Hybrid Ventilation Systems and High Performance Buildings

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ABSTRACT: Hybrid ventilation systems combined occupant controlled natural ventilation with mechanical ventilation systems. This paper describes the performance of three buildings designed with hybrid ventilation systems. The design and performance of each are detailed. Natural ventilation is shown to provide adequate ventilation when appropriately designed. Proper control integration of natural ventilation into hybrid systems is shown to reduce energy consumption in high performance buildings. Lessons learned from the three buildings are described.
Keywords: hybrid ventilation, natural ventilation, high performance buildings, occupant control, design process

INTRODUCTION

Until the second half of the nineteenth century buildings were ventilated through windows and shafts with winds and temperature differences providing the driving forces. Concerns over air quality both inside and outside buildings led to the development of complex ventilation systems driven by either fan or temperature differences and designed to filter incoming air and exhaust polluted air from the building. The advent of air-conditioning in North America early in the twentieth century led to an integration of ventilation and air-conditioning systems. With mechanical ventilation and air-conditioning, North American architects began designing buildings with deep floor plates containing large interior zones that could only be ventilated and air-conditioned mechanically. To keep floor to ceiling heights as high as possible, architects typically required smaller supply and return duct designs leading to larger power requirements for the fans. Reyner Banham provides an excellent history of HVAC systems and their impact on architectural form up to 1980[1].

As high-rise offices began to appear in Northern Europe late in the twentieth century, air-conditioning and ventilation systems were re-examined. Hybrid systems integrating natural ventilation and mechanical ventilation were developed as a means of conserving energy and meeting code requirements for operable windows in occupied spaces. A North American office building might require 1.25 l/s/m2 for outdoor ventilation air, but the air-conditioning system might require 5 to 8 l/s/m2. A well designed HVAC system using air as a heat transfer medium can transfer roughly 4 kJ/hr/°C per watt of fan power. Using water as a heat transfer medium the system can transfer more than 70 kJ/hr/°C per watt of pump power. Recognition that water is significantly more efficient transferring heat than air led to the development of radiant slabs and chilled beams to provide sensible cooling. Ventilation rates were reduced to what was required by occupants for health and de-humidification. Fan sizes went down and energy required to ventilate and cool buildings was reduced considerably. North American HVAC engineers, accustomed to the systems they know, have generally resisted using the natural ventilation and radiant cooling concepts developed in Europe. Presumed inappropriate behavior by occupants opening windows at the wrong time and higher summer dew point temperatures in the eastern USA have been given as reasons to stay with sealed buildings and standard HVAC systems.

This paper discusses hybrid ventilation design strategies and their impact on three high performance buildings located in southern Wisconsin, USA. All three buildings were designed by the Kubala Washatko Architects. The author served as energy consultant on all three projects. His responsibilities included designing the natural ventilation systems and integrating natural ventilation into the HVAC control strategy. He was also responsible for post occupancy evaluation of building energy performance and has used all three buildings as a learning laboratory for architecture students. The Schlitz Audubon Nature Center (SANC), completed in 2003, is an environmental education center open seven days per week. The Urban Ecology Center (UEC), completed in 2004, is an ecological education center open seven days per week. The Aldo Leopold Legacy Center (ALLC), completed in 2007, houses a non-profit foundation. It is open five days per week during winter and six days per week during the rest of the year. The size, measured energy utilization intensity and percentage of energy supplied by renewable solar power and bio-fuels on site for each building is given below (Table 1). The hybrid ventilation system of each building is considered in order of construction. Lessons learned from earlier buildings provide feedback to an evolving approach to hybrid ventilation.

Table 1: Gross floor areas, energy utilization intensity (EUI) and site renewable energy percent of buildings studied.

