Hybrid Ventilation Retrofit in a School Setting

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ABSTRACT

In recent years, the use of mechanical ventilation has been called into question mainly due to high energy consumption and natural ventilation of inadequate indoor air quality during much of the year. Hybrid ventilation systems capitalize on the strengths of both ventilation strategies, but there has been little operational experience or performance monitoring of such systems. The Tånga School in Sweden has therefore been retrofitted with a hybrid ventilation system controlled by a building energy monitoring system. The primary feature of the hybrid system is 6-meter-high solar chimneys, which are used as the main ventilation power source. When stack effect is not sufficient to ventilate the school, the chimneys contain low-energy exhaust fans to supplement the existing stack effect. Monitoring has shown that, with the exception of short periods of time when CO_2 concentration exceeds 1000 ppm, the hybrid system provides a good indoor environment with low energy consumption.

INTRODUCTION

Background

Increasingly, over the last few years, traditional mechanical ventilation systems have been questioned because of their high energy consumption. Although mechanical exhaust air ventilation and balanced ventilation systems facilitate heat recovery (either by an exhaust air heat pump or by a heat exchanger), the systems need to operate at high static pressure and thus require fan-motor sets with high energy consumption. Furthermore, mechanical ventilation systems can be poorly designed, installed, or maintained, so that

- there are high noise levels,
- there are health problems (sick building syndrome is often found in buildings with mechanical ventilation systems),
- there is little possibility for local occupant control,
- regular routine maintenance is required in order to ensure continued proper operation.

The advantage of mechanical ventilation is that indoor air quality is not dependent on the outdoor environment.

In the late 1990s, the design of new buildings and retrofit of old buildings have turned toward greater use of sustainable technologies such as passive solar input, daylighting, and natural ventilation and cooling (Delsante and Vik 2001). The 1994 revision of the Swedish Building Regulations permitted the use of natural ventilation in buildings (Thurell 1998). Since then almost 100 schools have been built with natural ventilation systems, with or without the assistance of supplementary fans. While natural ventilation has the disadvantage of not permitting heat recovery, in commercial and school buildings this is often of less significance since the highest air flows are designed to cool the internal heat loads from occupants and/or equipment. The advantages of natural ventilation include quiet operation and low energy consumption. However, experience has shown that the ventilation requirements of buildings with natural ventilation systems cannot be met during long periods of the year when the differences between indoor and outdoor conditions are too small to give sufficient driving forces. Problems with reverse flows have

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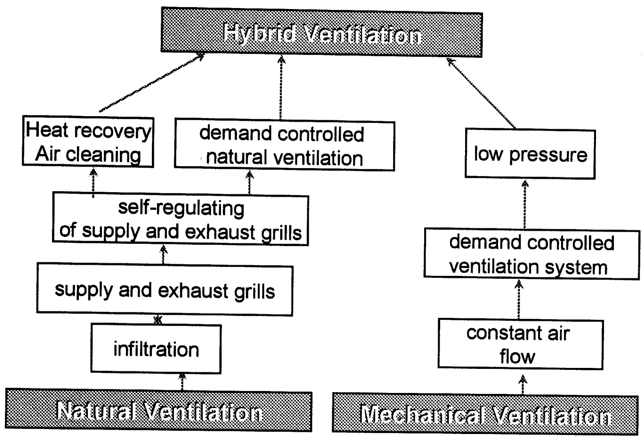

Figure 1 *Schematic diagram of hybrid ventilation system (Wouters et al. 2000).*

also occurred when interior occupation or use patterns have been changed, since the natural ventilation system is designed for certain behavior. Many of the buildings have also suffered from moisture problems in their air supply crawl spaces.

In order to tackle these problems, a few schools in Sweden have recently been built with hybrid ventilation. Hybrid ventilation systems provide the benefits of both natural and mechanical ventilation principles by combining the best of both. Wouters et al. (2000) describe the history of hybrid ventilation, as developed from the two basic operating modes of constant airflow mechanical ventilation systems and manually controlled natural ventilation systems. Demand-controlled mechanical ventilation systems have received quite a lot of attention. In recent years, development has been concentrated on low-pressure ventilation systems with high-efficiency fans (Wouters et al. 2000). Natural ventilation has also been developed during the past few years. Supply and exhaust grilles have become standard, and self-regulating devices are available to take into account varying weather conditions. More recently, demand-controlled natural ventilation systems have become available that utilize auxiliary fans to compensate for lack of sufficient natural driving forces during certain periods of the year. As a result, the development of both ventilation categories has merged into a system that combines the best of the two technologies (Figure 1).

