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Heiselberg, Per

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Per Heiselberg

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Per Heiselberg

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DESIGN PRINCIPLES FOR HYBRID VENTILATION

Per Heiselberg
Associate professor in Indoor Environmental Engineering, Aalborg University
Sohngaardsholmsvej 57, DK-900 Aalborg, Denmark
Tlf.: +45 9635 8541, Fax: +45 9814 8243, E-mail: ph@civil.auc.dk

ABSTRACT

For many years mechanical and natural ventilation systems have developed separately. Naturally, the next step in this development is the development of ventilation concepts that utilize and combine the best features from each system to create a new type of ventilation system – Hybrid Ventilation. The hybrid ventilation concepts, design challenges and principles are discussed and illustrated by four building examples.

Buildings ventilated by hybrid ventilation often include other sustainable technologies and an energy optimization requires an integrated approach in the design of the building and its mechanical systems. Therefore, the hybrid ventilation design procedure differs from the design procedure for conventional HVAC systems. The first ideas to a design procedure for hybrid ventilation are presented and the different types of design methods that are needed in different phases of the design process are discussed.

KEYWORDS: Design, hybrid ventilation, natural ventilation, office building.

INTRODUCTION

Today, in the design of new buildings and retrofit of old buildings an integrated approach is used with focus not only on thermal insulation, airtightness and heat recovery but also on optimal use of sustainable technologies as passive solar gains, passive and natural cooling, daylight and natural ventilation. Buildings are designed to interact with the outdoor environment and they are utilizing the outdoor environment to create an acceptable indoor environment whenever it is beneficial. The extent to which sustainable technologies can be utilized depends on outdoor climate, building use, building location and building design. Under optimum conditions sustainable technologies will be able to fulfil the demands for heat, light and fresh air. In some cases supplementary mechanical systems will be needed and in other cases it will not be possible to use sustainable technologies at all.

In well thermally insulated office buildings ventilation and cooling account for more than 50% of the energy requirement, and a well-controlled and energy-efficient ventilation system is a prerequisite of low energy consumption. Natural ventilation and passive cooling are sustainable, energy-efficient and clean technologies as far as they can be controlled, and they are well accepted by occupants and should therefore be encouraged wherever possible. Unfortunately, the design of energy-efficient ventilation systems in office buildings has often become a question of using either natural or mechanical ventilation. This has prevented a widespread use of sustainable technologies because a certain performance cannot be guaranteed under all conditions with natural ventilation. In fact, in the majority of cases a combination of systems would be beneficial depending on outdoor climate, building design, building use and the main purpose of the ventilation system. The development of sustainable ventilation technologies is far behind the development of other sustainable technologies and, certainly, there is a need for development.

For many years mechanical and natural ventilation systems have developed separately. Mechanical ventilation has developed from constant air flow systems through systems with extensive heat recovery and demand-controlled air flows to energy-optimized low pressure ventilation systems. Natural ventilation has in the same period developed from being considered only as air infiltration through cracks and airing through windows to be a demand-controlled ventilation system with cooling capabilities, heat recovery and air cleaning possibilities. The focus in the development has for both systems been to minimize energy consumption while maintaining a comfortable and healthy indoor environment. Naturally, the next step in this development is to develop ventilation concepts that utilise and combine the best features from each system to create a new type of ventilation system – Hybrid Ventilation.

