climatic design of buildings are well described in the literature, (Lechner, 1991; Brown, G.Z., 1985; Olgyay, V., 1992; Givoni, B., 1976).

Table 1. Typical design considerations at each design step. Revised from (Lechner,1991).

	Heating	**Cooling**	**Lighting**	**Ventilation**
Step 1	*Conservation*	*Heat avoidance*	*Daylight*	*Natural ventilation*
Basic Design	1. Surface to volume ratio 2. Zoning 3. Insulation 4. Infiltration	1. Façade design 2. Solar shading 2. Exterior colours 3. Insulation 4. Thermal mass	1. Windows (type and location) 2. Glazing 3. Interior finishes	1. Building form 2. Surface materials 3. Location of win-dows and openings 4. Atria, stacks
Step 2	*Passive solar*	*Passive cooling*	*Daylighting*	*Natural ventilation*
Climatic design	1. Direct gain 2. Exposed thermal mass 3. Sunspace	1. Evaporative cooling 2. Convective cooling 3. Radiant cooling 4. Earth cooling	1. Skylights 2. Light shelves 3. Light wells 4. Daylight control	1. Wind induced ventilation 2. Bouyancy induced ventilation 3. Air distribution 4. Ventilation control
Step 3	*Heating system*	*Cooling system*	*Electric light*	*Mechanical ventilation*
Design of Mechanical Systems	1. Radiators 2. Radiant panels 3. Floor/wall heating 3. Warm air system	1. Cooled ceiling 2. Cold air system 3. Cooled floor/wall	1. Lamps 2. Fixtures 3. Location of fixtures 4. Control	1. Air intake and exhaust 2. Air distribution 3. Mech. exhaust 4. Mech. ventilation 5. Air conditioning

2.1.1 Site design, building location and landscaping

The following main objectives should be taken into consideration when selecting and designing the site for a building project suitable for natural ventilation:

- The best exploitation of the air flow pattern due to topography and surrounding buildings
- The best compromise between summer and winter comfort conditions
- The avoidance of permanent unwanted wind sheltering situations
- The avoidance of discomfort due to outdoor conditions or caused by high wind velocities
- The avoidance of airflow paths transporting dust and pollutants

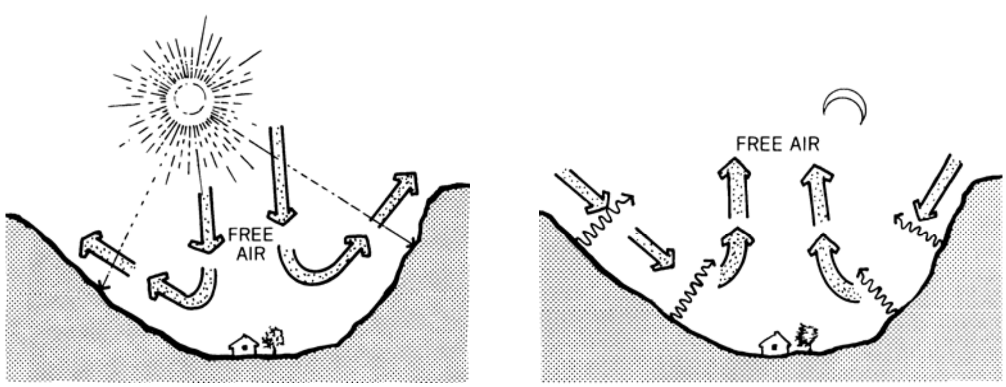
The location, layout, general form and orientation of the buildings, as well as landscaping of the site are the principal aspects to be considered.

Successful design of a naturally ventilated building requires a good understanding of the air flow patterns around it and the effect of the neighbouring buildings as well as the existing design strategies to improve ventilation.

Building location and layout

Mountains create local winds that vary from day to night. During the day the air next to the mountain surface heats up faster than the free air at the same height. Thus, warm air moves up along the slopes during the day. At night the process is reversed, the air moves down the slopes, because the mountain surface cools by radiation more quickly than the free air. The best location is therefore generally at the middle of a slope. In this position, temperate slope winds can drive cross ventilation through the shortest section of the building. A down-valley location would expose the building to colder and damper winds. A ridge position would expose the building to much higher wind velocities

In narrow valleys this phenomenon can create very strong winds up along the valley floor during the day and down the valley at night, see Figure 1. By proper location and control of openings this phenomenon can be used for ventilation in daytime and free night cooling.



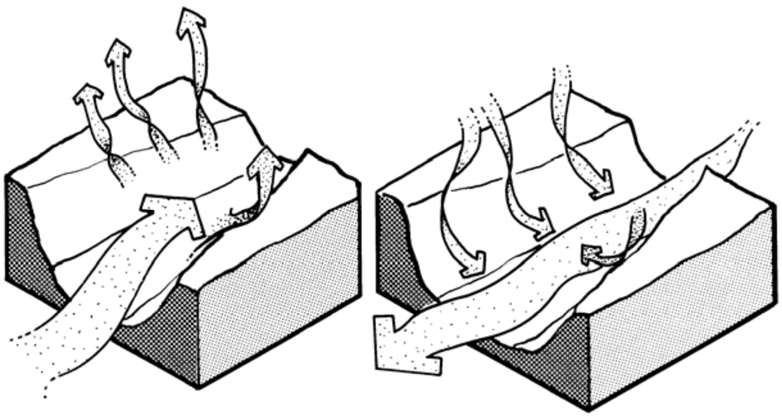


Figure 1. The principle of day and night mountain winds /Lechner/

A similar day-night reversal of winds occurs near large bodies of water. The large heat capacity of water prevents it from heating or cooling as fast as land. Thus during the day the air is hotter over land than over water. The resultant pressure differences generate sea breezes. At night the temperatures and air flows reverse. In the late afternoon and early morning, when the land and sea are at the same temperature, there is no breeze. Furthermore at night the breezes are weaker than during the day, because the temperature differences between land and water are smaller, see Figure 2. For buildings close to the sea or large lakes this phenomenon is used in the ventilation strategy. The building should be positioned fairly close to the shore and with the longitudinal axis parallel to the line of the coast or the bank in order to make use of day water and night land breezes. However constraints posed by danger of flooding, as well as environment and wildlife protection regulations, should take priority over natural ventilation criteria when a building near a shore line is designed.

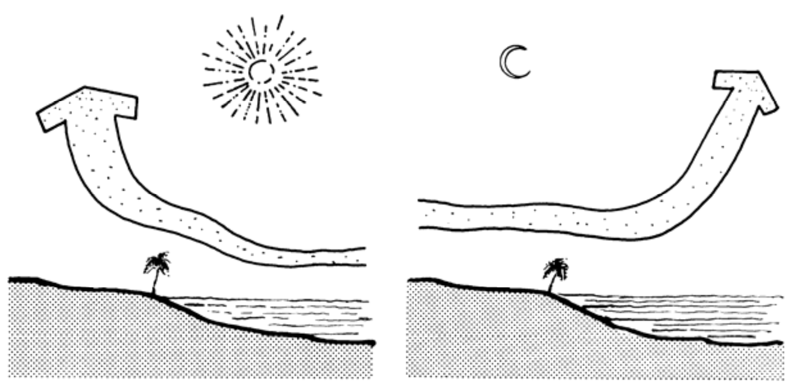


Figure 2. The principle of sea breeze. /Lechner/.

These local wind effects have to be estimated locally as they will not be covered by the analysis of wind data from a nearby weather station.

If a building is designed for an urban site, its location should be at a distance from other buildings that is greater than the depth of their wake so that they will not shelter if from summer winds. The extent of the wake at the leeward side of a building depends on the building's shape and the wind direction. For a typical house, the average wake length is four times the ground-to-eaves height. This is schematically shown in Figure 3.

Obviously, if the distance between two buildings is shorter than this, the one, which falls within the "wind shade" of the other will be poorly ventilated.

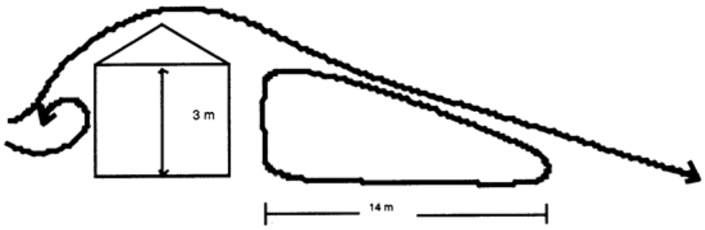


Figure 3. Wake of a typical house. /Santamouris/.

If it is not possible to position the building outside the wake of other buildings, the building should be positioned randomly with regard to the upwind buildings and with its longitudinal axis perpendicular to the prevalent summer wind direction in order to catch the streamline flow. If the prevailing winter wind direction is different from the summer one, as is usually the case, it is possible to optimise the location of the building in order to obtain a good summer wind exposure, while sheltering the building from cold winter winds, see Figure 4.

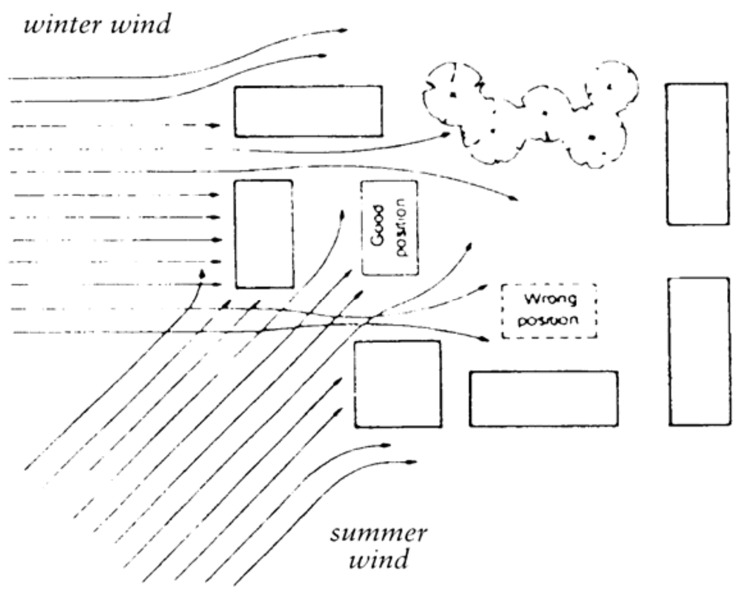


Figure 4. Examples of good and bad locations of a building on an urban site with respect to wind. /Allard/.

In very dense urban areas, spaces most needing ventilation should be put on the highest floors where wind flows is stronger and less turbulent than near the ground. Narrow passageways, corners of buildings too close together and arcades that go from side to side of the building should be avoided in order not to expose pedestrians to gusty acceleration of the airflow due to the Venturi effect, see Figure 5.

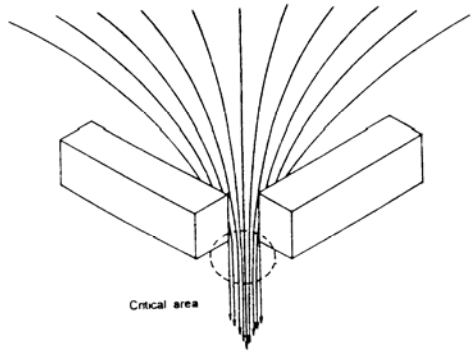


Figure 5. Critical positions for pedestrians discomfort due to wind on an urban site. /Allard/.

When a project involves a compound with several buildings, as far as possible their layout should satisfy the criterion of avoiding a wake interference flow regime in the prevailing summer wind direction in order to allow each building to be exposed to relatively streamline airflow when needed. However the best compromise should be chosen with consideration of the winter period, during which opposite, sheltered conditions are required. A scattered pattern layout is more appropriate to an optimum use of air movement within the buildings than a normal pattern layout, because the configuration provides less sheltering from the wakes. A similar effect can be obtained with a normal layout pattern, but with the buildings slanted with respect to the normal grid, see figure 6.

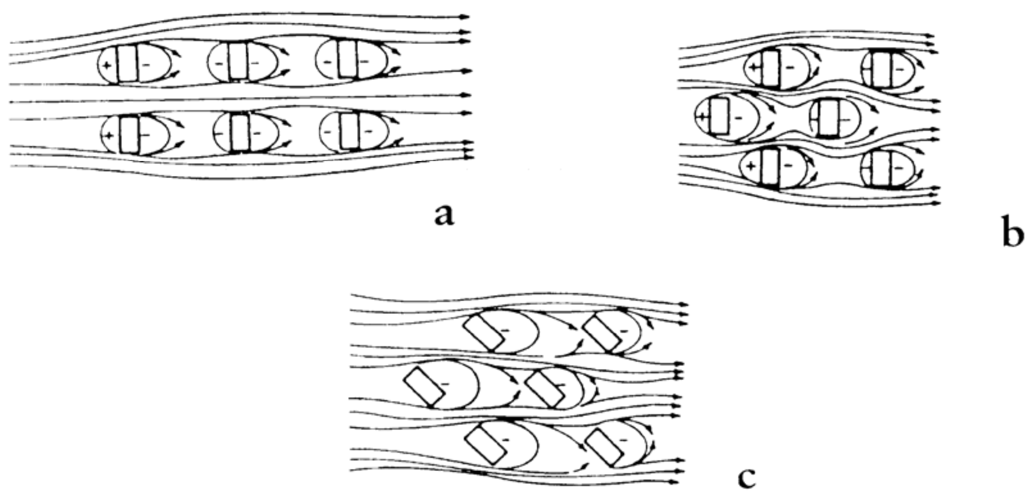


Figure 6. Airflow patterns through a) a normal, b) a scattered and c) a diagonal layout of buildings.

Landscaping

Landscaping has an important function in controlling the air movement around buildings for optimum natural ventilation. The type and layout of vegetation to be included in a site plan should be chosen with the airflow pattern taken into account, as well as aesthetic and environmental considerations. The main functions of vegetation as far as air movement is concerned are: wind sheltering, wind deflection, funnelling and acceleration of air, air conditioning.

In summer time, where the buoyancy forces are small, good natural ventilation requires locating openings in opposing pressure zones. It is therefore important to identify the prevailing wind directions in summer, as the ventilation has to rely much more on the wind. Windbreaks as trees or bushes can in the summertime be used to promote ventilation. They can prevent the wind from easily spilling around the sides of the building and significantly increase the natural ventilation potential. Vegetation can also create areas of higher wind velocities by deflecting winds or funnelling air through a narrow passage (Venturi effect). The zones of accelerated airflow are the zones where the highest negative pressures and, therefore, the highest suction effects occur. This should be taken into account when designing the openings on the walls facing those areas. Only outlet openings are appropriate in those walls.