Heiselberg (1998) defines hybrid ventilation as follows:

> Hybrid ventilation systems can be described as systems providing a comfortable internal environment using both natural ventilation and mechanical systems, but employing different features of the systems at different times of the day or season of the year. They are ventilation systems where mechanical and natural forces are combined in a two-mode system. The main difference between conventional ventilation systems and hybrid systems is that the latter are intelligent systems with control systems that can automatically switch between natural and mechanical mode to minimize energy consumption and maintain a satisfactory indoor environment.

This represents a further step than that provided by the mixed-mode *complementary changeover ventilation system* described by Dix (2000) since the hybrid ventilation system claims to be an intelligent system with advanced control systems.

Hybrid Ventilation System Demonstration Project Objectives

In 1998, interest in hybrid ventilation technologies resulted in a framework of IEA Annex 35 called HYBVENT, evaluating the performance of 12 pilot studies of hybrid ventilation systems around the world (Heiselberg 1998). One of these studies is of the Tånga School in Sweden, which has been retrofitted with a hybrid ventilation system controlled by a building energy monitoring system (BEMS).

A research project was undertaken to demonstrate and assess the performance of the hybrid ventilation system installed in the Tånga School. Specifically, the objective of the project was to evaluate if the hybrid ventilation system could provide the designed flow rates for both the natural and mechanical modes of operation, needed to provide the required indoor comfort performance, while minimizing electricity use for ventilation and energy for space heating. An additional objective was to evaluate if the occupants appreciate the ventilation system and their ability to manually control the air distribution system.

THE TÅNGA SCHOOL

The school, which is located in the town of Falkenberg, Sweden, was built in 1968 and contains 20 classrooms and 10 workshops, a dining hall, kitchen, and offices, with a total floor area of 6131 m^2. The building has two stories. Building A consists of kitchen, dining hall, offices, etc., and Building C of workshops and classrooms. Building B consists of three wings, with each wing having three classrooms on each story. Before the retrofit, ventilation was provided by a mechanical supply and exhaust ventilation system without heat recovery, with an approximate specific electric power requirement of 3 $kW/m^3/s$ and total electric energy consumption of about 140 MWh. The system was controlled by a timer set to start at 07:00 and stop at 17:00, with a ventilation rate of 6 L/s per person in the classrooms, or 6 m^3/s in Building B.

In January 2000, each wing was retrofitted with a hybrid ventilation system controlled by a building energy monitoring system (BEMS). The main principle of ventilation is passive stack effect. Solar chimneys have been installed on the roof of each wing in order to increase the available stack effect in the building. To achieve maximum passive stack ventilation, attention was paid to reducing the total pressure drop through the distribution ducts by utilizing large ducts with a minimum of obstructions. Existing stairwells have been used to lead the exhaust ducts from the classrooms to the solar chimneys. An