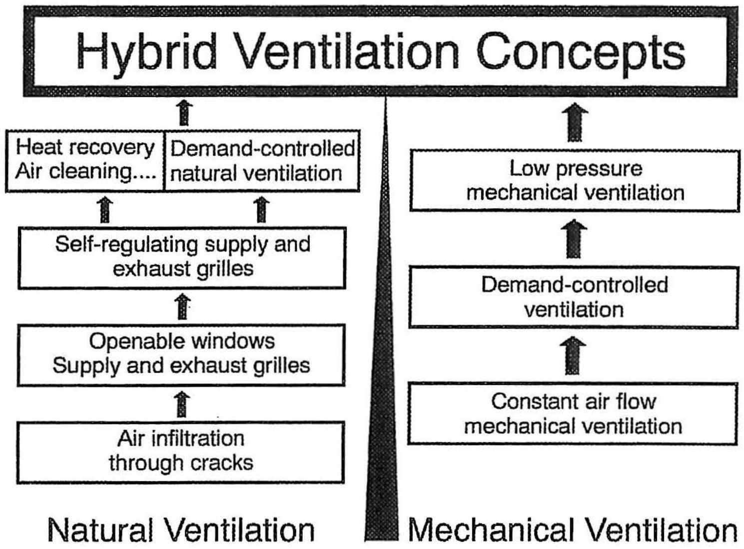

Figure 1. Development of natural and mechanical ventilation systems, [1].

HYBRID VENTILATION CONCEPT

Definition

Hybrid ventilation systems can be described as systems providing a comfortable internal environment using both natural ventilation and mechanical systems, but using different features of the systems at different times of the day or season of the year. It is a ventilation system where mechanical and natural forces are combined in a two-mode system. The basic philosophy is to maintain a satisfactory indoor environment by alternating between and combining these two modes to avoid the cost, the energy penalty and the consequentially environmental effects of full year-round air conditioning. The operating mode varies according to the season, and within individual days, thus the current mode reflects the external environment and takes maximum advantage of ambient conditions at any point in time. The main difference between conventional ventilation systems and hybrid systems is the fact that the latter are intelligent with control systems that automatically can switch between natural and mechanical mode in order to minimize the energy consumption.

Hybrid ventilation should dependent on building design, internal loads, natural driving forces, outdoor conditions and season fulfil the immediate demands on the indoor environment in the most energy-efficient manner. The control strategies for hybrid ventilation systems in office buildings should maximize the use of ambient energy with an effective balance between the use of advanced automatic control of passive devices and the opportunity for the users of the building to exercise direct control of their environment. The control strategies should also establish the desired air flow rates and air flow patterns at the lowest possible energy consumption.

Design challenges

Ventilation of buildings is an important aspect of all building projects. Today, 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 hybrid 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 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 reduction of the need for fan energy by low pressure duct work and for other components as well as optimization of natural driving forces from stack effect and wind. 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 minimizing the use of 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, 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 reduction of the need for fan energy by low pressure duct work and other components as well as optimization of natural driving forces from stack effect and wind. The major issues of concern with regard to thermal comfort are avoidance of too low temperatures at the start of the working hours and acceptable temperature increase during working hours. The issues of concern in optimization of hybrid ventilation for indoor air quality control and natural cooling are summarized in table 1.

Table 1. Issues of concern in optimization of hybrid ventilation for indoor air quality control

and natural cooling.

Indoor Air Quality Control	*Natural Cooling*
• Limitation of pollution sources (building materials, equipment, local exhaust, etc.)	• Limitation of heat load (low energy equipment, 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)
• Optimum air supply to occupants and removal of pollutants (ventilation efficiency)	• Optimum air supply to occupants (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)	•

Ventilation strategies

There is a whole range of hybrid ventilation principles and strategies and it is impossible to make a complete catalogue. Therefore, the following section focuses on the main principles and illustrates by building examples typical hybrid ventilation principles and strategies and demonstrates how design challenges mentioned in the previous section are solved. The criterion for selection of the building examples has been the innovative ideas with respect to ventilation for indoor air quality and natural cooling used in the buildings and not necessarily because the examples are excellent buildings with respect to indoor climate and energy efficiency. The buildings are IEA ECB& CS Annex 35 pilot studies. They will be monitored during the project and their performance will be reported at the end of the project.