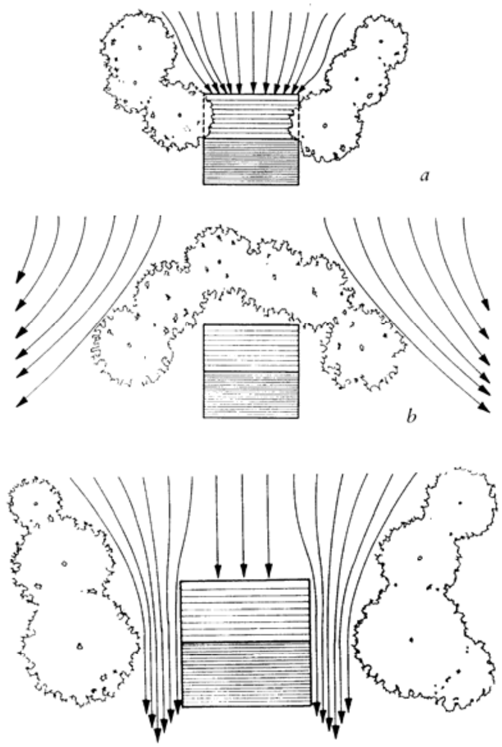


Figure 7. Windbreaks used to promote ventilation. /Allard/.

The objective is to ventilate the largest possible part of the indoor space. Fulfilment of this objective depends on window location, interior design and wind- and temperature characteristics. Figure 8a illustrates the wind flow pattern around a building with no openings. As the wind flows past the building, a positive pressure is created on the windward facade. The wind is diverted and a negative pressure is created along the side walls due to the high speed of the flow along them. A large slow-moving eddy on the leeward facade produces a smaller suction. Figure 8b shows the case of a single-zone building which is cross-ventilated as a result of two windows placed on the windward and leeward facades. Cross ventilation is improved if two outlets of total area equal to the inlet area are placed on the building sidewalls, see Figure 8c. This design permits more efficient ventilation for a wider range of wind directions.

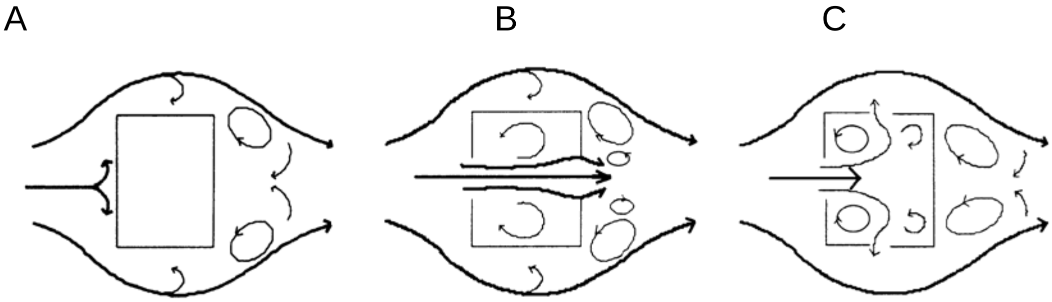


Figure 8. Air flow patterns around a building and impact of opening location on ventilation. /Sanatamouris/.

Dense hedges can be placed near a building to create positive and negative pressure zones in order to enhance the airflow through the building. Although less efficient than solid wingwalls in producing an increase of the pressure differential, hedges can be more cost effective and have a more pleasant appearance.

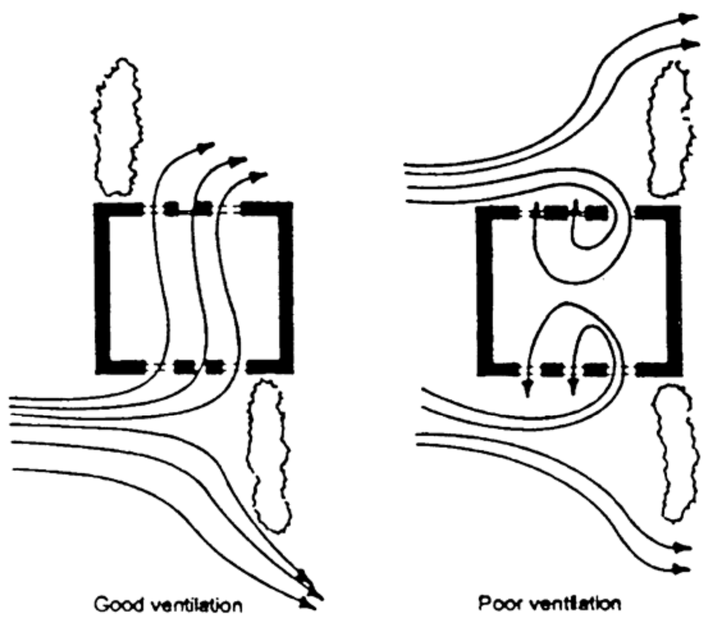


Figure 9. The effect of hedge positioning on the airflow pattern through a building. /Allard/.

2.1.2 Building Design

Designing a building for optimum natural ventilation means paying much more attention to the various aspects related to the airflow movement around and within the building than is generally paid by professionals in current practice. The aspects of building design related to air movement can be grouped according to their relation to:

- The form of the building envelope
- The internal distribution of spaces and functions
- The dimensions and location of openings
- The characteristics and dimensions of the exposed thermal mass
- The interactions with the HVAC system

The form of the building envelope

The wind velocity and pressure fields around a building are greatly affected by the form of the building envelope. This is in particularly by the height of the building, the roof form, the aspect ratios (the ratios of the height of the building to its length and width) and the corrugation of the building envelope (overhangs, wingwalls and recessed spaces.)

The wind velocity increases at higher levels inducing an increased airflow rate through the windward openings of the top floors and higher suction at the side-walls. As the building height increases the amount of air passing around the sides of the building increases in proportion to the amount of air travelling over it. This causes less upward air movement through the openings placed on the lower two-thirds of the building windward facade. The top one-third of the windward facade of a building will always experience upward airflow, regardless of the height of the building. Increasing the height of a multistorey building causes an additional strengthening of the stack airflow through stairwells and other shafts. This effect is used when the wind flow is weak. However, above a certain height, stratification of air density and temperature may cause an excess in temperature differential between the bottom and top of the building, which may not be easily eliminated by passive means.

In real building it is common to have spaces with only one external wall. Ventilation of such spaces will be negligible if there is only one opening, but can be improved by placing two widely spaced openings on the side of the external wall, see Figure 10a. Further improvement may be achieved by use of wing walls, as shown in Figure 10b. Wing walls are extrusions of the exterior walls and their role is to create positive pressure over one opening and negative pressure over another, so as to achieve cross-ventilation. This technique is effective for wind direction angles from 20 to 160°. Ventilation of spaces with exterior openings in adjacent walls can also benefit from the use of wing walls, see Figure 10c.

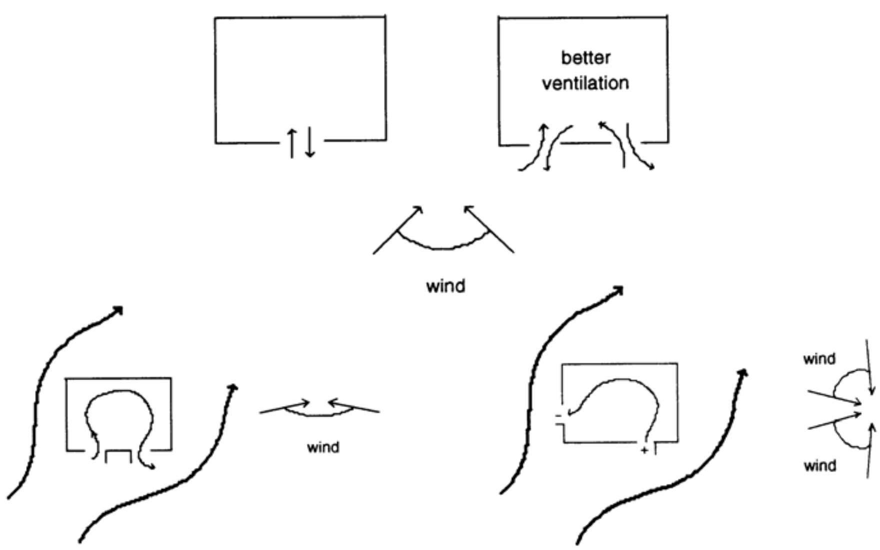


Figure 10. The impact of wing walls on single sided and cross ventilation. /Santamouris/.

The position of the wing-wall extrusion is critical to ventilation success. Every configuration gives improved airspeeds for a specific band of wind directions. Prevailing wind direction is, therefore, an important characteristic of the microclimate around the building, and it has to be taken into consideration for the design of the wing wall position. Figure 11a and b show the air flow patterns for two different configurations. In the case shown in Figure 11b ventilation is poorer, because positive pressures are created at both openings, which prevents air circulation and confines the flow to the areas near the windows. Comparison of Figure 11a and c shows that air circulation is larger when the openings are widely spaced.

The dimensions of wing-wall extrusions vary according to the exterior opening width. The optimum required dimension for the protrusion is equal to the opening width and the minimum recommended is equal to half the opening width. Fencing or dense shrubs can act as a barrier and change the wind direction, producing the same effect as wing-walls, see Figure 11d.

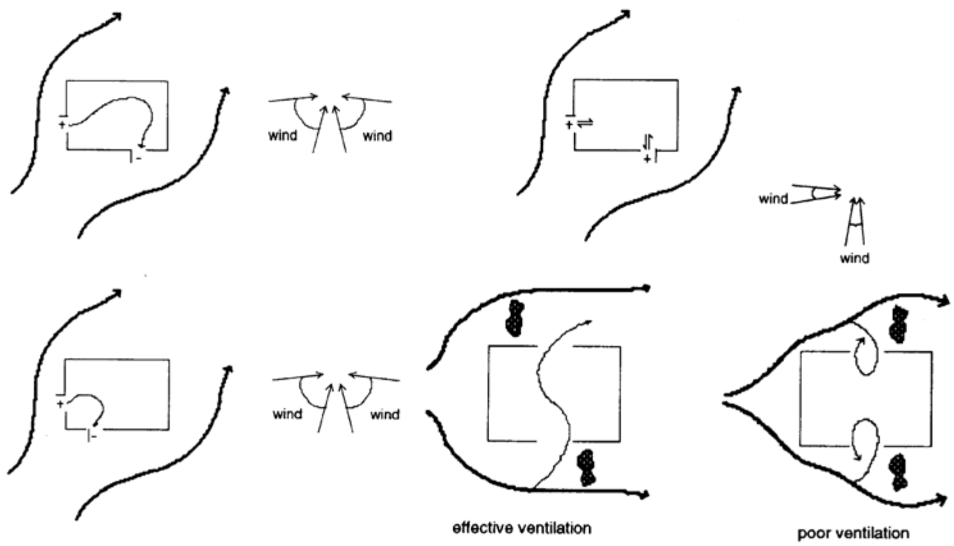


Figure 11. Ventilation quality by different wing-wall solutions. /Santamouris/.

As an example, the use of external walls as wing-walls, or the staggering of spaces, can solve problems such as a worst combination of wind and sun exposure in hot climates, where cross ventilation is required for comfort, see Figure 12. With wind and sun from the west, rooms with two external walls facing north and south will have little air movement, but will have protection from solar radiation. If the building is rotated 90°, the rooms with openings facing west and east will have cross ventilation but will have no protection from high solar radiation. A proper placing of external wind-deflecting walls can be used to create high- and low-pressure zones to achieve cross ventilation, directing the air movement while protecting the rooms from direct solar radiation. Alternative, the rooms can be staggered to achieve the same result.

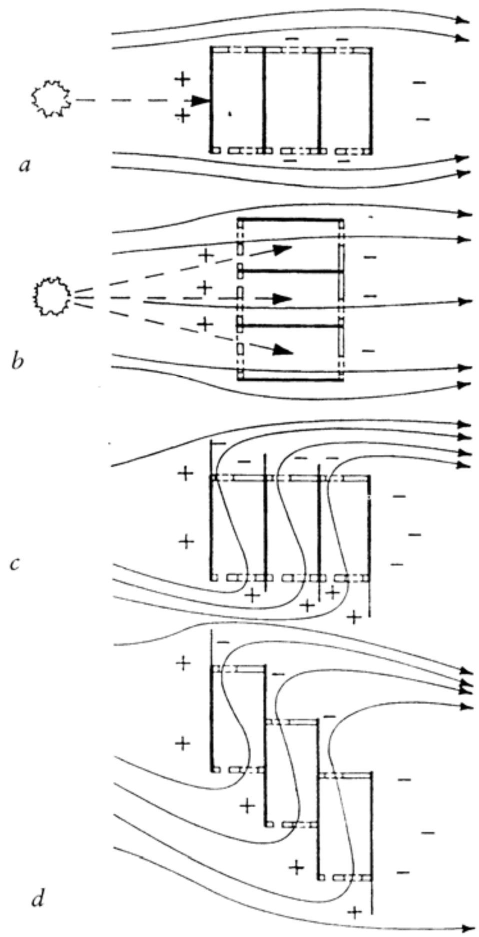


Figure 12. Building orientation and layout with respect to sun and wind exposure. A)sun protection, no ventilation. B) cross ventilation, no sun protection. C) and D) sun protection and ventilation. /Arens/.

2.2 Design Procedure

The natural ventilation process is very dependent on the outdoor climate, the microclimate around the building as well as the thermal behaviour of the building and, therefore, it is essential that these factors are taken into consideration in the basic design step. The output from the first step is a building orientation, design and plan that minimize the thermal loads on the building in overheated periods, which together with the selected ventilation strategy make it possible to exploit the dominating driving forces (wind and/or buoyancy) at the specific location, and which ensure a proper air distribution through the building. Appropriate zoning of the building with polluting activities in special rooms (printing, copying, smoking, canteen) as well as the use of low-emitting building materials are very important for minimizing contaminant loads and thereby the necessary air flow rate. It is also important that issues like night cooling potential, noise and air pollution in the surroundings as well as fire safety and security are taken into consideration.