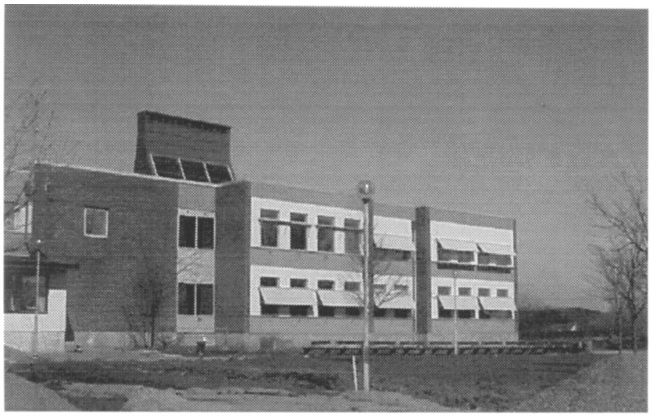

Figure 2 *The Tånga School with the solar chimneys.*

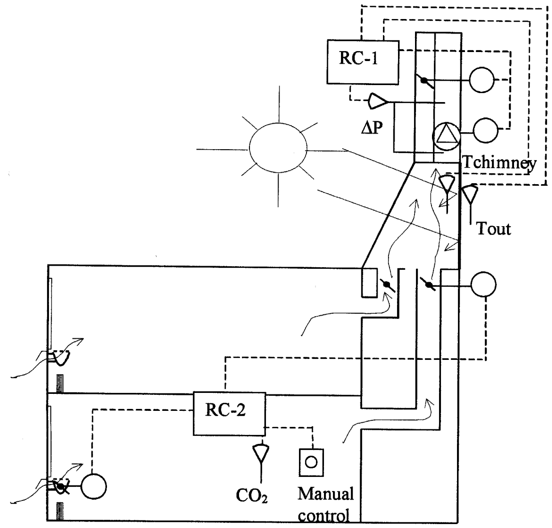

Figure 3 *Schematic diagram of the ventilation system with the solar chimney in the Tånga School.*

advanced BEMS system is used to control the air flows and to secure a good indoor climate.

In addition to the hybrid ventilation system, one-fourth of Building B has been fitted with new low-energy windows with a U-factor of 1 W/m²K. Building C has been retrofitted with a new balanced mechanical ventilation system with heat recovery, with an electricity consumption of 2 kW/m³ s and an annual energy budget of 18 MWh (Blomsterberg et al. 2001).

The Ventilation and Distribution Principle

The main principle of ventilating the two-story Tånga School is by passive stack ventilation. When stack effect is insufficient to provide the necessary differential pressure, auxiliary fans are used to maintain ventilation at a sufficient level. Outdoor air is drawn into the classrooms on the ground and first floors through several air intakes in the exterior walls. Stub ducts distribute the air to the rooms. Figure 2 shows the air intakes below the windows, while Figure 3 is a schematic diagram of the ventilation system. The incoming fresh air is heated when necessary by convectors inside the stub ducts, supplied with hot water from the town's district heating system. This is supposed to provide mixing ventilation in the classrooms. As the school is situated in a quite clean outdoor environment, it was considered acceptable to dispense with filters in the air inlets in order to decrease the pressure drop. Louvres and mosquito nets are used to prevent rain, snow, insects, and larger particles such as leaves from entering the ducts. The air intakes and the stub ducts are easily accessible and can be cleaned by hand. Exhaust air is evacuated through 3-meter-high wall air terminal devices on the opposite side of the room into vertical ventilation ducts. Local dampers are mounted both in the air intakes and in the exhaust duct of each room to allow individual control of the flow rate in each classroom. To prevent reverse air flow through the duct system, all the classrooms have their air intakes located on walls facing the predominant wind direction.

Balanced heat recovery systems were installed to ventilate the restrooms in the corridors, and the fume cupboards have additional fans.

Solar Chimneys

To increase the available stack effect, 6-meter-high solar chimneys were installed on the roof with auxiliary exhaust fans and central dampers mounted in parallel. In addition to extending the length of the exhaust duct, each solar chimney consists of a flat plate solar air collector that heats the air in the chimney when solar energy is available, thereby increasing the stack effect in the last 6 meters of the exhaust ducts. There are three solar chimneys, each serving a separate wing of the building, as shown in Figure 2. To cause equal stack effects on both floors, the cross-sectional area of the exhaust ducts from the first floor was made smaller than that of the ducts from the second floor in order to compensate for the greater available stack effect. Figure 3 shows the principle of the Tånga School ventilation system.