Building	Gross Floor Area	Annual Measured EUI	Site Renewable Energy Percent
SANC	2,785 m^2	97.9 kWh/m^2	3.8%
UEC	1,880 m^2	157.1 kWh/m^2	18.1%
ALLC	1,244 m^2	55.1 kWh/m^2	70.6%

CLIMATE AND NATURAL VENTILATION

Southern Wisconsin is located between 42.5° and 44.0° North latitude. The Schlitz Audubon Nature Center and the Urban Ecology Center are located in Milwaukee, Wisconsin near the shore of Lake Michigan in the upper reaches of the St Lawrence River watershed. The Aldo Leopold Legacy Center is located in a forested area near the Wisconsin River in the upper reaches of the Mississippi River watershed. Heating season in southern Wisconsin runs from early November to late April or mid May. The average January dry bulb temperature is roughly -10°C with design dry bulb temperature of -26°C. Occasional arctic air masses reach Southern Wisconsin and temperatures drop to -30°C. Air-conditioning is required when dew point temperatures become excessive. This occurs intermittently from mid June to mid September with an accumulated duration of four to eight weeks. Building zones with large occupancies or high plug load densities will require longer periods of air-conditioning. Poorly designed glazing systems will increase the length of the air-conditioning season due to solar gains. However, there is no excuse for poorly designed glazing systems. The average July dry bulb temperature in southern Wisconsin is roughly 23°C and the average dew point temperature is roughly 19°C. The design dry bulb temperature is 32°C with coincident 23°C dew point. Hot and humid air from the Gulf of Mexico can bring dry bulb temperatures up to 40°C.

Hybrid ventilation systems employ natural ventilation during mild weather and controlled mechanical ventilation during heating or air-conditioning operations. Based on the experience of the three buildings studied in this paper, natural ventilation can meet outdoor air and thermal comfort requirements when the dry bulb temperature is above 10°C and below 25°C with the coincident dew point temperature below 17°C. This range assumes solar gains are minimized and internal heat generation is not excessive. Given the southern Wisconsin climate, natural ventilation can be used in lieu of mechanical systems for a total of three to four months per year. If natural ventilation is well integrated into the design, the HVAC system can and should be shut down when natural ventilation is employed.

SCHLITZ AUDUBON NATURE CENTER (SANC)

All occupied spaces should have lights off during sunny days. During mild weather windows should be open and HVAC systems off. These were two design goals established during programming of the Schlitz Audubon Nature Center. To achieve these goals all occupied spaces needed to be perimeter zones with access to light and air. With the exception of six classrooms and two offices along a double-loaded corridor on the ground floor, all occupied spaces on the ground and upper floor have operable windows on at least two different exposures (Fig. 1). The classrooms are lined with windows facing the corridor providing natural light from north and south. The windows are capped with operable transom lights to allow cross-flow ventilation. Occupied basement spaces were added to the program after design development. Some were neither daylit nor naturally ventilated.

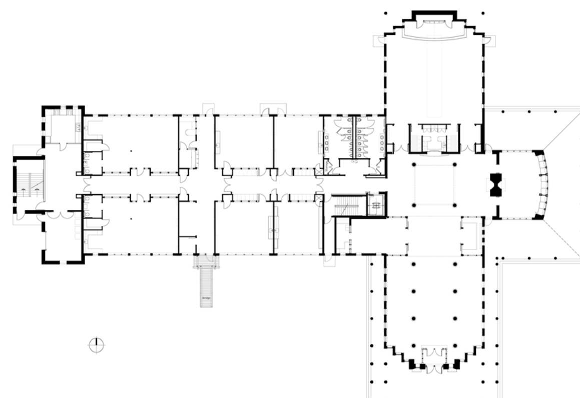

Figure 1: Ground Floor Plan, Schlitz Audubon Nature Center.

Ground source water-to-air heat pumps (one for each of the 22 occupied spaces) provide heating and cooling. 90 vertical wells, 38 meters deep, connect the earth source/sink to the heat pumps. Outdoor air is ducted directly to the three upper floor zones and the auditorium zone. Outdoor air for all remaining occupied spaces is provided via a heat recovery ventilator and water-to-air heat pump. The heat recovery ventilator served occupied spaces in the basement that did not have windows. Therefore it was always on during occupancy whether windows were open or not. Outdoor air flow rates met the requirements of ASHRAE Standard 62.1-1999. As described below, the natural ventilation system was also designed to meet the required ASHRAE ventilation rates.