In the climatic design step the natural ventilation strategy is designed. The location and size of openings in the building as well as features to enhance the driving forces as solar chimneys and thermal stacks are designed according to the selected strategy for both day and night time ventilation. Passive methods to heat and/or cool the outdoor air are considered as well as heat recovery and filtration. Appropriate natural ventilation control strategies are determined and decisions are made regarding the level of automatic and/or manual control and user interaction.

In the third step, if necessary, mechanical systems to fulfil the comfort and energy requirements are designed. These can range from simple mechanical exhaust fans to enhance the driving forces to mechanical cooling systems, balanced mechanical ventilation or full air conditioning systems. The whole system control strategy is determined to optimize the energy consumption while maintaining acceptable comfort conditions.

Effective ventilation of indoor spaces has the best chance of success when the design process is carried out in a logical, subsequent manner with increasing detail richness towards the final design and in the framework of a design procedure. In the case of natural ventilation the need for a design procedure is even more evident due to the comprehensive design team, where users, building owner, architect, civil engineer and indoor climate and energy counsellor must all be involved – simultaneously.

A natural ventilation design procedure consists of different phases: conceptual design phase, basic design phase, detailed design phase and design evaluation. The conceptual design phase includes decisions on building form, size, function and location. Targets are set for indoor air quality, thermal comfort and energy use as well as cost limits. The conceptual design of the natural ventilation system is based on these considerations as well as guidelines and experiences from previous buildings. The natural ventilation principle (stack and/or wind driven, single sided and/or cross ventilation) to be used is decided together with the principle of the necessary additional mechanical systems. In the basic design phase the building heat, sun and contaminant loads are estimated and the natural ventilation system layout designed (and if necessary additional mechanical systems). The necessary air flow rates as well as expected indoor air quality and temperature levels are calculated. A coarse yearly energy consumption is calculated together with the necessary peak power demands. If the results do not meet the targets, the building and its systems will have to be redesigned before entering the next phase. In the detailed design phase contaminants and thermal loads are reevaluated and source control options are considered and/or optimized. The type and location of natural ventilation system components are selected as well as the control strategy and sensor location. Based on hour by hour calculations through a design year the whole system (building and technical systems) is optimized with regard to indoor climate, energy consumption and costs. Finally, in the design evaluation phase detailed predictions of indoor air quality and thermal comfort are performed to control if the design fulfils the targets of the project.

The natural ventilation design procedure differs from the design procedure for conventional HVAC systems in the way that the design in all phases needs to focus on all three steps in the integrated design approach and not only on step three. The natural ventilation design must also be an integrated part of the design of the building and of other sustainable technologies.

Both integrated design procedures and procedures focused specific on natural ventilation design are developed, see i.e. (Larsson, 2003; Löhnert et al. 2003; CIBSE, 1997, 1998 and 2000).

2.2.1 Design Challenges

Ventilation of buildings is an important aspect of all building projects. The purpose of the ventilation system is in many projects not only to control indoor air quality but also in summer in an energy-efficient way to achieve thermal comfort through natural cooling. In design of natural ventilation systems it is often necessary to separate design of ventilation for indoor air quality control and design of ventilation as a natural cooling strategy in summer. The major reason for this is the fact that devices for indoor air quality control and thermal comfort control in general are quite different, and that the potential barriers and problems to be solved, including the optimization challenge also are fundamentally different.

In optimization of ventilation for indoor air quality control the challenge is during periods of heating and cooling demands to achieve an optimal equilibrium between indoor air quality needs and energy use. This includes first of all a minimization of the necessary fresh air flow rate by reduction and isolation of pollution sources, demand control of air flow rates and optimum air supply to occupants. Secondly, it includes reduction of heating and cooling demands by heat recovery, passive cooling and/or passive heating of ventilation air. Finally, it includes optimization of natural driving forces from stack effect and wind and reduction of pressure loss in duct work and other components to eliminate (or reduce) the need for fan energy. During periods without heating and cooling demands there is no need to reduce air flow rates as more fresh air only will improve the indoor air quality and the optimization challenge becomes mainly a question of eliminating (or minimizing) the need for fan energy. Besides the above-mentioned challenges the ventilation should of course be provided without creating thermal comfort problems like draught or high temperature gradients.

In optimization of ventilation as a natural cooling strategy the challenge is to achieve an optimal equilibrium between cooling capacity, cooling load and thermal comfort. This includes first of all reduction of internal and external heat loads by application of low energy equipment and lighting, by utilization of daylight and by effective solar shading. Secondly, it includes application of the thermal mass of the building as a heat buffer which absorbs and stores heat during occupied hours and returns it to the space during unoccupied hours with night ventilation. Finally, it includes optimization of natural driving forces from stack effect and wind and reduction of pressure loss in duct work and other components to eliminate (or reduce) the need for fan energy. The major issues of concern with regard to thermal comfort are avoidance of too low temperatures at the start of the working hours and achievement of acceptable temperature increase during working hours.

The issues of concern in optimization of natural ventilation for indoor air quality control and natural cooling are summarized in Table 2.

Table 2. Issues of concern in optimization of natural ventilation for indoor air quality control and natural cooling.

Indoor Air Quality Control	***Natural Cooling***
• Limitation of pollution sources (building materials, equipment, local exhaust, zoning, etc.)	• Limitation of heat load (low energy equipment and lighting, solar shading, daylight)
• Choice of appropriate indoor air quality targets and related air flow rates	• Choice of appropriate thermal comfort targets (min. and max. values, tolerances)
• Optimum air supply to occupants and removal of pollutants (high ventilation efficiency)	• Optimum air supply to occupants (high temperature efficiency)
• Minimize heating and cooling energy (heat recovery, passive heating, passive cooling, etc.)	• Minimize cooling load (thermal mass, night ventilation)
• Minimize fan energy (low pressure duct work and components, natural driving forces, etc.)	• Minimize fan energy (low pressure duct work and components, natural driving forces, etc.)
• Adapting air flow rates to indoor air quality needs (control strategy, demand-controlled ventilation)	

2.2.2 Design Methods and Tools

Different phases in the design process call for different types of design methods and tools. Guidelines, decision tools, experience from colleagues, and catalogues on products are useful in the conceptual design phase. In this phase input data are not well known and/or can vary within large ranges and output only needs to be accurate enough to make principle decisions on which systems and/or combination of systems that are appropriate to use in the given situation.

In the basic design phase analytical calculations and simulation programmes are used to develop the design. Input data are known with a much better accuracy and output data should be detailed enough to convince the designer that the system can fulfil the energy targets and the comfort requirements for the building. In the detailed design phase the individual components are designed and the system and control strategies are optimized with regard to energy consumption and comfort conditions. The design methods are the same as for the basic design phase, but input data on the building and individual components are well known in this phase and output becomes therefore accurate enough to perform a system optimization. Finally, detailed simulation methods or physical models are used to evaluate the final design. These analysis methods are expensive and time-consuming to use. They require very detailed input data and are able to give precise predictions on the performance (energy, IAQ and thermal comfort) of the building and the ventilation system.

As the natural ventilation process and the thermal behaviour of the building are linked design methods for natural ventilation must take both aspects into consideration at the same time and include efficient iteration schemes. This is the case for all types of methods from simple decision tools, analytical methods, zonal and multizone methods to detailed CFD analysis methods. Methods and tools that combines thermal simulation models with a multizone air flow models allow the thermal dynamics of the building to be taken into account and improve the prediction of the performance of natural ventilation considerably. Such models are capable of predicting the yearly energy consumption for natural ventilation and are therefore the most important design tool for natural ventilation systems.

There are a number of methods and tools are available. Tools like ESP-r, TRNSYS and EnergyPlus are examples of tools for integrated simulation of air flow and building thermal performance, while tools like COMIS, CONTAM are examples of tools for multizone air flow analysis. An overview can be obtained from (DOE).

3 Natural Ventilation Strategies

The principles of natural ventilation in buildings are relatively few and straightforward, relying on wind, thermal buoyancy or both as driving forces. However, to characterize the natural ventilation concept in a particular building is more difficult as different ventilation principles often are applied and because a whole range of subtle and sophisticated ways are used to take advantage of the natural driving forces to promote the ventilation principles applied.

3.1 Characterisation of Concepts

To define different natural ventilation concepts five essential aspects of natural ventilation can be used to describe and characterize various concepts, as suggested by (Kleiven, 2003). These are n*atural driving force, ventilation principle, ventilation element, building height* and the *supply and exhaust air paths.* The complete set of characteristic aspects and parameters is shown in Table 33.

Table 3. Characteristic aspects and parameters for natural ventilation concepts. (Kleiven 2003).

Characteristic Aspect	***Characteristic Parameter***
Natural Driving Force	• Buoyancy • Wind
Ventilation Principle	• Single-sided • Cross • Stack
Ventilation Element	• Ventilation openings in the façade • Wind tower • Wind scoop • Chimney • Atrium • Ventilation chamber • Embedded duct • ..
Building Height	• Low-rise • Medium-rise • High-rise
Supply and Exhaust Air Paths	• Local • Central

3.1.1 Natural driving force

The *natural driving force* can be wind, buoyancy or a combination of both. A natural ventilation system will often rely on both wind and thermal buoyancy as driving forces, but one of them will be predominant, and both the building and the ventilation system will be designed for optimal utilisation of this driving force. The dominating natural driving force has consequences for the shape and layout of the building, for the selection of ventilation elements to be utilised (e.g. a wind scoop or an atrium), and for the air paths into, out of and through the building (ventilation principle).

3.1.2 Ventilation principle

The *ventilation principle* used in the building to exploit the natural driving forces can be divided into three types, see Figure 13.

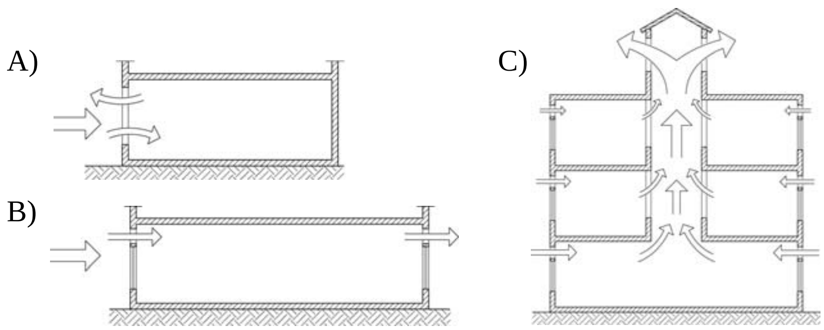


Figure 13. Natural ventilation principles. A) Single-sided ventilation, B) Cross ventilation and C) Stack ventilation.

- *Single-sided ventilation*, where ventilation opening(s) is only on one side of the room. The main driving force is thermal buoyancy in winter and wind turbulence in summer. Compared with other principles lower ventilation rates are generated, and the ventilation air does not penetrate so far into the space.
- *Cross ventilation*, where ventilation openings are on two sides of the room. The main driving force is wind-induced pressure differentials between the two openings. High ventilation flow rates can be achieved, but due to large and rapid variations in wind flows, it is difficult to control. As air is crossing the room larger room depths can be ventilated.
- *Stack ventilation*, where ventilation openings are at both a low and a high level. The main driving force is thermal buoyancy. High and steady ventilation flow rates can be achieved at moderate temperature differences. If ventilation air is crossing the room larger room depths can be ventilated.

Single sided ventilation relies on openings being on only one side of the ventilated enclosure. A close approximation is a cellular building with opening windows on one side and closed internal doors on the other side. With a single opening in the room, figure 14a, the main driving force for natural ventilation in summer is wind turbulence. Compared with other strategies, lower ventilation rates are generated, and the ventilating air does not penetrate so far into the space. Single sided single opening ventilation is effective to a depth of about 2 times the floor to ceiling height. Where ventilation openings are provided at different heights within the facade, see figure 14b, the ventilation rate can be enhanced by stack effect. The ventilation rate will be further enhanced by any wind pressures acting on the ventilation opening. Stack induced flows increase with the vertical separation of the openings and with the inside to outside temperature difference. To maximise the height over which the stack pressures act, it may be necessary to provide ventilation opening separately from the window. Care is needed in positioning any low level inlet because it may create draughts in cold weather. As well as enhancing the ventilation rate, the double opening increases the penetration of fresh air into the space. Single-sided double opening ventilation is effective to a depth of about 2.5 times the floor to ceiling height.

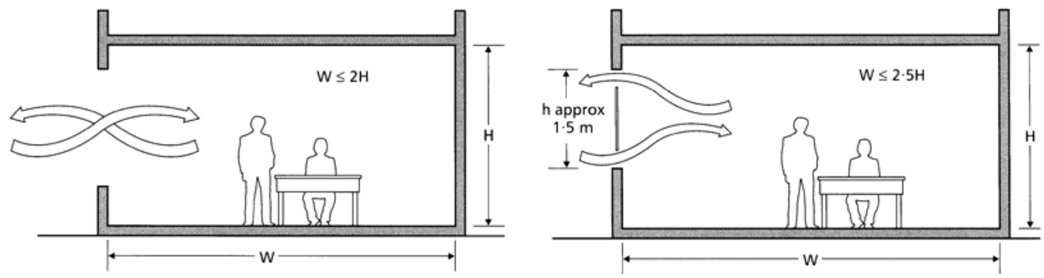


Figure 14. Single-sided single and double opening ventilation. /CIBSE/.

Cross-ventilation occurs where there are ventilation openings on both sides of a space. Air flow from one side of the building to the other and leaves through another window or door. Cross ventilation is usually wind driven. As the air moves across an occupied space, it picks up heat and pollutants. Consequently, there is a limit on the depth of space, which can be effectively cross ventilated. Cross ventilation is effective up to 5 times the floor to ceiling height. This limitation leads to a building with a narrow plan depth. The narrow depth is usually achieved with a linear plan form, but a similar effect can be achieved by wrapping the accommodation around an open courtyard. The narrow plan depth associated with this approach has the added benefit of enhancing the potential for natural lighting. The main challenge with such an approach is to create a building form that will ensure a significant difference in wind pressure coefficient between the inlet and outlet openings. This is more difficult to achieve for a courtyard approach, because the courtyard and the leeward side of the building will be at similar pressures. The second issue that needs careful consideration is the resistance to air flow. Insufficient flow may be generated, particularly in summer conditions, if openings on one side of the building are closed, or if internal partitions restrict the flow of air across the space. In such situations, the ventilation mechanism will be effectively single-sided.