Hybrid Ventilation System Design Procedure

There was frequent contact between the architect, the ventilation consultant, and the researchers to ensure optimum performance and aesthetics of the system. Computer simulations of air flow rates were performed for alternative design arrangements with respect to the dimensions and layouts of the ducts and the design of the solar chimneys in order to arrive at maximum stack ventilation performance. This is important, as the stack effect is frequently below 10 Pa. The auxiliary fans used are 370 W variable-speed fans. The design simulations predicted the functioning of the system during the worst conditions, i.e., warm weather and no wind. The results of the design simulations using the simple stack effect and solar chimney model showed how the changeover temperature between the different operational modes (Mode 1, stack effect only; Mode 2, fan-assisted stack effect) depends on whether the sun is shining or not. During cloudy weather, the changeover temperature is in the range 6ºC to 7°C. During sunny weather, the solar chimney increases the changeover temperature by 2°C. This means that, with the average outdoor temperature for this area, stack effect should be sufficient for ventilating the school in the winter months, early spring, and late autumn. An example of how much fan assistance would be needed during a warm and sunny day has also been calculated and shows that the stack effect still provides approximately 50% of the driving force (Nielsen et al. 1999).

The Ventilation Control System

The ventilation control system at the Tånga School is a combination of individual and central control. The BEMS and a CO_2 sensor in each room control the local dampers. At 06:00 the dampers are opened 50% so that the classrooms are aired before the pupils arrive at 08:00. During the day, the local dampers are controlled by the CO_2 sensor, and at 18:00 they are closed again. At a CO_2 level of 1000 ppm or less, the local dampers are set to a minimum position. If the CO_2 level exceeds 1000 ppm, the dampers increase their opening. An increase of CO_2 levels over 1000 ppm also causes a signal lamp to activate in the classroom to make the teacher aware of the situation so that corrective measures can be taken. If the CO_2 level reaches 1500 ppm, the local dampers are opened 100%. In addition, the classroom teacher can override the local control system and manually change the position of the local dampers. At extremely low outdoor temperatures, or low indoor temperature, maximum damper opening is restricted to 50% opening to prevent excessive energy consumption and problems with dry or cold indoor air.

As stack effect decreases in the summer, the temperature difference between the outdoor air and the air in the solar chimney may be no longer sufficient to maintain the design air flow rates. In such instances, the central dampers in the chimneys are closed and the auxiliary exhaust fans are started. To avoid a high frequency of starting and stopping the fans, the dampers are opened and the fans are stopped at a somewhat higher temperature difference. During operation, the exhaust fans are controlled by the pressure drop across the fans. As the temperature difference decreases, the pressure drop is increased and more fan power is needed.

The ventilating system strategy allows for window opening when necessary. This is considered necessary when the CO_2 level in the indoor air exceeds 1000 ppm for a longer time or if the indoor temperature rises to an uncomfortable level in the summer. In the summer, the stack effect can also be utilized for night cooling of the building.

From a centrally located control panel, the caretaker can, if necessary, override both the local and the central control strategy and set a fan-controlled design air flow rate of 7 L/s per person in the whole building.

Tånga School Hybrid Ventilation System Design Requirements

The requirements for energy conservation were, for the building as a whole, to meet the national requirements. For the ventilation system, the mean energy consumption should be 50% lower than for a constant air volume (CAV) system without heat recovery, and the air flow rate should meet the national requirement during occupancy. As the actual system does not incorporate any means for heat recovery of the exhaust air, energy conservation for the ventilation system is achieved by using a variable air volume (VAV) control system to limit fan-motor and space-heating energy requirements. It should also be noted that for a large part of the year the moderate local climate limits the demand for heating in the classrooms when they are in use. As such there is no need for heat recovery during periods of high air flow rates.

The requirements for the ventilation system in the Tånga School are shown in Table 1.

The national requirement for minimum ventilation air flow rate is 7 L/s per person during periods of occupancy and 0.35 L/s m² during periods of nonoccupancy, and this is the design air flow rate for fan-assisted ventilation (210 L/s per classroom). However, the design air flow rate for the actual hybrid ventilation system (natural ventilation) is only 4.5 L/s per person (135 L/s per classroom), based on maximum occupancy in the classrooms. The arguments for this design value are that there is seldom maximum occupancy, children have lower metabolism rates than adults, a CO_2 level over 1000 ppm can be permitted for shorter periods of time, and since there are classroom breaks at frequent intervals, the reservoir of air in the room will recover rapidly. The latter argument is in accordance with Dix (2000) who suggests that the ventilation rate can be reduced to 4 L/s per person in a large space such as a sport arena due to the reservoir effect, on condition that the volume per person is comparable between the two cases.