Volumetric flow rates for wind driven and stack natural ventilation systems were estimated using procedures given by the American Society of Heating and Refrigeration and Air-Conditioning Engineers [2]. The volume flow rate equations given by ASHRAE were modified to output zone air change rates. The air change rate for wind driven ventilation is given by

$$ACH = 3600\, C_{vent}\, A_{opening}\, v_{wind} / V_{zone} \qquad (1)$$

Where ACH is the number of zone air changes per hour; $A_{opening}$ is the smaller of the inlet or outlet opening areas given in square meters; v_{wind} is the wind velocity in meters per second; V_{zone} is the occupied zone air volume in cubic meters; and C_{vent} is the effectiveness of the opening path to wind driven ventilation. The value of C_{vent} is between 0.25 and 0.65 depending on whether winds are quartering or perpendicular. For each zone the air change rate was estimated as a function of the percent of window opening area (inlet or outlet) actually open and wind velocity ranging from 20% to 100% of the average summer wind velocity. C_{vent} was assumed to be 0.25. The expected natural ventilation rate was compared with the ventilation rate required by ASHRAE. The environmental classrooms required an air change rate of 5.4 or higher. This ventilation could be met at low wind velocities when windows were fully open (Table 2). Only the grey areas did not meet the required air change rate.

Table 2: Environmental classroom wind driven air change rates (ACH) as a function of wind velocity and opening area.

	Percent of Average Summer Wind Velocity				
	20%	40%	60%	80%	100%
20%	1.58	3.16	4.75	6.33	7.91
40%	3.16	6.33	9.49	12.66	15.82
60%	4.75	9.49	14.24	18.99	23.73
80%	6.33	12.66	18.99	25.32	31.64
100%	7.91	15.82	23.73	31.64	39.56

Proper integration of window operation by occupants with the HVAC system is critical for energy efficient building performance. The control strategy was to shut down the zone heat pump any time a window in the zone was opened. This was accomplished by placing a window contact on each operable window in a zone. When a window was opened, the magnet on the operable sash moved away from a sensor and the building automated control system sensed a window was opened in a thermal zone. The heat pump in that zone was shut down. Once the window was closed, the heat pump would return to its normal mode of operation. The staff appreciated this control strategy. They choose to enter or leave natural ventilation mode by opening or closing windows. The audible sound of the heat pump shutting down or starting up provides feedback that window operation is integrated with the systems. In addition, the building manager could check the window status screen at the end of the day to determine which of the 115 operable windows might be open.

While the operation of the window control system was very successful, installation was problematic. At the time of construction wireless controls were not available. Each contact had to be wired through the window frame to the operable sash. At commissioning 20% of the contacts did not function properly and needed to be re-wired. In addition, the contacts and installation added $7,800 to the controls budget (the installer would charge a higher price in the future after their experience). The design team felt that use of contacts as a part of the building control strategy would require wireless contacts and a less expensive controls package.

The Schlitz Audubon Nature Center is a LEED™ Gold certified building. The impact of natural ventilation on annual energy performance was not modelled in the energy simulation as the control strategy was deemed to complex to model to insure the comfort performance required for LEED compliance.

URBAN ECOLOGY CENTER (UEC)

The Urban Ecology Center is more compact than the Schlitz Audubon Nature Center (Fig. 2 and 3). The site was more restricted and ground source heat pumps were not an option. Construction budget was an issue and the cost of the LEED submission determined prohibitive. The team choose to emphasize daylight, high enclosure insulation levels (double code levels in the walls and roof) and natural ventilation. The building was divided into three thermal zones: the staff offices, the public and classroom spaces and the basement occupied spaces. Each zone is served by a constant volume air handling unit. A high efficiency boiler delivers hot water to the air handling units and four cabinet heaters at fire stairs and vestibules. Only the office zone was provided with air-conditioning. The public spaces were naturally ventilated in summer and the basement zone was mechanically ventilated.