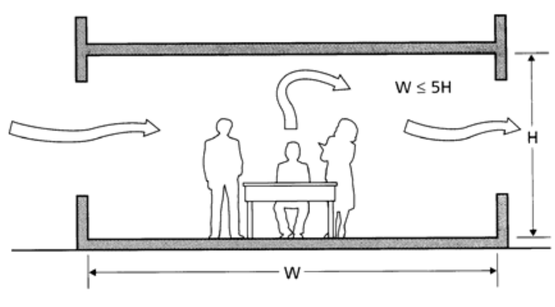


Figure 15. Cross-ventilation. /CIBSE/.

Stack ventilation is used to describe those ventilation strategies where driving forces promote an outflow from the building, thereby drawing in fresh cool air via ventilation openings at low level. The strategy makes use of the difference in density between a column of warm air and the surrounding cooler air. Because air flow into the building at low level, then up to a high level exhaust point, great care has to be taken when determining the different sizes of ventilation opening on each floor of the building. For equal ventilation rates, the ventilation openings at lower floors need to be smaller than those nearer the top of the building. The effectiveness of stack ventilation can be enhanced by designing the stack outlet to be in a region of wind-induced negative pressure. This requires care when designing the position and form of the stack outlet. By its nature, stack ventilation is essentially cross-ventilation as far as the individual occupied zones are concerned, in that air enters one side of the space and leaves from the opposite side. The air may flow across the whole width of the building and be exhausted via a chimney, or it may flow from the edges to the middle to be exhausted via a central chimney or atrium. Stack ventilation can be effective across a width of 5 times the floor to ceiling height from the inlet to where the air is exhausted to the stack.

Chimneys provide a means of generating stack ventilation and the essential requirement is for the air in the chimney to be warmer than the ambient air. If, as shown in Figure 16, the chimney has a large surface area exposed to the weather, it needs to be well insulated. Chimneys provide no functional purpose other than ventilation. Consequently, they are sized simply to satisfy the pressure drop requirements. They can be in the form of a single linear chimney or several smaller chimneys distributed around the building to suit the required ventilation flow path. Fx, if the building faces a busy road, it would be possible to place the inlets on the facade away from the noise and pollution source with the chimneys on the road side.

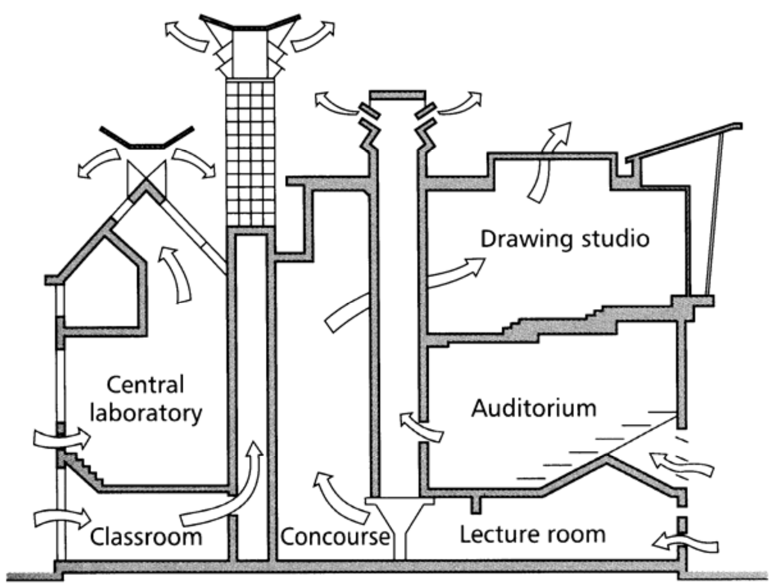


Figure 16. Chimney ventilation at De Montfort University. /CIBSE/.

It is possible to enhance the stack pressures by using solar chimney, in which glazed elements are incorporated into the chimney structure. Solar radiation enters the chimney through the glazing and is captured by absorbing surfaces. Heat is then released to the air by convection, promoting buoyancy. Care has to be taken to ensure that there is a nett heat gain into the chimney during cooler weather (The solar gain must be greater that the conduction loss. If this balance is not achieved, buoyancy will be reduced and the chimney will be less effective. In cold weather, the conduction heat loss will result in the glass having a low surface temperature. This may be sufficient to generate down draughts, inhibiting the general upward flow through the chimney. An advantage of the solar chimney is that, by definition, the chimney is likely to be placed on the sunny side of the building. Consequently, the ventilation air will be cooler, it being drawn from the opposite (shaded) side of the building. Another important part of the design is the detail of the chimney outlet, which should be located in a negative wind pressure zone. This negative pressure zone can be created by careful design of the roof profile and/or the chimney outlet. To provide adequate ventilation on very hot and still days, an extract fan can be installed in the shaft to pull air through the building. This should be designed so that the fan does not provide a significant resistance to air flow when the chimney is operating in its natural draught mode.

An atrium is a variant of the chimney ventilation principle. In fact, the same effect could be achieved by a central spine of chimneys. The essential difference is that the atrium serves many more functions than the chimney. For example it provides space for circulation and social interaction. Because it provides attractive, usable space, the location of the atrium is a key element in the organisational planning of the building. Thus other criteria may restrict the flexibility to locate the atrium to maximum advantage for ventilation. An atrium does provide one significant ventilation advantage. With an atrium, the air can be drawn from both sides of the building towards a central extract point, thereby doubling the width of building that can be ventilated effectively by natural means, see Figure 17. For natural ventilation to work effectively, the maximum distance from building perimeter to atrium must conform to the cross-ventilation limits. As with the chimney strategy, roof vents must be carefully positioned within the form of the roof so that positive wind pressures do not act on the outlets, causing reverse flow. In fact, it is normally possible to organise the outlets so that they are always in a negative pressure zone. This can be achieved by designing the roof profile so that for all wind angles, the opening is in a negative pressure zone or using multiple vents which are automatically controlled to close on the windward side and open on the leeward side. As for chimneys, natural ventilation can be supplemented on hot still days by using extract fans in the atrium roof.

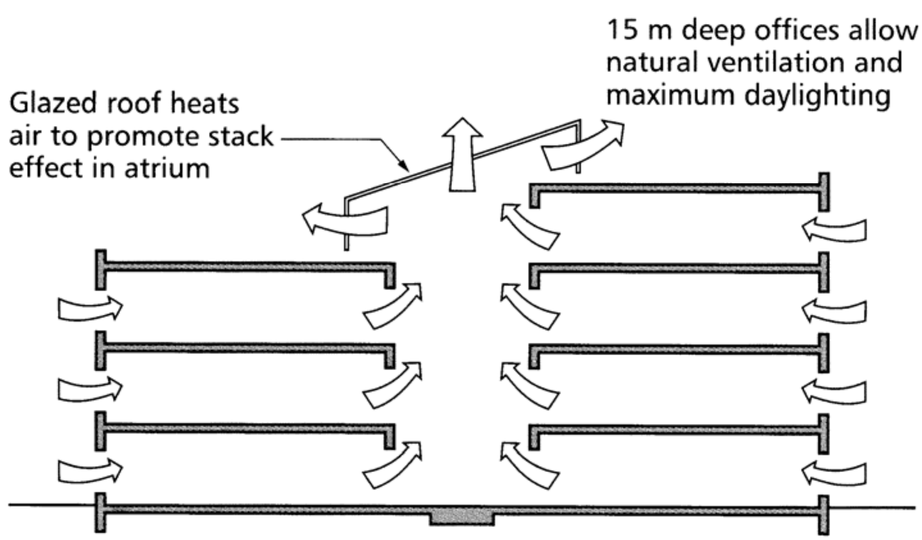


Figure 17. Atrium ventilation of an office building. /CIBSE/

Typically, different ventilation principles are applied in a specific building for different rooms and depending on outdoor climate and user behaviour. For the building principle in Figure 13C the ventilation principle will be single-sided ventilation in a cellular office, when door is closed, while it will be stack or cross ventilation, when door is open. For doors open the ventilation principle will be stack ventilation in the building in winter and intermediate season, while it will be cross ventilation in summer season, when the temperature difference is very small.

The ventilation principle has implications for both the shape of the building (e.g. its depth) and its plan layout. Single-sided-, and to some extent cross-ventilation, requires relatively narrow building plan depths, which is usually achieved with linear building forms. Stack ventilation can be used for considerably deeper building plans, and by e.g. puncturing a plan with chimneys for inlet and outlet, there are almost no limitation on building depth.

3.1.3 Ventilation element

The third aspect is the *ventilation elements* used to realise the natural ventilation strategy. Each of these ventilation elements has both a set of technical and architectural consequences and possibilities linked to it, which requires close attention of both the engineer and the architect. The most important elements are openings in the façade, wind towers, wind scoops, chimneys, double façades, atria, embedded ducts, ect.

3.1.4 Building height

Utilisation and characteristics of natural driving forces are influenced by the height of the building and lead to distinctions in the natural ventilation concepts. Wind velocity and -direction are more stable and less influenced by surrounding buildings and vegetation in a distance from ground level. The vertical distance between the inlet and the outlet can also be significant for utilization of thermal buoyancy. A tall building therefore tends to utilise other ventilation elements and principles than a low building. A logical and practical way of sorting by building height would be to distinguish between high-rise buildings (more than 10 storeys), medium-rise buildings (3-6 storeys) and low-rise buildings (1-2 storeys).

3.1.5 Supply and exhaust air paths

The supply and exhaust air path is the route ventilation air travel between the outside and the occupied spaces inside a building. The supply and exhaust paths can be local or central. A local supply and exhaust air path typically implies that several inlets/outlets are scattered on the building envelope. A central inlet/outlet in most cases need horizontal and/or vertical ductworks and/or chambers inside the building to distribute the ventilation air to the desired locations. Central airflow paths facilitate heat recovery, preheating and filtering, whereas this is harder to achieve with local airflow paths. Local paths offer on the other hand greater flexibility for future changes as they usually are organised in a modular manner (e.g. inlets located in narrow horizontal bands at every floor level across the width of the façade), and are not encumbered with being linked to a dedicated distribution network in the interiors.

3.2 System solutions and –characteristics

A natural ventilation system design is often a tailored solution based on demands for indoor climate, energy use, total costs, building design, building use and user requirements as well as user expectations. In this section typical system solutions are described and their different characteristics evaluated.

For all natural ventilation systems the most important issues are related to optimal use of driving forces and minimising the pressure losses in the system.

Natural driving forces can be increases by:

- Locating intake and exhaust with as large vertical distance as possible to increase thermal buoyancy
- Optimal use of wind conditions at the building site, i.e. by using wind towers
- Using large room heights and room volumes to even out variations in ventilation air flow rates

To minimise the pressure losses the main strategy is to aim at low air velocities in the system by:

- Efficient air distribution in the building to exploit the ventilation air optimally
- Controlling ventilation air flow rates according to demand
- Using as few ventilation components as possible
- Using ventilation components with low pressure loss through aerodynamic shape
- Using ventilation components with low pressure loss through large dimensions
- Using components that are easy to inspect and clean
- Minimising the need for distribution channels by intake of air through the façade and using direct air transfer between rooms
- Using air paths with large dimensions and good aerodynamic design, where air speeds are lower than 1 m/s at design conditions

Considering maintenance, indoor climate and air quality air distribution paths should be accessible without special equipment by:

- Passable air distribution channels – minimum height 2 m and width 0.8 m
- Short and straight channels, where passable channels are not possible
- Access of ventilation components from both up- and downstream side

Large dimensions, a large number of ventilation components and long air distribution paths are space demanding and can reduce usable building area. This can be minimised by:

- Low rise buildings (or sectioning of the ventilation system for high-rise buildings)
- Supply air through the façade or channels below occupied areas (basement)
- Exhaust air through the façade or channels above ceiling (loft)
- Supply air to the rooms through the façade (or channels) and exploit corridors and staircases as air distribution paths for exhaust air – or opposite.

Energy use for heating and cooling can be reduced by:

- Using demand controlled ventilation
- Using heat recovery
- Exploiting building thermal mass
- Using embedded ducts to reduce variations of outdoor temperature by preheating and precooling of intake air

For systems with air intake in the façade in each room, air is supplied either trough high or low positioned openings dependent on the air distribution principle used. For systems with a central air intake, air is distributed through an embedded duct to each room and is supplied to the room either trough high or low positioned openings.

The air exhaust can be located in the ceiling/roof in each room. Air can also flow via openings to corridors, common areas or atria and be exhausted through staircases, chimneys or openings in the roof. In this way optimal use of both wind and thermal buoyancy forces are ensured. Intake and exhaust openings can be constructed to take advantage of wind direction or controlled always to open in the windward or leeward side, respectively, to ensure proper air flow direction through the building.

The embedded duct can be used for passive heating and cooling of intake air and settling of large particles in the air will also take place. Filtration, heat recovery, preheating and/or cooling coils can also be installed in the duct, if necessary for conditioning the air.

The pressure loss in systems with opening in the façade is usually very low. For systems with embedded ducts careful design of the system is necessary to minimize the pressure losses in the system, especially if filtration, heat recovery, heating and/or cooling coils are included in the design. Alternatively, the system is equipped with assisting fans in cases where the natural driving forces are too low.

For buildings with several stories care must be taken in both design and control with regard to distribution of opening areas in the building to ensure inflow of air on all stories.

3.2.1 Air distribution and ventilation efficiency

For high positioned openings in the façade the aim is to supply air as an air jet and mix it with room air. However, for small driving forces or pressure differences (0,2 – 0,4 Pa) and/or low outdoor temperatures supply air will flow along the wall and drop towards the floor, see (1) on Figure 18 (Bjorn et al., 2000). Air distribution in the room will follow the displacement principle and the draught risk will be highest along the floor, (Heiselberg et al., 2001). Therefore, the opening period is often limited to a minimum in the heating season. At higher pressure differences (Dp > 4 -6 Pa) and/or higher outdoor temperatures (Dt < 5 K) the supply air flow will act as a thermal jet, see (2) and (3) on Figure 18, and traditional jet theory can be used to predict air flow path and draught risk in the occupied zone (Heiselberg et al., 2001 and 2002). For bottom hung windows close to the ceiling, the air jet will attach to the ceiling and reach further into the room with reduced air speed and draught risk in the occupied zone as a result. In the summer situation, where the temperature difference is very small, the air will act as an isothermal jet, see (4) on Figure 18.