However, if, for any reason, the hybrid ventilation system does not produce acceptable indoor air quality, it should always be manually possible to change to a third CAV operation mode with the fans running to ensure an air flow rate of 7 L/s per person based on maximum occupancy in the whole building.

The hybrid ventilation system in Building B had a total cost, with manufacturing and installation, of 61 Euro/m^2 and the balanced mechanical ventilation system in building C had a total cost of 87 Euro/m^2.

PERFORMANCE MONITORING

The objective of the performance monitoring program was to evaluate the performance of the hybrid ventilation system with respect to ventilation (air flow rates, air change efficiency), thermal comfort, use of electricity for ventilation, energy use for space heating, and other requirements as shown in Table 1.

TABLE 1
Overall Requirements for the Tånga School

Requirements for the Tånga School	Swedish Building Regulation Requirements
Outdoor air 0.35 L/s m²	0.35 L/s m²
Outdoor air 7 L/s per person, should be possible to reach with fan assistance Outdoor air 4.5 L/s per person, with natural ventilation	7 L/s per person (recommendation)
No recirculated air	No recirculated air
Air velocity within the occupied zone: winter <0.15 m/s, summer <0.25 m/s	Winter <0.15 m/s, summer <0.25 m/s (recommendation)
Air exchange efficiency >40%	>40% (recommendation)
Airtightness of building envelope < 1.6 L/s m² at 50 Pa	1.6 L/s m² at 50 Pa
Outdoor air intake located in order to minimize pollution from vehicles and other outdoor sources	
Indoor air outlet from the school located at a safe distance from the outdoor air intake, in order to prevent recirculation	
Ducts should be accessible for cleaning	Ducts should be accessible for cleaning
Particles <60 µg/m³ (> 5 µm)	
TVOC <200 µg /m³	
CO_2 <1000 ppm (indicator of IAQ) with normal occupancy CO_2 <1500 ppm for short periods	<1000 ppm (recommendation)
Recommended relative humidity 30%-60 % at normal indoor temperature	
Formaldehyde <50 µg/m³	
No humidifier	
Flexible ventilation system that can be adapted to the needs of the occupants	
Operative temperature in winter conditions between 20°C and 22°C and in summer conditions between 20°C and 26°C with normal occupancy	Directive operative temperature >18°C
The vertical temperature difference between 0.1 m and 1.1 m above floor level should not exceed 3°C	
The surface temperature of the floor shall be between 19°C and 26°C	>16°C
The radiant temperature asymmetry from windows or other cold vertical surfaces shall be less than 3°C	Difference in directive operative temperature <5°C

The monitoring period was started in January 2000 with single tests to discover if the installed ventilation system was functioning as designed, using both active and passive tracer gas techniques. In April 2000, the actual monitoring period was started. The monitoring system was integrated with the BEMS system and included continued measurements of outdoor conditions, indoor conditions, energy use, and system operation for one year. Table 2 shows a detailed list of the measured quantities.

The monitoring with the BEMS has been complemented with single measurements of thermal comfort as well as a standard indoor climate questionnaire.

RESULTS AND DISCUSSIONS

Single Tests

The single air exchange tests with active and passive tracer gas showed that the air change rate in February was low, especially in one of the classrooms. During daytime the average air change rate was below 1.0 L/s m^2, which should be compared with the designed rate of 2.25 L/s m^2 with 100% opening of dampers. Small changes, such as adjustment of opening of dampers, were therefore made to the system to improve the ventilation. In addition, the tests also confirmed that measurements of air change rate, based on the airflows in the exhaust ducts, produced similar results to measurements based on the tracer gas measurements. This indicates that the air is being evacuated properly through the exhaust ducts.

Indoor Comfort

The air temperatures in the occupied zones of the respective rooms have been between 21ºC and 24°C during the one-year monitoring period. During only a few days when the outdoor temperature exceeded 25°C did the indoor temperature exceed 24°C. The air temperature at floor level (measured at 0.1 m height below the blackboard) has been above 19°C, except for a few very cold days when it was around 18°C. The vertical temperature difference between 0.1 m and 1.7 m has not exceeded 3ºC. The relative humidity has been between 30% and 60%, except for a few very cold days when it fell to 24%.