The main hybrid ventilation principles are:

- **Alternating natural and mechanical ventilation**
  This principle is based on a combination of two fully autonomous systems where the control strategy consists of switching between both systems. It covers for example systems with natural ventilation in intermediate seasons and mechanical ventilation during midsummer and/or midwinter. It can also be systems with mechanical ventilation during occupied hours and natural ventilation for night cooling.
- **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 fan assistance.
- **Stack and wind supported mechanical ventilation**
  This principle is based on a mechanical ventilation system which 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.

Example 1: Liberty Tower, Meiji, Japan. (Architects and engineers Nikken Sekkei Ltd.)

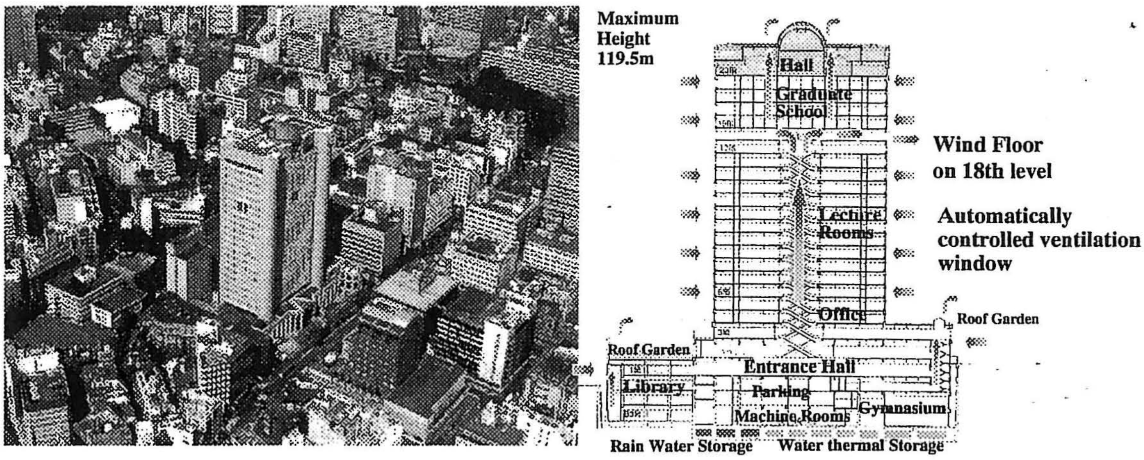

Figure 2. The Liberty Tower of Meiji University. Right: The natural ventilation principle with the central core and the wind floor to enhance natural driving forces.

The Liberty Tower of Meiji University is a high rise building at the centre of Tokyo Metropolitan area, [2]. The hybrid ventilation principle is based on natural ventilation for controlling the indoor climate in spring and fall seasons and a mechanical air-conditioning system in the rest of the year, when the outdoor air is not comfortable.

To enhance natural ventilation driving forces a "wind-floor" concept has been used. A central core is designed for utilization of the stack effect at each floor and above the centre core a wind floor is designed to enhance driving forces from the wind. On every floor there is air intake via perimeter counter units and exhaust through the opening at the top of the centre core. As the wind floor is open to four directions the driving force is expected to be stable through the year regardless of wind direction. The system includes automatically controlled natural ventilation windows at night time, an automatic intake of outdoor air and wind floor outlets. Outdoor air intake control is based on CO_2 and temperature sensors and is controlled via BEMS.

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.

The use of the natural ventilation system reduces the cooling energy of the building considerably, 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 18^{th} floor, incorporating the automatically controlled ventilation windows on each of the other lower floors, increases the ventilation rate by 30%.