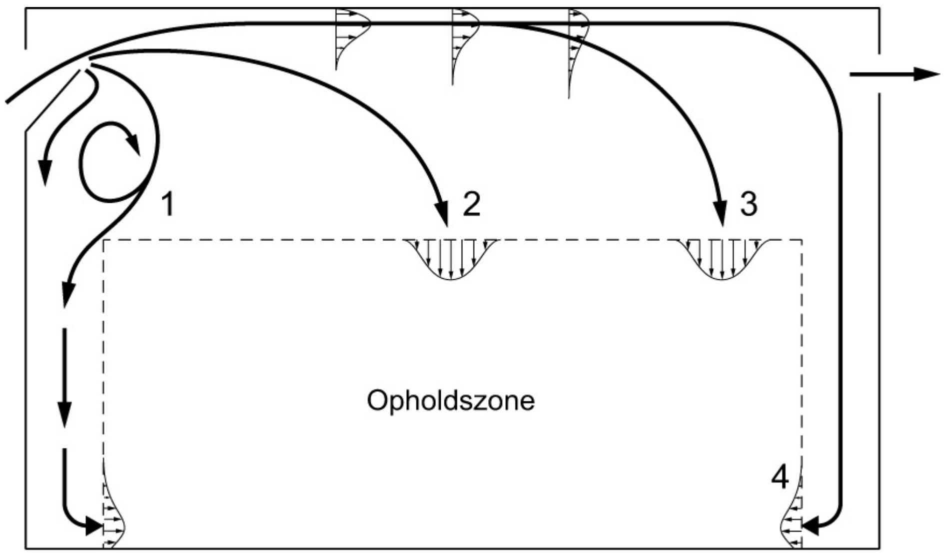


Figure 18. Typical air distribution conditions in room with high positioned openings.

For systems with passive heating in the embedded duct there is a risk for periods with low supply air temperature and draught in winter season. Therefore, careful design of openings and opening locations are needed to minimize the risk of draught. For systems with heat recovery and/or preheating the risk of draught can be eliminated.

For low positioned openings in the façade the aim is to distribute air to the room according to the displacement principle to achieve a high ventilation efficiency. Preheating with a controlled supply air temperature in the heating season is necessary to avoid draught. A number of “of the shelf” solutions are on the market as well as a number of examples of tailored solutions are seen. The pressure loss for these systems can easily be much higher than for window openings in the façade.

In many buildings a combination of openings is used with low positioned openings in the heating season (high natural driving forces) to benefit from a high ventilation efficiency and to avoid draught by preheating and with high positioned openings in the cooling season (low natural driving forces) to benefit from low pressure loss, large air flow rates and night cooling of exposed ceilings.

3.2.2 Control strategy, automatic and user control

The ventilation flow rate is often controlled by motorised openings according to time, presence detection or set points for room temperature, CO_2 concentration level and/or humidity levels depending on room size and typical use. It is an advantage to control openings as part of a system as the ventilation flow rate through an opening often is dependent on other openings. It is especially important with appropriate relation between opening areas of intake and exhaust openings to ensure proper air distribution in the building, i.e. inflow of air through façade openings on all floors in a multistory building. Alternatively, for systems with central air intake the flow rate can be controlled by a measured air velocity in a characteristic point in the supply or exhaust air duct.

User control and/or manual override of automatic control is very important as it affects user acceptance of the indoor climate positively, (Rowe 2003). It is beneficial to include openable windows in the façade, that can be controlled manually by the users dependent on the need for additional airing or ventilation on warm days. For systems with central air intake openable windows must not affect the ventilation system negatively. In situations, where the outdoor temperature increases above the indoor temperature, occupants should be advised to keep openings closed and reduce ventilation to a minimum for achieving acceptable indoor air quality.

Preheating of intake air should be controlled according to a set point temperature and must be separated from room temperature control.

3.2.3 Heat recovery

For systems with air intake openings distributed in the façade heat recovery cannot be used and demand control becomes essential for reduction of energy use. Preheating is used for low positioned opening and is often controlled by constant supply air temperature set point. In practice demand control is not as ideal as in design predictions and energy use for heating might therefore be slightly higher than predicted.

For systems with central intake and exhaust openings heat recovery is possible and the main challenge is to design for minimum pressure loss. Alternatively, a fan can assist the natural driving forces in periods, where heat recovery is beneficial.

3.2.4 Thermal comfort and indoor air quality

Intake of air through openings in the facade without preheating can result in draught problems at low outdoor air temperature. The problem can be reduced by minimization of ventilation demand and opening periods in the heating season, by room arrangement and by high positioned openings. For intake of air through low positioned openings it is important to ensure satisfactory preheating of intake air in winter to avoid draught problems along the floor. For systems with passive heating in the embedded duct the periods with low supply air temperature and risk of draught in winter season is much smaller. With heat recovery and/or preheating of air in the duct the draught risk can be avoided.

In summer time when indoor and outdoor temperatures are almost equal openable windows close to the occupied zone can increase air speed around occupants and improve comfort conditions. For systems with embedded ducts the maximum air temperature on warm days will be reduced. In the Scandinavian countries this can amount to several degrees and indoor air temperatures for well designed buildings can be kept below 25^{o}C on days with maximum temperatures up to 30^{o}C. Night ventilation will often be necessary to cool down the building, which requires burglar prove intake openings, exposed thermal mass and high ventilation air flow rates (n> 4-6 h^{-1}). In larger buildings night ventilation control needs to be automatic. Utilization of large room heights and air distribution by the displacement principle are also efficient to remove excess heat and avoid high air temperatures in the occupied zone.

Under the assumption that the outdoor air quality is good this system can provide good indoor air quality, especially when the displacement principle is used, even if filtration is not possible. There are only few ventilation components and short air flow paths that can pollute the air and it is straight forward to keep the system clean. For high positioned openings without preheating, where the ventilation air flow rate is reduced to a minimum, short periods with low indoor air quality can appear, but for rooms with a large room volume per person and periodic airing the air quality can be acceptable always. As the air speed is very low in the embedded duct, particles in the air (especially large particles) will settle in the duct and regular inspection and cleaning of the embedded duct is necessary, (Schild 2001). If constructed well no problems with moisture is seen in the Scandinavian countries, even if condensation occurs in shorter periods in summer.

3.2.5 Night ventilation

Air movement through the building during the night, when the outside air temperature is low, lowers the indoors ambient temperature and is also associated with storage of its coolness in a storage mass. The storage mass can be distributed in the structure itself, for example walls, floors, ceiling or in a specialised thermal store, such as a rock bed or water store mass. The building is kept cool during the next day, provided the windows are closed, as the cool structural mass is able to absorb the heat that penetrates through the envelope or is generated inside the building. When the storage mass is outside the building, it can be used to pre-cool the ventilation supply air or to cool the building by a closed- circuit flow. The effectiveness of night ventilation is linked to the ventilation rate, the storage area, the area that comes into contact with the flowing air and the heat capacity and thermal conductivity of the storage material.

During the night, outdoor temperatures are lower than the indoor ones. Consequently, it is possible to ventilate the building by allowing the outdoor air to enter the spaces and remove the stored heat that has been trapped during the day. The air movement increases heat dissipation from the building materials and the warmer air is then exhausted into the low temperature atmospheric heat sink. This process continues during the night and, as a result, the indoor air temperature and mass of the building are at lower levels when the temperature-increase cycle starts again the following day. Consequently, in the morning, occupants enter a cooler environment, which means that even in air-conditioned buildings, one could have substantial energy savings from the reduced operation of the mechanical system.

The design of the building should ensure a high ventilation rate through the building and especially over the storage surfaces.

The success of night ventilation depends on the relative difference of indoor and outdoor air temperatures. The lower the outdoor night-time temperatures, the higher the effectiveness of night time ventilation. It is also necessary to achieve the best possible air movement of the outdoor air through the indoor spaces. The heat convected from the mass of the building is increased by the relative velocity of the air passing over the various surfaces. The process can be facilitated by the use of ceiling fans, which will increase indoor air movement and, as a result, raise the convective heat transfer coefficient between the various surfaces and the passing air. This strategy is beneficial in climates with a large diurnal temperature swing, over approximately 15°C, where the night minimum temperature during summer is lower than about 20°C. The indoor air temperature pattern in a night ventilated building follows the outside one. In a high mass, well insulated building, shaded and closed during the day, a drop of 35-45% in the internal air temperature, relative to the outdoor temperature, is possible through night ventilation.

Night-time ventilation for cooling purposes can be successful in heavy buildings, with large diurnal outdoor temperature variations. In buildings of large thermal capacity the indoor air temperature can be close to the average outdoor temperature. Buildings where night-time ventilation techniques are applied are often equipped with specially designed windows with top openings. For reasons of safety and privacy, ground-floor windows remain closed and safety window screens are used.

3.2.6 Complexity, robustness and maintenance

As the air flow path in this system is clear and simple and the number of components and movable part are few the principle should be relative robust and require a minimum of maintenance. There can be extra costs for cleaning, for systems where intake air is not filtered.

If the system consists of a large number of openings in the façade, the automatic control requires a number of motors and control points with can be expensive and also by experience requires a long period of tuning before the system works according to the design intention for all weather conditions.

In case of a pure user controlled system periods with low IAQ can be expected, especially for systems without preheating, but also periods with excess ventilation can be seen. Automatic control of intake and exhaust opening supplemented by possibilities for user override result in a more robust solution.

3.2.7 Systems limitations

On locations exposed to varying wind speeds and directions problems with excess ventilation and draught can be experiences for systems with openings in the facade, because of rapidly changing pressure differences across openings. The system will have a limited cooling capacity, even with exposed thermal mass and night cooling. This is also the case for systems with embedded ducts and reduction of maximum supply air temperatures on warm days.

With air intakes in the facade the system cannot be used in deep buildings. Systems with central air intake are difficult to implement and requires lot of space in buildings with many room or several stories

3.3 Practical example – NCC headquarters Denmark

This example illustrates how simple calculations and considerations in the conceptual design phase can assist in the development of a natural ventilation concept for a particular building.

3.3.1 Building description

The headquarters of NCC Contractors in Denmark is an office building of five floors with a central atrium, see Figure 19. The building was finished in 2000. The design team consisting of architects, consulting engineers and NCC as contractor was supported by a specialist team mainly in the first phases of the design with the purpose of improving the indoor environmental quality and the application of passive technologies like daylighting, passive cooling and natural ventilation in the building.

Figure 19. NCC Headquarters, Denmark. View from the outside and atrium.

The building is located at the water front in the centre of Copenhagen with surrounding buildings of similar height. It is a square building and each floor has three landscape office rooms with east, north and west orientation, see Figure 20. Larger meeting rooms, the canteen and a glazed buffer zone is located towards the south. These are air-conditioned, which will prevent the solar radiation on the south façade to heat the office zones.

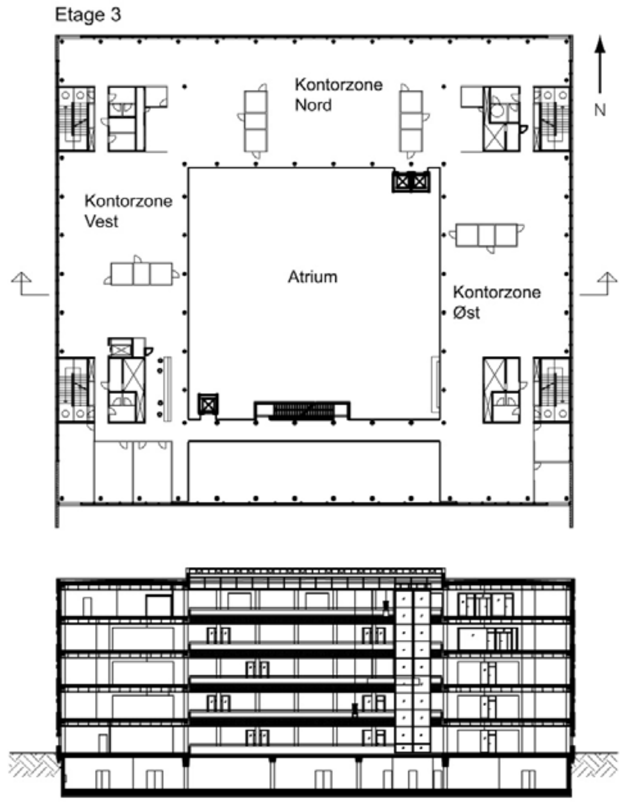


Figure 20. Plan and cross section of NCC Headquarters, Denmark.

3.3.2 Building design and constructions

In each landscape office separate zones with small meeting rooms, printer rooms and service rooms with mechanical exhaust are distributed. Zones with high heat or contaminant loads (larger meeting rooms, toilets, kitchens, etc.) are located in the corners of the building and have mechanical ventilation or air- conditioning. This reduces the heat and contaminant loads of the landscape offices and thereby the need for ventilation.

The room depth of the office zones is 15 m, the floor height 4 m and the room height 3 m. As the relation between room depth and room height is 5 cross ventilation of the office spaces is necessary to achieve acceptable conditions. This requires that the landscape offices are open to the square atrium in the middle of the building and a stack ventilation principle with air intake in the facades and air exhaust in the atrium. The building has five stories, which will create large thermal buoyancy forces in the lower floors, while it will be quite low at the upper floor, due to the relatively small height distance between intake openings and exhaust openings in the roof.

The building has fully glazed facades against south and north and in all facades it is possible to establish both small high positioned openings and larger openings close to the occupied zone.

Landscape offices have suspended ceilings and wooden floors. Only the walls in the staircases in the corners of the building have high thermal mass. Therefore, the building cannot be considered to have significant thermal mass.

3.3.3 Ventilation flow rate for indoor air quality and passive cooling

All offices are equipped with low energy artificial lighting and low energy equipment, i.e. flat computer screens to reduce the heat load, while all other office equipment is located in separate rooms with mechanical exhaust. The total internal heat gain from light and equipment can therefore be kept at about 10-18 W/m^2 floor area, depending on amount of artificial lighting, which is controlled in sections according to the level of daylight.

Windows in east and west facades have efficient external solar shading (solar transmission 19%) with automatic control and the north façade glass with reduced transmission of solar heat (solar heat transmission 41%, light transmission 65%). In this way solar radiation in landscape offices in occupied hours can be limited to an average of 5-8 W/m^2 floor area and an hourly maximum value of 10-12 W/m^2 floor area in the warmest summer month.