Detailed measurements of thermal comfort were carried out in two classrooms with hybrid ventilation during a warm and sunny spring week (average outdoor temperature of 13.0°C). The measurements showed that the radiation asymmetry was less than 3.5ºC and that the air velocity was less than 0.15 m/s. The operative temperature was between 20ºC and 22°C, except for short periods (20 to 30 minutes) when it could be up to 24°C at points close to the windows. The air velocity was also below the requirement of 0.15 m/s during measurements made when the ambient temperature was 4°C.

The staff is so far satisfied with the indoor environment except for some complaints about noise from trucks that pass every second hour on a small road beside the air intakes for some classrooms.Otherwise, the staff are very satisfied with the quiet ventilation system.

TABLE 2
Parameters Measured with the BEMS System

Measured quantity	No. of sensors	Frequency of data reporting	Measurement uncertainty
Energy use for space heating	5		± 5%
Use of electricity	20		± 2%
Air temperature in classrooms (at 0.1 m, 1.1 m, and 1.7 m height)	18	Every 5 minutes	± 0.5 K
Air temperature in exhaust ducts	6	Every 5 minutes	± 0.5 K
Air temperature in group rooms	8	Every 5 minutes	± 0.5 K
Relative humidity in classrooms	6	Every 5 minutes	± 5%
CO_2 in classrooms	6	Every 5 minutes	± 100 ppm
Air velocity in ducts	6	Every 5 minutes	± 0.1 m/s
Air flow direction in ducts	6	Every 5 minutes	
Manual or central control	6	Every change	
Position of local dampers in classrooms and group rooms	20	Every 5 minutes	
Outdoor air temperature	1	Every hour	± 0.5 K
Global horizontal solar radiation	1	Every 5 minutes	± 5%
Relative humidity, outside	1	Every 5 minutes	± 5%
Wind speed	1	Every 5 minutes	± 0.5 m/s
Wind direction	1	Every 5 minutes	

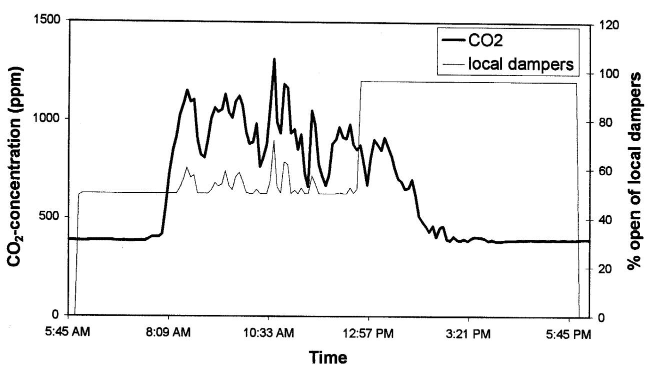

Figure 4 *CO_2 concentration and opening of the local dampers during one working day (September 28, 2000) in a classroom on the ground floor.*

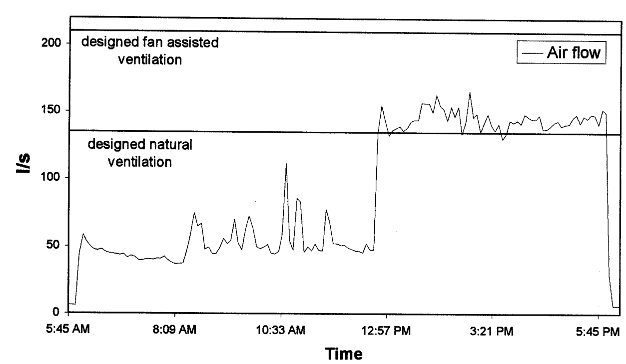

Figure 5 *Air flow through the exhaust duct during the same working day (September 28, 2000) and classroom as in Figure 4.*

Ventilation Operation

Figure 4 shows the monitored data for how the system works for a classroom during a typical working day with fan-assisted ventilation. The light line shows the opening of the local dampers in the classroom. At 06:00 the local dampers open to 50% and the classroom is aired before the students arrive at 08:00 and the CO_2 concentration (heavy line) starts to increase. When the CO_2 concentration reaches 1000 ppm the dampers open further and are then controlled by the central control system in response to the CO_2 concentration. The figure shows that the CO_2 concentration exceeds 1000 ppm for short periods (around ten minutes) before the system increases the ventilation rate.