Example 2: PROBE Building, Limelette, Belgium. (Architect Y. Wauthy, Engineers BBRI)

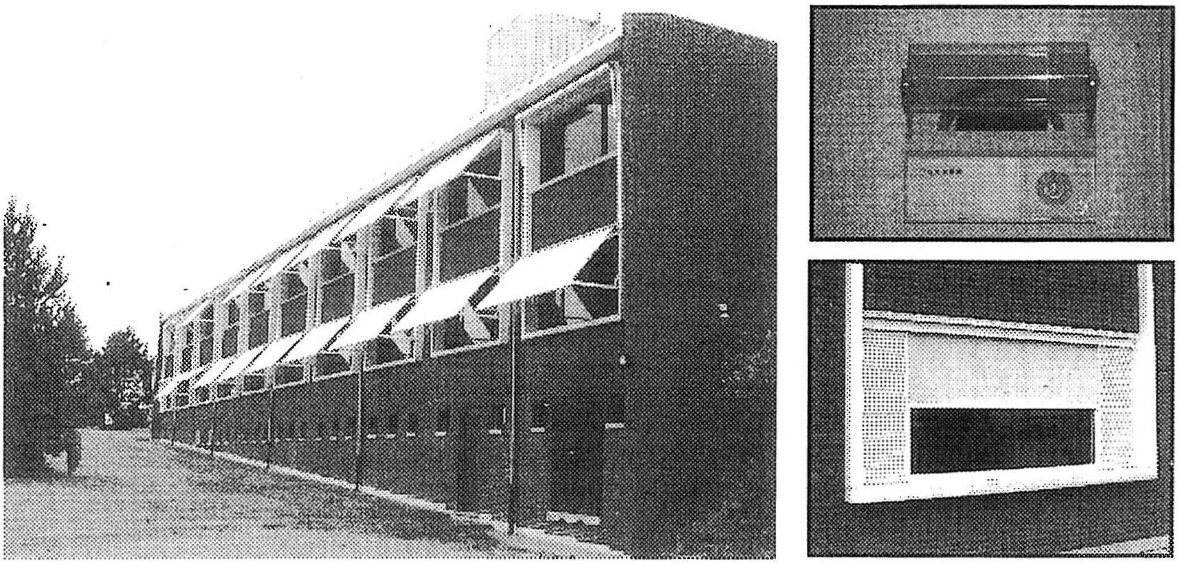

Figure 3. The PROBE building. Top right: Supply grille with presence detection. Bottom right: Louver's for intensive ventilation.

The PROBE building is a renovated office building located on the test site of the Belgian Building Research Institute (BBRI) at Limelette in a rural and very quiet environment, [1]. The hybrid ventilation principle is based on natural ventilation for achieving thermal comfort in summer and mechanical ventilation for indoor air quality control in the heating season. Currently, there is no interaction between the two systems. Each of the systems has their own goals.

Air quality in the heating season is maintained using an infrared-controlled mechanical ventilation system. Fresh air is supplied into each office at 25 m^3 per hour per person and is extracted from the lavatories. Every office has its own infrared presence sensor which restricts supply ventilation to periods in which the office is occupied. This leads to a reduction of ventilation losses of 35%. Airtight duct work and a well-regulated fan are important conditions for the proper operation of this system.

The major problem of the existing building was overheating in summer. An overall solution strategy is chosen that includes passive measures (solar shading, roof insulation, intelligent lighting) and intensive night ventilation with the objective to cool down the internal mass of the building with cold external air for improved daytime thermal comfort. For night cooling the necessary high rates of natural ventilation (14 volumes per hour on average) are provided by means of large grilles located on both sides of the building. Monitoring activities in the summer of 1997 and 1998 have shown significant improvement in thermal comfort. Measurements showed that the indoor temperature remained below 27°C even when the outdoor temperature was above 31°C.