All materials and coverings are chosen to be low-emitting materials as well as flat computer screens are used and contaminating activities (copying, printing, etc.) are located in separate rooms. Therefore, the occupants will be the main sources of contaminants.

The large volume in the atrium will act as a buffer and even out the need for ventilation both for cooling and for providing acceptable indoor air quality. It is however difficult to predict the level of mixing between the office zones and the atrium. In the following the need for ventilation is therefore estimated in two different situations, either looking at a landscape office as a closed zone or at the landscape offices as open to the atrium with full mixing of air between offices and the atrium.

In the heating season indoor air quality will be the determining factor for the ventilation flow rate. When occupants are the main sources the CO_2 concentration can be used as an indicator for the indoor air quality. The building should be designed for an occupant load in the offices zones corresponding to $10m^2$ floor area/person of which only 85% is present at the same time. If the office zone is regarded as separated from the atrium, this corresponds to an air volume of 35 m^3/person. If the air in the office zone is regarded as fully mixed with the atrium air, it corresponds to an air volume of 61 m^3/person. Figure 21 shows the CO_2 concentration as a function of time for different ventilation flow rates and strategies. If the ventilation flow rate is limited to infiltration ($n = 0.3\ m^3/h$, which is quite high due to mechanical exhaust from the building) the CO_2 concentration will exceed the target of 1000 pm after a period of 1.5-3 hours, depending on the amount of mixing between offices and atrium. If the infiltration flow rate is supplemented by periodic airing ($n = 6\ h^{-1}$) by window opening in 12 min an average concentration level of 1000 ppm can be achieved by less than 2-4 hours between consecutive opening periods, depending on the level of mixing.

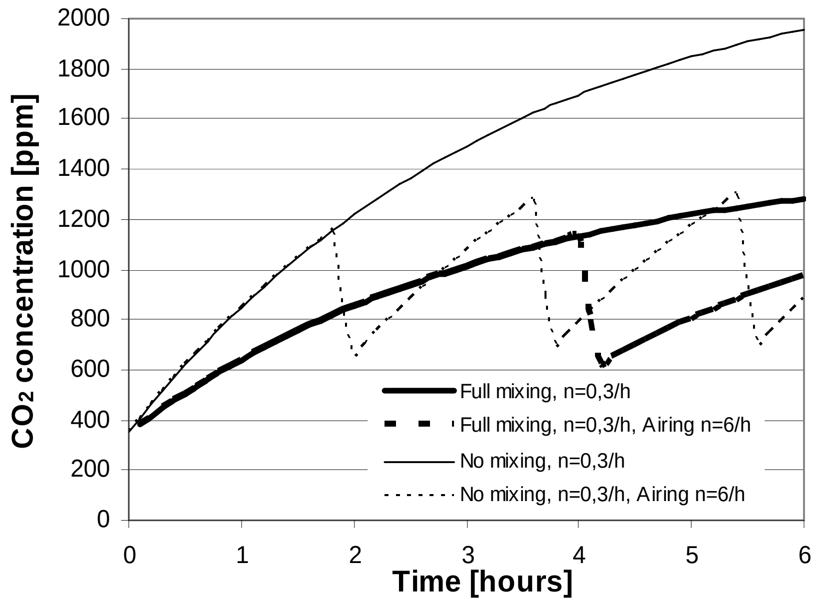


Figure 21. CO_2 concentration as a function of time for different ventilation flow rates and strategies.

In the summer period (cooling season) the ventilation flow rate will be determined by the need for passive cooling. The necessary ventilation flow rate in the summer period for passive cooling of the whole building is found by using the simplified method described in the appendix. Figure 22 shows the necessary ventilation flow rate for both an average day and the warmest day in each month and both with and without solar shading. The necessary ventilation flow rate is quite small ($n = 1\text{-}2\ h^{-1}$), due to the very low heat loads in the buildings, compared to typical air exchange rates of $n = 4\text{-}6\ h^{-1}$ in Danish office buildings.

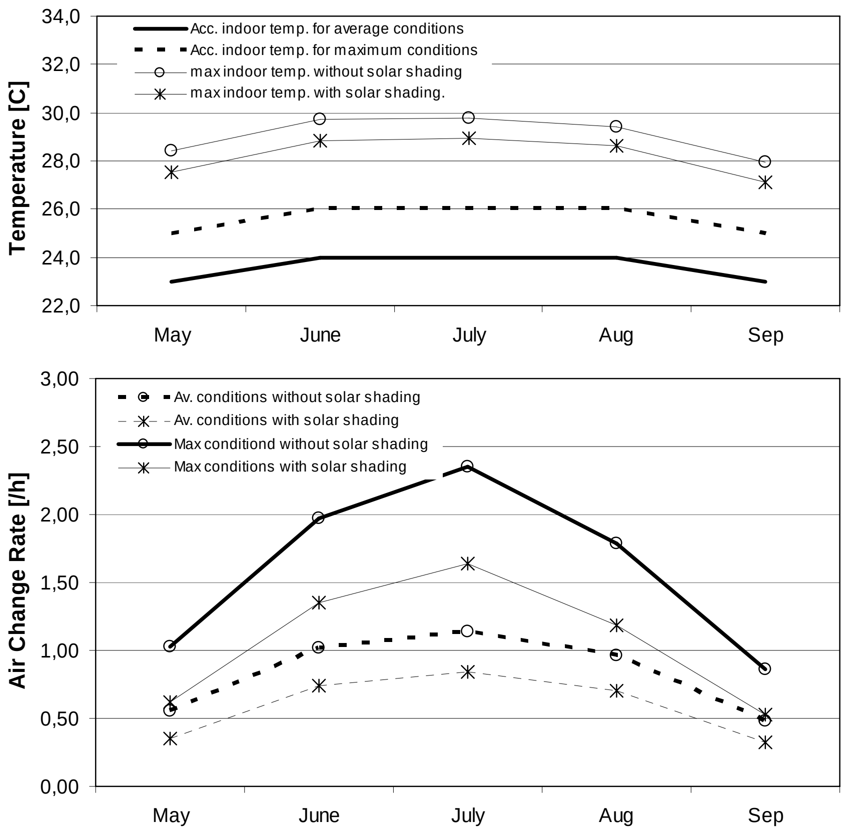


Figure 22. Necessary air change rate for passive cooling in the summer period and calculated maximum temperatures.

3.3.4 Control strategy, automatic and user control, thermal comfort and indoor air quality

In the heating season an acceptable indoor air quality can be obtained by infiltration and periodic airing by window opening. During the 2-3 short airing periods each day air velocities and low temperatures will cause draughts and the solution can only be used, if this is accepted by the occupants. Alternatively a solution with preheating needs to be established. The opening period and time between airing periods can be controlled by a timer or by a CO_2 sensor. A timer is preferable because airing periods are known to the occupants and they can act accordingly. The time between airings can initially be set according to calculations and be adjusted during the tuning of the systems. In cases of extreme conditions (large number of occupants) a CO_2 sensor could prevent the indoor air quality to exceed a certain maximum level. Individual preferences can be ensured by implementing a possibility of the occupants to manually override the automatic control system.

In the summer season a continuous air change rate of n = 1-2 h^{-1} is necessary. This can be controlled by a temperature sensor. As the wind forces can be very different at the different facades, separate control for each façade is necessary. In order to take into account the pressure differences on each façade, the control could even be divided in several zones per façade. In the present case three zones per façade is chosen. In situations with extreme weather conditions additional openings, that can be controlled manually by the occupant is useful. In periods where outdoor temperatures are above indoor temperatures the control strategy should minimise ventilation. Indoor air quality should be the determining parameter and occupants should be advised to keep manually openable windows closed. Night ventilation is necessary in the building to cool it to an acceptable starting temperature in the morning.

In some buildings the intermediate season requires and additional control strategy. In this case it is not necessary as the necessary ventilation flow rate in this period is very small, see figure 6 for May and September. The needed ventilation flow rate for cooling corresponds to the needed air flow rate for acceptable indoor air quality, which for an air flow rate of 10l/s person will be $n \approx 1\ h^{-1}$.

3.3.5 Air distribution principles and opening locations

The ventilation principle applied the building is stack ventilation with air intake in the façade, air flow across the landscape offices and exhaust through opening in the roof of the atrium. As no preheating is included, small openings located far from the occupied zone will result in the best thermal comfort conditions. Therefore, openings are located close to the ceiling. Narrow openings along the whole length of the façade are used as they can be opened during the night too. The air distribution principle will be mixing.

To improve to possibility of occupants to control ventilation all openings can be controlled by the occupant. High positioned openings are automatically controlled with manual override by the occupants, while larger openings close to the occupied zone can only be controlled manually.

The openings in each landscape office is divided into three zones to improve the possibility to fine tune the system according to the local wind and surface pressure conditions as well as user preferences.

3.4 Conclusions

Natural ventilation is a sustainable, energy-efficient and clean technology that is well accepted by occupants. It can be used to provide fresh air for the occupants, necessary to maintain acceptable air quality levels, and to cool buildings in cases where the climatic conditions allow it. Successful application of natural ventilation techniques are determined by the prevailing outdoor conditions and microclimate as well as building design and building use. Therefore natural ventilation systems need to be designed together with the building.

Integrated design of the heating, cooling, lighting and ventilation of buildings can be accomplished in three separate steps, where the first step includes design of the building itself, the second step the climatic design of passive systems and the third step consists of design of mechanical equipment. In this way heat and contaminant loads as well as the need for mechanical equipment can be reduced greatly and the limited capacity of natural ventilation systems will suffice.

Natural ventilation concepts can be defined by five characteristic aspects: Natural driving force, Ventilation principle, Ventilation element, Building height and the Supply and exhaust air paths. A natural ventilation system design is often a tailored solution based on demands for indoor climate, energy use, total costs, building design, building use and user requirements as well as user expectations.

4 HYBRID VENTILATION STRATEGIES

There is a wide range of hybrid ventilation strategies and the concepts vary widely in the level of building integration and industrialization (de Gids, 2001; Wouters et. al., 1999 and 2000). In order to characterize a hybrid ventilation strategy it is necessary to describe the hybrid ventilation principle, the control strategy for IAQ and summer comfort, the specific boundary conditions and components as well as the level of building integration.

4.1 Characterisation of hybrid ventilation principles

The main hybrid ventilation principles are:

- **Natural and mechanical ventilation**
  This principle is based on two fully autonomous systems where the control strategy either switches between the two systems, or uses one system for some tasks and the other system for other tasks. It covers, for example, systems with natural ventilation in intermediate seasons and mechanical ventilation during midsummer and/or midwinter; systems with mechanical ventilation during occupied hours and natural ventilation for night cooling; or systems with a mechanical system for task ventilation and/or cooling and a natural system for building ventilation.

- **Fan assisted natural ventilation**
  This principle is based on a natural ventilation system combined with an extract or supply fan. It covers natural ventilation systems which during periods of weak natural driving forces or periods of increased demands can enhance pressure differences by mechanical (low-pressure) fan assistance.

- **Stack and wind supported mechanical ventilation**
  This principle is based on a mechanical ventilation system that makes optimal use of natural driving forces. It covers mechanical ventilation systems with very small pressure losses where natural driving forces can account for a considerable part of the necessary pressure.

4.1.1 Indoor air quality control

Acceptable indoor air quality can be achieved by either of the above ventilation principles. Demand controlled systems are important during periods of heating and cooling demand, as the control strategy needs to focus on achieving an optimal equilibrium between IAQ and energy use. The level of demand control can vary from manual by occupants, simple timer control, motion detection to direct measurement of IAQ.

4.1.2 Control of summer comfort

Acceptable thermal comfort conditions can be achieved by passive means (free cooling with outdoor air, free cooling in embedded ducts, night cooling, etc.) or by a combination of passive means and active cooling (cooled ceilings, air conditioning) during extreme weather conditions. The control of room temperature during occupied hours can be either manual or automatic.

4.1.3 Specific boundary conditions and ventilation components

There are only a few real hybrid ventilation components as such. In most cases hybrid ventilation systems consist of a combination of components, which can be used in purely natural systems or in purely mechanical systems. However, the availability of appropriate components is essential for the successful design and operation of a hybrid ventilation system to handle the specific boundary conditions of the site and the building like draught control, security, air preheating, outdoor air pollution and noise and fire regulations. To facilitate combining natural and mechanical forces in the air distribution system, appropriate components can include:

- Low-pressure ductwork,
- Low-pressure fans with advanced control mechanisms such as frequency control, air flow control, etc…
- Low-pressure static heat exchangers and air filters,
- Wind towers, solar chimneys or atria for exhaust. Underground ducts, culverts or plenums to pre-condition supply air.

To facilitate the control of thermal comfort, indoor air quality and air flow in the building, appropriate components can include:

- Manually operated and/or motorised windows, vents or special ventilation openings in the façade- and in internal walls,
- Room temperature, CO_2 and/or air flow sensors,
- A control system with weather station

4.1.4 Level of building integration

Hybrid ventilation strategies can vary widely in the level of integration with the building. An integrated approach is a necessity for all hybrid ventilation systems, but the integration of the building and the ventilation system is more important when natural ventilation plays a dominant role. In extremes cases the whole architectural concept and installation design is fully linked and integrated. In this case, a very close collaboration between architects and mechanical engineers is essential.

4.2 Practical Solutions

Quite a number of hybrid ventilated buildings have been built around the world. In this chapter the characteristics of typical hybrid ventilation systems are illustrated by a few built examples. Specific components for hybrid ventilation are not yet available, but typical solutions are described.

4.2.1 Existing office and educational building examples

The following few examples show the state-of-the-art with regard to ventilation systems, control strategies, ventilation components, thermal comfort, IAQ and energy use. The examples include both office and educational buildings.

The Liberty Tower of Meiji University

Location:

Tokyo, Japan

Architect:

Nikken Sekkei Ltd.