At about 13:00, the teacher switched over to manual control of the local dampers and chose to increase the opening of the dampers. This increased the ventilation and reduced the CO_2 concentration, as can be seen in Figure 5. The diagram also shows that the flow rate does not reach the designed flow rate for fan-assisted ventilation even though the dampers are opened 100% in the manual control mode. However, the system seems to manage to keep a low CO_2 concentration except for short periods. Even though all classrooms on the ground floor have very low flow rates compared to designed

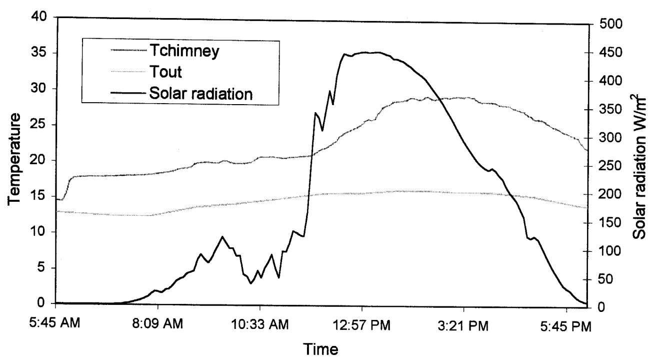

Figure 6 *Outside temperature, temperature in the chimney, and solar radiation during one working day (October 4, 2000).*

rates, the CO_2 concentration is not very high. This might be due to the fact that there are not as many pupils in the classrooms as assumed in the design procedure.

The pattern of CO_2 concentrations exceeding 1000 ppm for short periods is typical for all six classrooms in which performance was carefully monitored. This is matched by a corresponding behavioral pattern by which the teacher often takes manual control of the local dampers to reach maximum ventilation. This happens especially during the afternoons, probably due to the fact that the indoor temperature then often is higher than in the mornings, which may indicate that the air change rate actually is too low or that the heating system is controlled inadequately. Another reason may be related to the behavior of the classroom occupants. A red lamp in each classroom indicates when the classroom CO_2 concentration is above 1000 ppm. However, as the ventilation system responds slowly under automatic control to correct such conditions, the teacher tends to notice the delay in restoring fresh air in the classroom and switches to manual control mode. The system is seldom switched back to central control when the class leaves, which results in an unnecessarily high ventilation rate, and associated energy loss in unoccupied rooms.

Figure 6 shows the ambient temperature, the temperature in the chimney, and solar radiation. At the beginning of the day, the temperature difference was insufficient for natural ventilation and so the auxiliary fans were in operation, as can be seen in Figure 7. At about 13:00, the sun appeared and the increase in solar radiation raised the temperature in the chimney so that fan operation was no longer needed. Figure 7 shows that the air flow reached the design value of 210 L/s, with 50% fan assistance and 100% opening of the local dampers (Figure 8). The fan was turned off and the flow rate decreased to the design value for natural ventilation. This applied for all classrooms on the second floor. On the ground floor, the ventilation rate did not reach the design value for fan operation, as can be seen in Figure 5. This may be due to the ducts being only 315 mm in diameter on the ground floor, while they are 400 mm in diameter on the second floor. The smaller diameter first floor ducts were intended to compensate

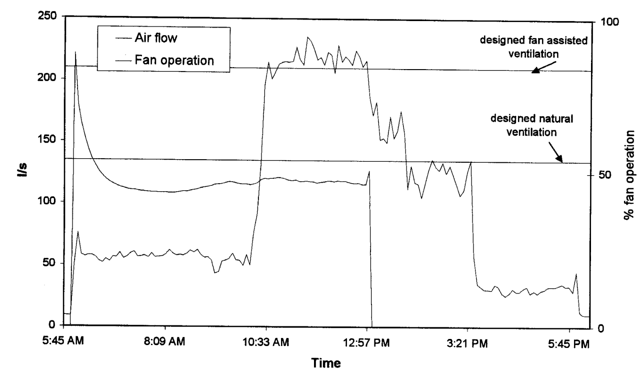

Figure 7 *Air flow through the exhaust duct and fan operation during the same working day as in Figure 6 (October 4, 2000), in a classroom on the second floor.*