Example 3: B&O Headquarters, Struer, Denmark. (Architect KHR A/S, Engineers Birch & Krogboe A/S)

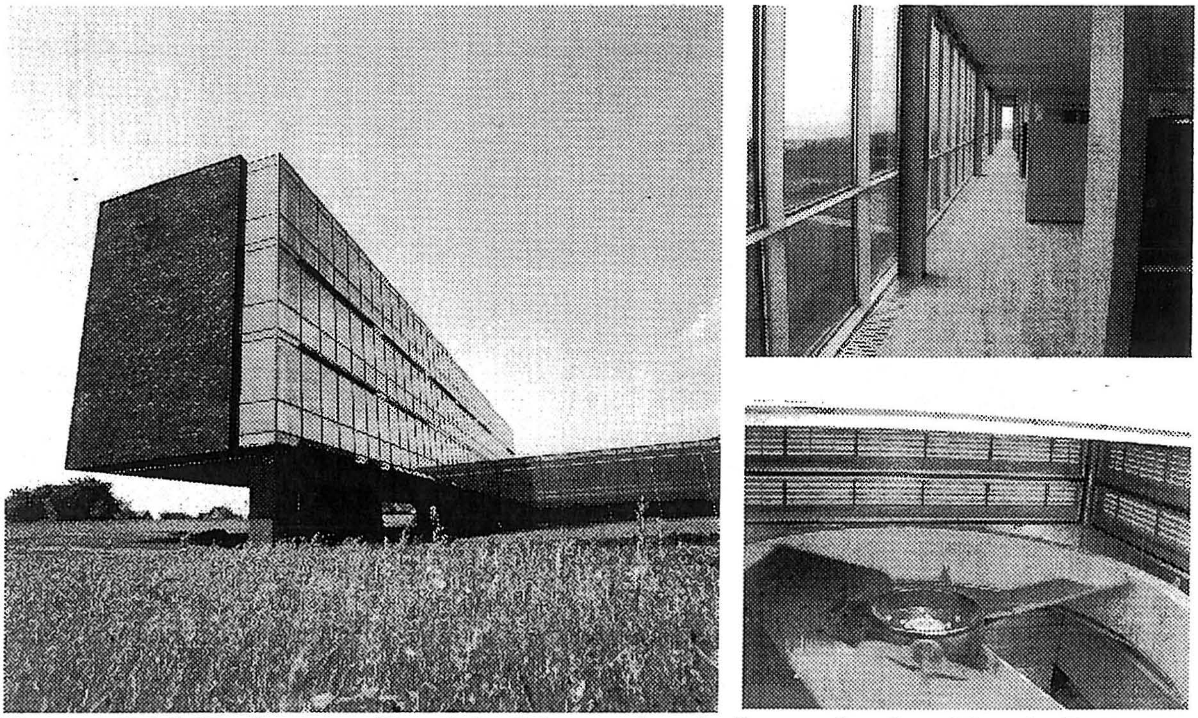

Figure 4. B&O Headquarters. Top right: Inlet openings in floor at the glazed facade. Bottom right: Axial fan at the top of the stairwell.

The B&O headquarters is a three-storeyed open plan office building. The hybrid ventilation principle is stack and wind driven natural ventilation with fan assistance. The north facade, which is shown in figure 4, is fully glazed. Outdoor air is supplied and preheated through low-positioned ventilation windows placed in a narrow band in the glazed north facade at each floor. Ribbed heat pipes, with inlet temperature sensors, are used to preheat the supply air in the heating season. The south facade has a moderate window area for daylighting and has user-controlled windows which are automatically controlled at night to cool the building. Air is extracted through the top of two stairwells which are open to the office floors. Two frequency-controlled axial fans that assist the natural driving forces are located at the top of the stairwells. The fans are controlled by CO_2 sensors in the rooms or air velocity sensors in the extracts. Baffles of sound-absorbent material are placed at the top of the stairwells to reduce the noise level of the fans to a specified low level.

The hybrid ventilation system is automatically controlled by CO_2 level, room temperature or occupancy. The hybrid ventilation system is active according to a certain time schedule or when the building is occupied. The BEMS system has three control modes: Constant mode based on time schedule or occupancy, CO_2 mode based on time schedule and occupancy or a night cooling mode with fan support based on room temperature.

Preheating of supply air reduces the risk of draught in cold periods and will therefore lead to improved thermal comfort. Displacement ventilation with supply openings in the floor is used as air distribution principle to increase ventilation efficiency. Occupants can increase the air change rate by opening supplementary windows and the risk of overheating is reduced by use of night time ventilation.