HVAC Engineers:
Nikken Sekkei Ltd

More information:
Chikamoto 2002

Building description and system integration	A new 23 stories high-rise building located at the centre of Tokyo Metropolitan area. The natural ventilation system, especially the central core and the wind floor, are integrated with the building design.
Ventilation principle and components	Natural and mechanical ventilation. The ventilation system consists of a natural ventilation system for controlling indoor air quality and temperature in intermediate seasons, and a mechanical air-conditioning system for the rest of the year, when the outdoor climate is not comfortable. In the natural ventilation system air enters via perimeter counter units on every floor and is exhausted through openings at the top of the centre core. The central core is designed to utilize the stack effect at each floor and above the centre core a wind floor is designed to enhance driving forces from the wind. As the wind floor is open to four directions the driving force is expected to be stable through the year regardless of wind direction
Control of indoor air quality and summer comfort	Outdoor air intake control is based on CO_2 and temperature sensors and is controlled via a BEMS. The system includes automatically controlled natural ventilation windows at night with an automatic intake of outdoor air and wind floor outlets. In the mechanical air-conditioning system the supplied air flow rate is controlled by a VAV system, where the fresh air flow rate is automatically controlled based on indoor CO_2 concentration and the air flow rate and inlet temperature is controlled by room temperature and humidity sensors.
Building performance	The use of the natural ventilation system reduces the annual average energy use for cooling the building by 17%, ranging from 90% in April (Spring) to a minimum of 6% in July (Summer), and continues to reduce cooling to about 62% in November (Autumn). The wind floor design on the 18th floor increases the ventilation rate by an average of 30%. Acceptable thermal comfort and IAQ conditions were achieved. The most significant problem was encountered close to the low-positioned openings, where occupants experienced draughts. Another problem was high pressure loss in overflow ducts with smoke and fire dampers between rooms and the centre core.

B&O Headquarters

Location:

Struer, Denmark

Architect:

KHR Architects A/S

HVAC Engineers:

Birch & Krogboe A/S

More information:
Hendriksen et al. 2002

Building description and system integration	A new three-storied and narrow (width 8.3 m) open plan office building located in the outskirts of a small city. The natural ventilation system is integrated with the building design.
Ventilation principle and components	Fan assisted natural ventilation. Inlets are low-positioned narrow hatches (windows) located in front of the floor slab. Inlet air is preheated with a ribbed pipe to improve thermal comfort and distributed by the displacement principle to improve ventilation efficiency. Air flows through the occupied space to the staircase and is extracted from the top of the staircase. If needed the system is assisted with a fan located in a cowl on the roof. The glass facade with ventilation hatches is facing north and has no solar shading. The south facade has a moderate window area with user-controlled windows, which are automatically controlled for night cooling.
Control of indoor air quality and summer comfort	The ventilation system is demand-controlled by temperature and CO_2 sensors in the offices and run with a constant air flow rate of 1.5 ach in daytime and 3.0 ach in summer during night cooling. The constant-flow is achieved by measurement of the air speed in the extract hood. When ventilation is needed, the hatches and the dampers in the extract cowl open. If the necessary ventilation air flow rate is not achieved by natural means the fan speed is controlled. The hatches on each floor are controlled by the temperature and CO_2 level of the floor. The ventilation is controlled by a building management system with a weather station on the roof. If the external temperature is below 5 ^oC the ventilation system is shut down to protect the ribbed pipes and the window hatches from freezing. The ventilation system is also shut down in case of rain or high wind speeds.
Building performance	The initial cost of the system is only about 60% of a conventional system. The displacement air distribution principle works quite well, resulting in a high ventilation efficiency. Energy use of the assisting fans are very low (1,7 kWh/m^2 year) and accounts for only about 3% of the electrical energy use. The measured IAQ (CO_2 used as an indicator) was very high. The energy demand for heating was remarkably higher than expected. This can be related to the large areas for transmission heat loss, a very large glazed area towards the north, and an infiltration rate larger than expected.

Mediå School	
Location: Grong, Norway	
Architect: Letnes Arkitekter A/S	
HVAC Engineers: SINTEF and NTNU	
More information: Tjelflaat 2002	
Building description and system integration	A new single-story school building located in a small town. The hybrid ventilation system is fully integrated with the building design.
Ventilation principle and components	Stack and wind supported mechanical ventilation. It is a balanced, low-pressure mechanical system with both air supply and extract in the classrooms. Air is taken from an inlet tower at some distance from the building, that utilizes wind forces and where the inlet fan is located. Air flows through an underground culvert with large thermal mass to reduce daily temperature swings, and is distributed via a purpose-made basement corridor to low-positioned supply air terminal devices in classrooms to increase ventilation efficiency. Air is extracted from classrooms through a high-positioned hatch into a purpose-made lightwell corridor and exhausted through a roof tower with outlet valves that ensure suction by wind from any direction. A heat recovery unit and a low-pressure exhaust fan are located in the tower. The system also includes filtering, preheating of the ventilation air, and heat recovery with bypass, which is located in the basement between the underground culvert and the basement corridor. The flow is driven by low-pressure fans in the supply and extract, supported by wind and stack effects. Window opening is possible and the ventilation system will normally adapt to it.
Control of indoor air quality and summer comfort	Ventilation is demand-controlled by a CO_2-sensor in each classroom. If the CO_2 level exceeds the set point the extract hatch is opened and adjusted by a motor. The supply fan is controlled by the pressure in the basement supply corridor to 2 Pa overpressure compared to the external. The extract fan is controlled to maintain a 5 Pa pressure drop between the basement supply corridor and the lightwell extract corridor to avoid overpressure in the building. Both fans are frequency controlled. The ventilation is controlled by the building management system.
Building performance	The performance shows acceptable indoor air quality and thermal comfort. The cooling effect of the underground culvert and the basement corridor is higher than expected. The energy use corresponds to the reference consumption in Norway, but is higher than predicted. The reasons for this are initial failures in the control system (now solved), and under-prediction of the energy loss by cold bridges and energy use by BEMS, pumps, etc.

Wilkinson Building		
Location: Sydney, Australia		
Architect:		
HVAC Engineers: McConnel, Smith and Johnson, Sydney		
More information: Rowe 2002 and 2003		

Building description and system integration	A five-story cellular office building located in a suburban area of Sydney. Built in 1978 and renovated in 1997. There is no integration of hybrid ventilation systems and building design.
Ventilation principle and components	Natural and mechanical ventilation. The natural ventilation is mainly wind driven by window airing and with possibility of cross flow through corridors. Each cellular office is equipped with an occupant controlled supplementary Variable Refrigerant Flow (VRF) heating/cooling fan-coil system. Air distribution is by the mixing principle. There is no night ventilation and solar shading is manually controlled.
Control of indoor air quality and summer comfort	The control strategy is laissez faire. Window airing and door opening is controlled manually by occupants. The fan-coil units are operated by occupants, but are disabled at 9pm and midnight to save operation cost. The system is however immediately available for re-start if required. Fan-coil units are controlled by room temperature with the setpoint controlled by the user. The occupant can also control fan speed and air flow direction.
Building performance	Occupants perceive thermal comfort and air quality better than reported by occupants in 36 other (mainly air conditioned) settings. Air quality depends on window adjustment , but an average CO_2-concentration of 930 ppm was measured in winter. Fan-coil units tend to default to “off”; i.e. if conditions in a room are acceptable then the system is not turned on. Occupants prefer to open windows and doors in pleasant weather but close them when hot dry or warm humid winds occur in summer or on the colder days in winter. Energy use over four years has averaged about a quarter of what is typical of spaces with conventional mechanical heating, cooling and ventilation.

Tånga School

Location:
Falkenberg, Sweden

Architect: Christer Nord-ström Arkitektkontor AB

HVAC Engineers:
J&W Consulting Engineers

More information:
Blomsterberg et al. 002a, l

Building description and system integration	A two-story school building located in a residential area in the city of Falkenberg. Built in 1968 and renovated in 1997. There is some integration of hybrid ventilation systems and building design.
Ventilation principle and components	Fan assisted natural ventilation. Three air intakes are positioned below windows in each room and air is preheated by convectors. Air is distributed by the mixing principle. Air is exhausted below the ceiling and evacuated through a vertical ventilation duct. Local dampers are mounted both in the air intakes and in the exhaust duct from each room. To increase stack effect a 6 m high passive stack and solar chimney have been installed on the roof with assisting fan and a central damper mounted in parallel. The pressure drop in the air distribution system is very low. Low-pressure vents in the façade and low pressure exhaust air terminal devices are used. There are no filters, large ventilation ducts and no heat recovery. Window airing is possible at any time. Night cooling can be used
Control of indoor air quality and summer comfort	The control system is a combination of individual and central control. A CO_2 sensor in each room controls the local inlet and outlet dampers. At a CO_2 level of 1000 ppm or less the local dampers are set to a minimum open position, which can be varied as a function of the outdoor temperature. At low outdoor temperatures the air flow rate is therefore automatically limited to prevent excessive energy use and problems with dry indoor air. If the CO_2 level exceeds 1000 ppm, this is indicated by a signal lamp in the classroom. At CO_2 levels above 1500 ppm the local dampers open 100%. The teacher can always override the local control system and manually change the position of the local dampers between 50% and 100%. At low temperature differences the fan is started and the central damper is closed. The fan is frequency controlled. The fan speed is controlled by the pressure difference across the fan, which is increased as the temperature difference decreases.
Building performance	The occupant perceived the indoor climate as rather good. The CO_2 concentration is mostly around 1000 ppm or lower and only for short periods (10-20 minutes) higher, but very seldom above 1500 ppm. The personnel appreciate that the system can be operated manually and do so fairly often. 30% reduction in energy use for space heating, 55% in reduction in use of electricity for ventilation and 45% reduction in use of electricity for lighting was realised.

4.2.2 Ventilation components

The availability of appropriate components is essential for the successful design and operation of a hybrid ventilation system. Some components are fully integrated with the building design, while others are of-the-shelf components or traditional ventilation components adjusted for use in hybrid ventilation.

In hybrid ventilation building-integrated components for the natural ventilation mode play a very important role. Apart from strongly characterizing the building architecture, these components, if well designed, allow supply, distribution and extraction of air from the building at very low pressure drops. Almost all new built designs apply building-integrated components. Besides building integrated components there exist only a few real hybrid ventilation components as such. Most hybrid ventilation systems apply a combination of components, which can be used in purely natural systems or in purely mechanical systems. However, to handle the specific boundary conditions of the site and the building like draught control, security, air preheating, outdoor air pollution and noise or fire regulations some adaptation is essential for the successful performance of a hybrid ventilation system. This section briefly summarizes some typical components used in hybrid ventilation systems.

4.2.3 Enhancing natural driving forces

The effect of wind forces can be enhanced by the use of wind towers, Tjelflaat (2002). Openings in the towers can be controlled by a weather station, so for intake towers openings open on the windward side and for exhaust towers on the leeward side. A special solution of the Liberty Tower of Meiji University, Chikamoto (2002a), is the wind floor, where large openings in four directions allows wind to cross the floor and thereby enhance the driving forces from the wind on the exhaust stack. It is expected that the ventilation flow rate is increased by 30%. Wind turrets and roof cowls must be designed to ensure negative pressure at the opening for all wind directions both to enhance the natural driving forces but also to avoid backflow in the system, Hendriksen et al. (2002). The stack effect can be enhanced by stacks and/or solar chimneys, Blomsterberg et al. (2002).

4.2.4 Ensuring low pressure drops

In hybrid ventilation low pressure drops in the air paths is ensured by avoiding the use of ducts, by using other components to transport air, e.g. corridors, stairwells, atria, (Hendriksen er al. 2002; Chikamoto, 2002a, b; Tjelflaat, 2002; Meinhold et al., 2002; Principi et al., 2002) or by using large ducts. Windows or similar openings results in very small pressure losses. In cases where these openings are not suitable, i.e. because of the need for preheating, air filtration, sound attenuation or security, it is important that low-pressure intake vents and exhaust terminal devices with low pressure drop dampers are used (van der Aa, 2002; Heijmans et al., 2002; Blomsterberg et al., 2002, Elmualim et al. 2002). This is often ensured by choosing large component sizes, as it is also the case with static heat exchangers and air filters. There are not yet specially designed low pressure components on the market.

4.2.5 Ventilation openings

Ventilation openings for air intake must besides having a low pressure drop also provide air according to the need of the occupants and without creating unnecessary draught risk in the occupied zone. Zeidler et al. (1999) investigated the cooling capacity for an office room with two windows close to the occupied zone. It was concluded that the draught risk was to high for outdoor air temperatures below about 10-12^{o}C, depending on the window construction, and that the cooling capacity was in the range of 25-40 W/m^2 for a room depth of 4.5 m. It was emphasized that windows of different sizes and positions with adjustable window panes was needed in future designs to provide occupants with opportunities for adjusting volume flow and thermal comfort conditions.

Heiselberg et al. (2001), (2002) and Wildeboer et al 2002 investigated comfort conditions for air flow trough different types of window openings. It was concluded for a single-sided ventilation strategy that the high-positioned bottom hung window was the best choice in winter because air was supplied outside the occupied zone and was easily controlled by changing the opening angle. A side hung window close to the occupied zone was not a good choice as air was supplied directly to the occupied zone and was difficult to control, because the amount of air and the velocity levels increase very rapidly with increasing opening angles. In summer with small temperature differences the bottom hung window will not be able to supply enough air to the room, but will have to be combined with a side hung window. For a cross- or stackventilation strategy the bottom hung window was the best choice in winter because the air travels the largest distance and mixes with room air before it reaches the occupied zone. For the side hung window the problems are even worse compared to the single-sided situation because the pressure difference is increased.

Trickle ventilators are also used in hybrid ventilation systems and with the development of both passive and electronic self-regulating trickle ventilators with direction-sensitive flow sensors they offer good opportunities for control of both air flow and comfort. Low-positioned adjustable intake grills are often used in cases where preheating and air filtration is needed, either as stand-alone units (Elmualim, 2002) or in combination with perimeter radiators.

4.2.6 Energy conservation

The possibility of heat recovery depends of the ventilation principle. For systems based on the natural and mechanical ventilation principle, the mechanical ventilation system are often equipped with heat recovery as this often is the main reason for choosing this principle, especially in cold climates. For other hybrid ventilation principles heat recovery can only used in systems with central intake and exhaust of air and the typical solution is heat exchangers with water circulation, (Tjelflaat, 2002).

Passive cooling, including automatically controlled solar shading devices, is adopted in many buildings as well as the use of underground ducts, culverts or plenums to precondition the supply air are often seen (Tjelflaat, 2002; Schild, 2002, Narita et al. 2002). Underground culverts can be quite effective both for preheating of intake air in winter, especially for culverts in the basement of buildings, and precooling in summer and the performance is often better than expected from predictions, (Wachenfeldt, 2003).