The window opening area and distribution were determined using the same procedures as on the Schlitz Audubon Nature Center. The control strategy was much simpler. From late May to mid November the public spaces and office spaces are in natural ventilation mode. If conditions in summer become extremely hot or humid, the office air handling unit is turned on in air-conditioning mode and office windows to the outside and the public spaces are closed. The building manager switches the system on or off through a web interface to the building controls. After the second year of occupancy, a cooling coil was added to the public space. The staff felt guilty that they would retreat to their air-conditioned offices when visitors suffered in the heat and humidity. When weather is mild, windows are open in the office and public zones and the air handling units are off. A staff member checks the entire building to close and lock all windows at the end of the day.

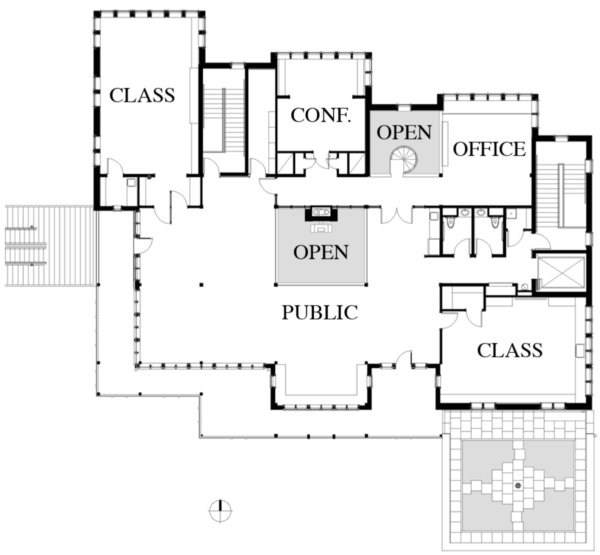

Figure 2: Upper Floor Plan, Urban Ecology Center.

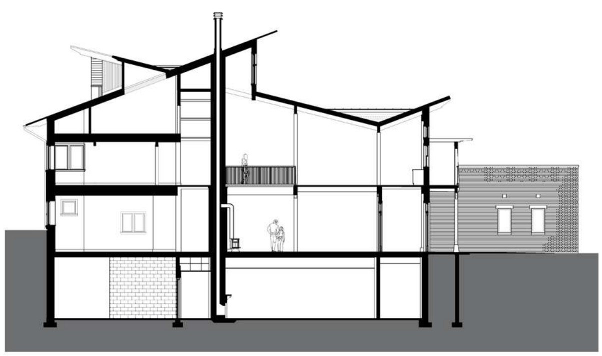

Figure 3: Building Section, Urban Ecology Center.

To determine the effectiveness of natural ventilation a carbon dioxide sensor was located on a work surface between two UEC administrators. This location was chosen because the administrators were often at their desks and the location was not ideal for the natural ventilation flow paths. Carbon dioxide concentrations and outdoor air temperatures were recorded at 5 minute intervals from June 21, 2005 to November 28, 2005. Each day the office was open average carbon dioxide concentrations during office hours were plotted as a function of average outdoor air temperature during office hours for (Fig. 4). With the exception of cold fall days, natural ventilation performed as well or better than mechanical ventilation. As temperatures during fall became cooler, staff restricted window openings and carbon dioxide concentrations rose. On cold, sunny November days the office temperature would be 17°C at 8 A.M. and would rise to 21°C by mid afternoon. Staff would dress in layers allowing adjustment between comfort conditions over the day. Over the entire period, the heating system was on for 10 days; the cooling system was on for 7 days and the building operated in natural ventilation mode for 85 days (over 12 weeks).

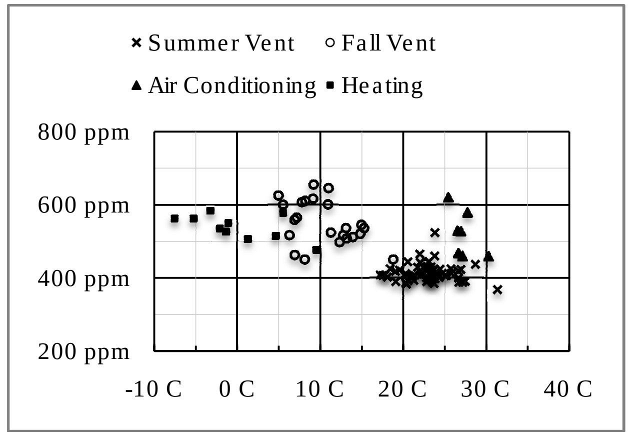

Figure 4: Average daily UEC office CO_2 concentration as a function of average daily outdoor air temperature for heating, cooling and natural ventilation.