Example 4: Mediå school, Grong, Norway. (Architect Letnes Arkitekter A/S, Engineers SINTEF and NTNU)

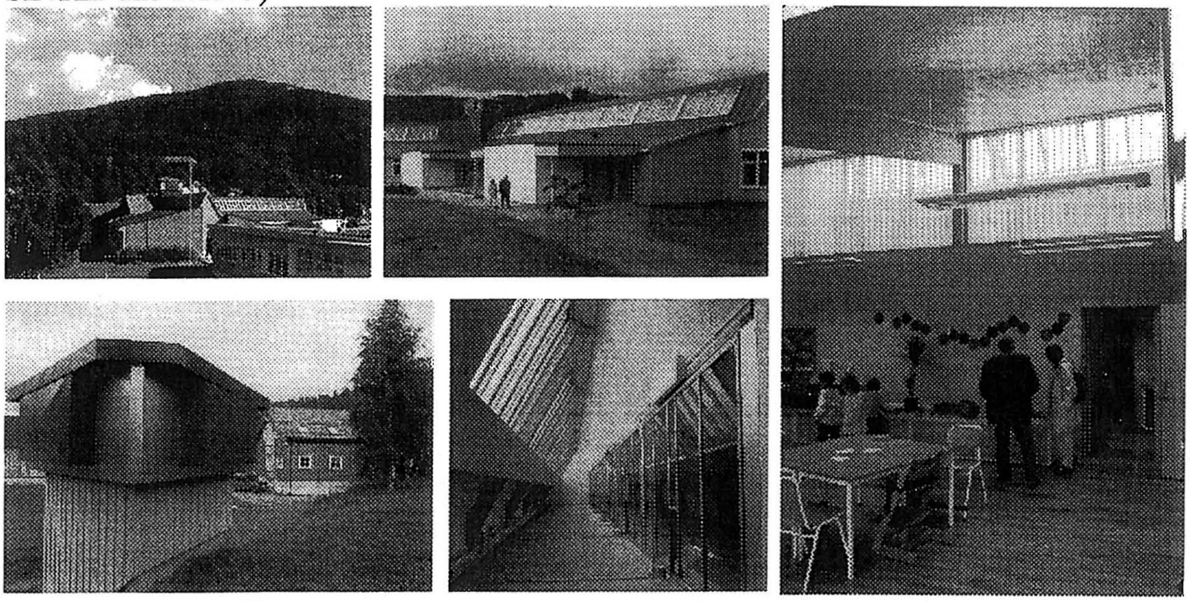

Figure 5. Mediå school. Bottom left: Air intake tower. Bottom middle: Exhaust plenum. Right: Classroom with air supply at floor level and exhaust through top window.

The Mediå school is a new single-storeyed building of 1000 m^2 designed to accommodate 223 occupants, [3]. The hybrid ventilation principle is based on buoyancy-driven natural ventilation assisted by fans. The ventilation air flow path through the building is sized to allow for velocities up to 1 m/s and components like filters and heat exchangers are much larger than those used for regular mechanical ventilation systems. To overcome the total pressure drop frequency-controlled fans are installed at the ventilation intake side and at the outlet. Both fans are expected to run when a large air flow rate is needed, for example for free cooling in summer. In a typical winter scenario only the supply-side fan is expected to run and at partial speed. An exhaust tower has been designed to utilize wind force when available.

CO_2 and temperature sensors control both outlet dampers for each room and supply and exhaust fans for the building. When the building is unoccupied the ventilation air flow rate is low and when the CO_2 concentration reaches a preset level the BEMS signals the outlet air damper of the room to open one step at a time. If the damper is fully opened and the CO_2 level at the sensor still is too high the BEMS signals to the fans to increase the speed. The supply and exhaust fans are also regulated in steps, and the two fans are controlled together to ensure that the rooms are not pressurized compared to the outside under winter conditions. A similar strategy, as used for CO_2 control, is also used for temperature control.