4.2.7 Air filtering

Filtering of intake air is not very common in existing buildings with hybrid ventilation. Traditional back filters are used and the pressure loss across the filter is reduced by a large face area, (Tjelflaat, 2002).

Underground culverts and in air intake ducts has a measurable filtration effect due to settlement of particles, especially large particles, Schild (2001). For a 60 m culvert the amount of particles with sizes above 0,3 μm was reduced by 85% and for particles above 10 μm with 95%.

4.2.8 Draught

To avoid draught risk, buildings located in the coldest areas with distributed air intakes preheat supply air by means of specific components (diffusers or fan coils), or by means of radiators located below windows, (Hendriksen 2002, van der Aa 2002, Blomsterberg 2002). In buildings with central intake, air is preheated in the intake duct and supplied to rooms by low-velocity low level diffusers, (Schild 2002, Tjelflaat 2002).

4.3 Hybrid Ventilation Control

In hybrid ventilation the control is as important as the ventilation system itself and there is a strong interaction between the ventilation system and the control system. It is therefore important that the ventilation system and the control system are designed together in one process. Many of the hybrid ventilation components are also integral parts of the building. This makes a strong co-operation between the architect, the HVAC engineer and the control engineer necessary.

4.3.1 Control Strategies

Hybrid ventilation systems can be made quite complex. However, it is very important to develop a control strategy and design a control system that is easy to understand for the users and can be operated by the maintenance staff. Therefore, simplicity and transparency of the user/system interface is of the utmost importance. Control system designers need to recognise that most users are not technically literate and are not interested in learning complex operations to suit varying outdoor conditions. They want a system that responds to their needs unobtrusively and allows them to change a condition if it is perceived as unsatisfactory, with rapid feedback.

The control strategy for a building should at least include a winter control strategy, where IAQ normally is the main parameter of concern, and a summer control strategy, where the maximum room temperature is the main concern. It should also include a control strategy, to be used in the interval between winter and summer, where there might occasionally be a heating demand as well as excess heat in the building.

Demand control is very important in hybrid ventilation systems, and in many case demand control also proved to be very energy-efficient. However, one of the main problems encountered in automatic control of indoor air quality is the cost and reliability of CO_2 sensors used to control the ventilation demand, Willems et al. 2002. If a sensor is needed in each building zone, it can become expensive both in initial cost and in regular calibration. In some cases the ventilation demand was controlled by infrared detection. The major advantage of this system is its relatively low cost (compared to CO_2 sensors) and its autonomy (it can work on a long-life battery, no wiring is required). The major disadvantage is that the airflow is only indirectly correlated to the demand. Sometimes the airflow can be too low, or too high. Presence detection can be a good way to control the ventilation demand in rooms with low occupancy variation, such as cellular offices. In some cases it has also been successfully applied in school classrooms. For rooms such as conference rooms, a CO_2 strategy is more suitable because it usually better estimates the real needs. There is a strong need for reliable and cheap CO_2 sensors to be developed.

Both the hybrid ventilation strategy and the control strategy are significantly influenced by the general climate in the region where the building is located. In cold climates the control strategy should focus on minimising the ventilation energy needed to achieve good IAQ, and on achieving a good indoor climate in summer and spring without mechanical cooling. In warm climates the control strategy should focus mainly on reducing the energy consumption for mechanical cooling in summer.

4.3.1.1 User interaction

One of the advantages of natural ventilation systems is higher user satisfaction due to individual control of windows and indoor environmental conditions, Rowe (2003). If possible this feature should be maintained in the control of a hybrid ventilation system even if it could conflict with the possibility of guaranteeing a specific level of indoor thermal comfort or air quality in the rooms. Unfortunately the relationship between the indoor climate and user acceptance in user-controlled rooms is not well known. Recent research indicates that users are more tolerant of deviations in the indoor thermal climate if it is controlled by themselves, see de Dear 1999.

Occupants want to be able to alter conditions quickly in response to unpredictable events (like glare, draughts, or noises outside). If conflicting or unsatisfactory conditions occur, occupants want to decide for themselves, how to resolve the conflicts by overriding default settings rather than having conditions chosen for them. Occupants demonstrate a tendency to use supplementary mechanical cooling/heating equipment sparingly and in an energy-efficient way, Rowe (2002), and prefer to use operable windows and other adaptive behaviours to modify conditions. Most occupants do, however, appear to have an upper “tolerance” limit, when active intervention will be applied if the opportunity is available. This upper tolerance limit will be very individual and can be different from day to day, Rowe (2002).

Even though users should have the maximum possibility of controlling their own environment, automatic control is needed to support the users in achieving a comfortable indoor climate and to take over during non-occupied hours. In rooms for several people, e.g. open-plan offices, and in rooms occupied by different people, e.g. meeting rooms, a higher degree of automation is needed. In some cases, Meinhold and Rösler (2002), users strongly appreciated the manual control and refused a fully automatic system, but measurements showed that the mechanical system was seldom applied and that the air quality in some periods was very low. Automatic control is also needed during non-occupied hours to reduce energy use and to precondition rooms for occupation, i.e. to provide and control night cooling.

4.3.1.2 Typical strategies

Recommendation for typical control strategies for office and educational buildings are given in Aggerholm (2002a).

Users greatly appreciate the possibility of manually controlling the indoor environment and full responsibility of occupants for controlling their own indoor climate during occupied hours can work very well in cellular offices, Rowe 2002. The individual control can be either manual or motorised. During non-occupied hours automatic control is needed for cooling of the building structure by night ventilation, as occupants do not according to their needs of tomorrow.

In landscape offices automatic control is needed, but it can be difficult to find an acceptable strategy for window control, that satisfies all occupants. If windows are operated automatically during occupied hours, and the external temperature is more than a few degrees lower than the room temperature, there is a great risk of user dissatisfaction due to the sensation of draft. Therefore, it is important that occupants have a possibility to override the control for openings close to their work station.

If the inlet air is preheated, the best solution is to have separate control of the inlet temperature, because preheating of the inlet air can be needed even when there is excess heat in the room, van der Aa (2002). This is especially important to consider in cases where openings are below windows and perimeter radiators are used for preheating of intake air. There is a risk that the inlet temperature set point will be raised to compensate for insufficient room heating. This is very critical for systems with low-positioned low-velocity inlet diffusers, because the displacement air distribution principle can be destroyed with very low ventilation efficiency as a consequence. The control of the outlets and of night ventilation seems less problematic.

In classrooms a simpler control strategy and control system is often installed with manual control and supplementary window airing in breaks. With the high density of occupancy, the CO_2 level quickly exceeds the limit in winter, if assisting fans or mechanical ventilation systems are not operating. In schools, where the occupants were responsible for the indoor air quality control, there is a great risk of high CO_2 concentrations for some of the time, Meinhold et al. (2002). This risk also applies in classrooms where the inlet air is preheated. Automatic control or a combined manual and automatic control strategy is therefore advisable in school buildings with the possibility of manual override, Blomsterberg 2002.

In buildings that also have active mechanical cooling, where the operation mode is automatically switched between hybrid ventilation and mechanical cooling depending on the temperature or enthalpy difference between external and internal air, there is a risk that once activated the system will stay in active cooling mode.

4.3.2 Control Tasks

The control strategy should determine both time and rate control. It should also determine different control modes in relation to different weather conditions. The actual control strategy should reflect the demands of the building owner, the needs of the users and the requirements in standards and regulations. Recommendations for typical control tasks for office and educational buildings are given in Aggerholm (2002a) and Heiselberg (ed.) 2002.

4.3.2.1 Indoor air quality

The control of ventilation for indoor air quality can either be manual by the occupants, simple timer control, motion detection (occupants present), based on direct measurement of indoor air quality, or a combination of these. For direct measurement of indoor air quality the CO_2 concentration is a useful indicator, if occupants are the only or dominating pollutant source. If other significant sources influencing indoor air quality are present, e.g. pollutants from materials and cleaning, then the CO_2 concentration in the room may be less satisfactory as indicator.

In small rooms with work desks for one or a few people, e.g. cellular offices, it can normally be expected that the occupants will be able to control the indoor air quality to their own satisfaction, if the ventilation system provides them with the necessary facilities, e.g. user-controlled windows and vents of different sizes and positions.

In large rooms for many people, e.g. landscape offices, and in rooms occasionally occupied by different people, e.g. meeting rooms, automatic control of ventilation for indoor air quality is normally needed. The purpose of the control in this case is to reduce the ventilation energy consumption by limiting the operating hours and the ventilation rate according to the occupancy pattern. The optimum strategy should have both a good user control to allow occupants to adjust conditions locally at their work station and an automatic back up.

Even during non-occupied hours there might be a need for indoor air quality controlled ventilation, especially in tight buildings. This includes ventilation after the end of the occupancy period, to remove built-up pollution, ventilation during non-occupied periods to remove pollution from materials and cleaning and ventilation before occupancy to start the occupancy period with fresh air in the building.

4.3.2.2 Thermal comfort and draught

Room temperature control during occupied hours in summer can be either manual or automatic. Occupants do have a very clear sense of their own thermal comfort, but typically they react too late, when the temperature already is above the acceptable temperature limit. Automatic control of openings as well as solar shading can be beneficial, as it ensures action as soon as the indoor temperature begins to increase. The need for direct automatic control of room temperature during occupancy is mainly related to large rooms catering for many people and to rooms occasionally occupied by different people. Direct automatic control of room temperature is also necessary, if comfort is achieved by mechanical means, e.g. mechanical cooling or additional mechanical fan-forced air flow.

In summer the normally small difference between indoor and external air temperature on warm summer days has limited potential to reduce the room temperature, even if the flow rate is high. In many cases the body cooling potential of air movement due to open windows might be the most important in relation to thermal comfort. If the external air temperature is higher than the indoor air temperature, external air flow will increase room temperature. This will often be the situation for buildings with efficient night cooling, mechanical cooling and/or efficient solar shading. In such cases this can be handled by an automatic control system by changing the control mode from temperature control to indoor air quality control.

To avoid sensations of draft it might be necessary to preheat incoming external air; this might also be necessary even if cooling is needed in the room. Coils or radiators for preheating the supply air should normally be controlled based on the temperature of the inlet air. It is important that the occupants are carefully instructed how to operate the windows, when outdoor air temperature is high or when cooling is on.

4.3.2.3 Night ventilation during summer

The control of night ventilation is of great importance to the possibility of achieving acceptable thermal comfort during hot summer days in buildings without mechanical cooling, and in reducing the energy consumption for mechanical cooling. The building structures should be as cold as possible without creating thermal discomfort in the morning.

The control of night ventilation should normally be automatic, but it is possible to have night ventilation with manual user-controlled windows or hatches in the individual rooms. Manual control by the occupants requires clear easy-to-understand instructions. Automatic control can be local per room or central for the building or a section of the building. Local control is normally only relevant in larger rooms and especially if local fan assistance is used. Central control must normally be based on measured temperatures in representative rooms. The selection of the representative rooms is of great importance.

The actual night ventilation strategy depends on the system. If fans are included it is preferable to have a few degrees cooling potential available from the external air before fans are started because of the fan power consumption. Night ventilation must continue until the building is sufficiently cooled or occupied again. If the building structures are cooled to low temperatures it might be necessary to interrupt the night ventilation before the end of the non-occupied period in order to regain acceptable surface temperatures before the start of the occupation.

4.3.2.4 Natural and mechanical mode switch

One of the main characteristics of a hybrid ventilation system is the ability to switch automatically between natural and mechanical modes in order to optimise the balance between indoor environmental quality and energy use. This challenge differs between the different hybrid ventilation principles

For a fan assisted system the fan can be controlled by the temperature or the indoor air quality in the rooms, by the pressure in the supply or exhaust ducts or by the air flow rate through the fan. If the fan is in the natural ventilation flow path the control can be either on/off, stepped or continuous depending the natural driving forces. If the fan is in parallel to the natural ventilation flow path and uses part of the same flow path it is difficult to have continuous control and also to determine when the conditions allow the fan to be switched off again.

Alternating natural and mechanical ventilation must normally be controlled based on the external temperature and humidity. Alternatively, it can be controlled by a time schedule. Good information for the occupants is needed about the actual mode of the ventilation system.

4.3.3 Sensors

To fulfil the determined control strategy sensors are needed in the building to measure temperature, indoor air quality and occupancy. Sensors are also needed to measure the actual weather conditions.

In hybrid ventilation demand control of indoor air quality is very important for increasing the energy efficiency of the system. At present CO_2 is the most promising indicator of air quality in buildings, and to ensure satisfactory conditions an air quality sensor in every building zone is the optimum solution. CO_2 sensors have been applied in a number of buildings, (Hendriksen 2002, Tjelflaat 2002, Schild 2002, Blomsterberg 2002, van der Aa 2002) and with regular calibration they have performed well. In Willems et al. (2002) a market survey of more than 30 CO_2-sensors is documented. The survey shows that the main disadvantage of existing sensors on the market, with acceptable quality for indoor air quality measurements, is the price, which is about €300-500. The report also shows that there is a potential for development of low-cost and reliable sensors, if the market is developed.

The table shows conclusions and recommendations with regard to sensors in buildings and weather station from IEA-ECBCS Annex 35, Heiselberg (ed.) 2002.

Sensors in the building	
Temperature	Ordinary room and duct temperature sensors are reliable and not expensive. Surface temperature sensors exist but there is not so much experience with their use in control systems.
CO_2	CO_2 is an IAQ indicator of body odour but is not harmful to people in the concentrations normally found in buildings. CO_2 sensors are quite expensive and need regular calibration, see Willem et al. 2002.
PIR	Infrared presence sensors are reliable and not expensive. They are easy to test and can also be used for other purposes e.g. control of artificial light.
Air speed	Air speed sensors can be used to measure the airflow rate in ducts. Air speed sensors are quite expensive and need regular cleaning and calibration
Weather Station	
External temperature	External temperature sensors are reliable and not expensive. The problem is often to find a position to install them where the temperature is not influenced by the building or solar radiation.
Wind	Traditionally wind speed is measured with a cup anemometer and wind direction is measured with a wind vane. A new type without moving parts is available where both speed and direction is measured by using the Doppler effect in two directions.
Solar radiation	Solar radiation sensors do not need to be very accurate for control purposes. It is preferable to have a sensor on the upper part of each main facade.
Precipitation	Precipitation sensors are reliable and not expensive. They normally only need to produce an on/off signal for overrule purposes.

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