Natural ventilation was not desired on the hottest day observed (Fig. 4). The staff wanted air-conditioning, but the three staff members with access to the control systems password were out of the office. The control system set the building in natural ventilation mode at the start of each day. Staff would choose to enter air-conditioning by closing windows and entering the controls web site to change the HVAC mode. This control system strategy requires more staff with knowledge and skill manipulating building control systems.

ALDO LEOPOLD LEGACY CENTER (ALCC)

The Board of Directors of the Aldo Leopold Foundation requested that the design team provide a carbon neutral design for the Aldo Leopold Legacy Center. The design team and board agreed that this meant designing a net-zero building. To accurately model all energy flows in the building, the design team integrated natural ventilation processes into the simulation model. An experiment comparing measured and modelled ventilation rates had been conducted at the Schlitz Audubon Nature Center [3]. The results of that study convinced the design team that natural ventilation could be reasonably simulated with a multi-node bulk flow model. The CONTAMW bulk flow pollution and air ventilation model [4] was modified to allow variation of the window openings during simulation and integrated into the TRNSYS thermal simulation program [5]. The simulation model of ventilation systems for the Aldo Leopold Legacy Center has been presented elsewhere [6]. Of note here is that the simulation model was used to study the effectiveness of different operable windows on different orientations. The administrative offices were designed with individual offices on the north, common office activities in the center of the space and a circulation zone along the south wall (Fig. 5). Cross flow ventilation moves through the three spaces. Clerestory windows above the offices were found to be less effective for total building ventilation. As a result, the number of operable clerestory windows was reduced.

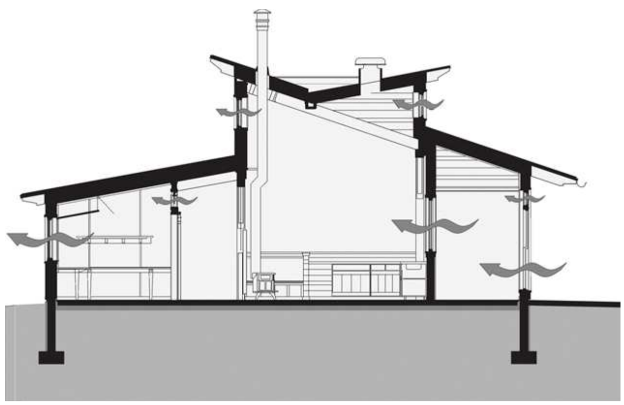

Figure 5: Building section through administrative offices, Aldo Leopold Legacy Center, looking east.

The Aldo Leopold Legacy Center has four building components (Fig. 6). The Workshop and Seed Hall are not tempered spaces. From April to November the Seed Hall is used for classes and meetings and is rented to groups. The remainder of the year the space is not used. The Conference Wing is used intermittently. Those spaces are maintained at 55 during the heating season and a wood-burning stove brings the space up to comfort when it is occupied. The administrative offices and exhibit spaces are heated and cooled by a radiant slab. Slab temperatures are maintained by ground source water-to-water heat pumps. When the building is not in natural ventilation mode, a 100% outdoor air mechanical ventilation system provides required ventilation air. The air-handling unit cools and dehumidifies or heats the ventilation air as required. Using a radiant slab for cooling creates difficulties for natural ventilation integration. Because the slab is maintained at 18°C, natural ventilation should be prohibited of the outdoor air dew point temperature exceeds 17°C. Otherwise there is a risk that condensation will occur on the cooled slab. Dew point temperature is monitored at three locations in the administration and exhibit wing as well as the outdoor dew point. When the outdoor dew point is within 1°C of the slab temperature, the building automated controls system issues an alarm that conditions are not appropriate for natural ventilation. When outdoor air temperatures are between 10°C and 25°C and the dew point is below 16°C, the controls system issues a message indicating conditions are appropriate for natural ventilation. The building systems operator can switch the building between natural ventilation mode and cooling (or heating) mode. When the building is switched into natural ventilation mode, the air handling unit shuts down and the ground source heat pumps, ground loop circulation pumps and floor loop pumps shut down.