Outside air is led through a 15 m long underground duct before it enters the building to dampen the daily temperature swings of the outside air and to avoid the need for mechanical cooling. Low-emissivity materials, displacement ventilation, demand-controlled ventilation and heat recovery of exhaust air have been applied in order to ensure a satisfactory indoor environment combined with the lowest possible energy consumption. Daylighting, using skylights, has been designed in all classrooms to improve the indoor environment and to reduce electric energy consumption of artificial lighting. Draught is avoided by using low-velocity and low-level diffusers in rooms and by using panel heaters below the windows.

HYBRID VENTILATION DESIGN

As it was seen in the examples buildings with hybrid 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.

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. The integrated design approach achieves this improved energy utilization due to the relationship that exists 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.

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 figure 6.

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 is 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.

	Heating	**Cooling**	**Lighting**	**Ventilation**
Step 1	*Conservation*	*Heat avoidance*	*Daylight*	*Natural ventilation*
Basic Design	1. Surface to volume ratio 2. Insulation 3. Infiltration	1. Shading 2. Exterior colours 3. Insulation	1. Windows 2. Glazing 3. Interior finishes	1. Building form 2. Location of windows and openings 3. Stacks
Step 2	*Passive solar*	*Passive cooling*	*Daylighting*	*Natural ventilation*
Climatic design	1. Direct gain 2. Thermal storage wall 3. Sunspace	1. Evaporative cooling 2. Convective cooling 3. Radiant cooling	1. Skylights 2. Light shelves 3. Light wells	1. Wind induced ventilation 2. Bouyancy induced ventilation 3. Air distribution 4. Control system
Step 3	*Heating system*	*Cooling system*	*Electric light*	*Mechanical ventilation*
Design of Mechanical Systems	1. Radiators 2. Radiant panels 3. Warm air system	1. Refrigeration machine 2. Cooled ceiling 3. Cold air system	1. Lamps 2. Fixtures 3. Location of fixtures	1. Mechanical exhaust 2. Mechanical ventilation 3. Air conditioning

Figure 6. Typical design considerations at each design step. Revised from [4].

Hybrid ventilation design procedure

The hybrid 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. 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 mode of the hybrid system 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 is considered as well as heat recovery and filtration. Appropriate control strategies for the natural ventilation mode are determined and decisions are made regarding the level of automatic and/or manual control and user interaction. In the third step the 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 balanced mechanical ventilation or full air conditioning systems. The hybrid ventilation and the corresponding whole system control strategy are 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 hybrid 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 hybrid 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 hybrid 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 hybrid ventilation system layout designed. 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 hybrid 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 hybrid 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 hybrid ventilation design must also be an integrated part of the design of the building and of other sustainable technologies. A design procedure for hybrid ventilation, that complies with the above mentioned requirements is currently under development in the international co-operation project IEA-ECB&CS Annex 35 "Hybrid Ventilation in New and Retrofitted Office Buildings".

Hybrid ventilation design methods

Different phases in the design process call for different types of design methods. 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.

Suitable methods as we know them from mechanical systems are not available for hybrid ventilation systems yet. Valid methods would give architects and engineers the necessary confidence in system performance which in many cases is the decisive factor for choice of system design. As the hybrid ventilation process and the thermal behaviour of the building are linked the development of design methods for hybrid 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. A model that combines a thermal simulation model with a multizone air flow model will allow the thermal dynamics of the building to be taken into account and will improve the prediction of the performance of hybrid ventilation considerably. Such a model will be capable of predicting the yearly energy consumption for hybrid ventilation and will therefore be the most important design tool for hybrid ventilation systems.

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Dept. of Building Technology and Structural Engineering
Aalborg University, December 2000
Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark
Phone: +45 9635 8080 Fax: +45 9814 8243
http://iee.civil.auc.dk