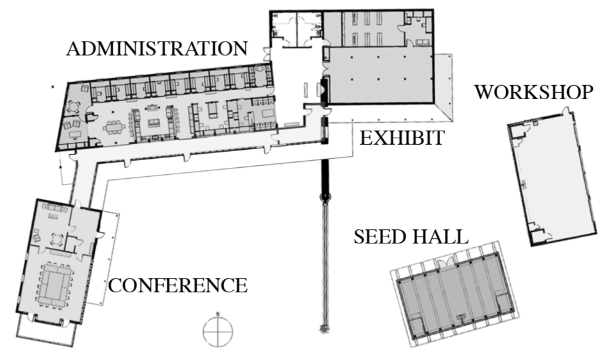

Figure 6: Floor Plan, Aldo Leopold Legacy Center

The simulation model indicates that natural ventilation saves 1,156 kWh per year (0.93 W/m^2 per year), nearly 10% of the cooling and associated fan and pump loads and roughly 1.7% of the total annual energy load. While this number may seem small, every bit of savings is important. Comparing the energy utilization intensity of the three buildings studied is illuminating (see Table 1). The Aldo Leopold Legacy Center requires half the energy per unit floor area as the Schlitz Audubon Nature Center and just over one third of the energy demand of the Urban Ecology Center. For buildings designed by the same architect with similar wall and roof insulation levels, one would not expect so much difference between energy requirements. The Urban Ecology Center is the most compact of the three buildings with the Aldo Leopold Legacy Center having the most enclosure area per unit floor area. Energy use is the opposite. On the one hand, the decision to not pursue LEED for the Urban Ecology Center led to a decision to forgo commissioning and energy simulation. Both of these activities provide a second look at all the pieces in the design allowing questions to be raised concerning the appropriateness of decisions. After examining the energy use of SANC and UEC, the design team decided to always recommend energy simulation modelling and commissioning to a client that did not wish to invest in LEED certification. Simulation modelling of the Aldo Leopold Legacy Center was well integrated into the design process informing decisions concerning operable window areas, insulation levels, the effectiveness of the circulation hall along the south wall as a thermal buffer and the appropriateness of earth tubes to pre-treat ventilation air. The commissioning agent pressed the design team to increase the efficiency of fans and pumps. The installed fan power at SANC is 5.7 Watts per square meter. It is 1.9 Watts per square meter at ALLC.

CONCLUSION

To achieve energy savings with natural ventilation, the HVAC system must be integrated with the architectural design and building program to allow the HVAC system to be shut down if windows are open. This is not easy. Two of the three buildings studied had the program expand into the basement during the design development process. For the Schlitz Audubon Nature Center, this meant a fresh air ventilation system that could not be shut down when ground floor spaces were in natural ventilation mode. If building zones are not compatible with natural ventilation because of occupancy use (e.g. large auditoriums or sensitive laboratories), those zones should have a separate ventilation system. The Urban Ecology Center has a separate HVAC system for the basement zones.

Simulation modelling, when it can accurately include natural ventilation and control strategies, is indispensible to evaluation of high performance building design. However, the integration of natural ventilation systems and building automatic control systems requires careful discussions with the client/owner that will be operating the building. Contacts on windows that automatically shut down the HVAC system for the space when a window is open seem like the best solution. It is if each space is a separate zone (eg. a school building classroom). With multi-zone HVAC systems, it is more appropriate to shift the control of going into or out of natural ventilation mode to a building system operator allowing communication to all staff that windows can be opened or should be closed.

When well designed, a natural ventilation system can result in significant reduction of cooling and ventilation energy. More important, occupants often have a greater sense of control over their workspace when they can control windows near their desk. In all three buildings, no staff member wanted to return to a sealed building. All spoke of enjoying the feeling of fresh air moving through the building on the first warm spring day. The emotional attachment to an outdoor connection may be as important as the energy savings.

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