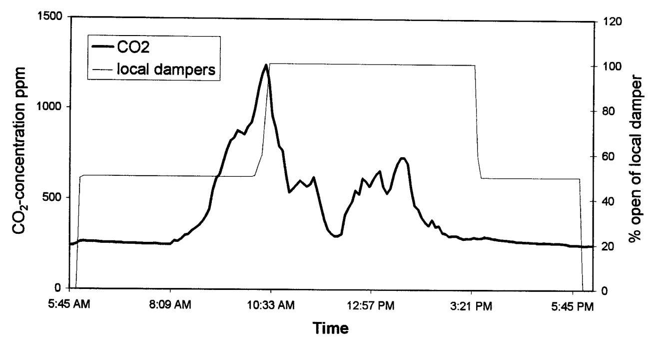

Figure 8 *CO_2 concentration and opening of the local dampers during the same working day and classroom as in Figure 7 (October 4, 2000).*

for the greater height difference and duct resistance to the chimney.

Performance at the Tånga School has been monitored for a year, both in warm and moderate weather conditions with fan-assisted ventilation and in cold weather with natural ventilation. During these conditions, the requirements for the indoor climate have been fulfilled on the first floor, except for short periods when the CO_2 concentration has exceeded 1000 ppm. The latter could probably be improved if the control system's setpoint for regulating the local dampers was lowered to 800 ppm instead of 1000 ppm or if the dampers opened fully at 1000 ppm instead of at 1500 ppm. This would raise the ventilation flow rate earlier and, with more fresh air in the classrooms, the system might succeed in keeping the CO_2 concentration below 1000 ppm at all times. This would be in agreement with the work reported by Seppänen et al. (1999) in which they examined several carbon dioxide studies and found that about half of them suggest that the risk of sick building syndrome decreases significantly with decreasing CO_2 concentration below 800 ppm.

On the ground floor the airflows in the classrooms have not reached requirements.

Energy Use

The energy used for space heating of Building B has been reduced by the retrofit. Measurements normalized to a reference year, Gothenburg 1988, show that the energy consumption in Building B has been reduced from 85 to 58 kWh/m^2 per year as a result of the demand-controlled and time-controlled hybrid ventilation system and the new low-energy windows in one fourth of the building. The energy consumption in Building C has been reduced from 133 to 62 kWh/m^2 per year.

At the same time, the use of electricity for ventilation in Building B been reduced from 22 to 10 kWh/m^2 per year and in Building C from 22 to 7 kWh/m^2 per year. The assisting fans in the chimneys used 0.5 kWh/m^2 per year, while the balanced heat recovery ventilation system for the restrooms and the fans for the fume cupboards used 9.5 kWh/m^2 per year. The latter high electricity consumption is due to the fact that the heat recovery ventilation systems in the restrooms were set to work continuously (Blomsterberg et al. 2001).

A comparison of the yearly energy used for space heating per square meter in Buildings B and C indicates that a demand-controlled and time-controlled hybrid ventilation system can be of the same order of magnitude as a mechanical ventilation system with heat recovery. However, the two buildings are not completely comparable, as the type of activity is not identical and therefore requires different flow rates (Building B has primarily classrooms and Building C workshops).

If the settings for the balanced heat recovery ventilation system for the restrooms are adjusted to work only during the daytime, the electric consumption of the two systems will be comparable.

The performance measurement of the retrofitted school shows a reduction in energy used for space heating of 32%. This reduction can be further improved considering the fact that during the first year of operation the building has been thoroughly aired in order to dry out residual building moisture. The dampers of the hybrid ventilation system were fully open for ten minutes every hour during the nights and weekends, resulting in greater energy use than anticipated. This night and weekend airing will not continue in normal operation, and this will cause the energy consumption to fall. Also, the teachers tended to override the ventilation system and leave it on a high setting far longer than necessary.

The total cost saved by reduced energy consumption with the hybrid ventilation system (Building B) is 10,800 Euro/year and for the balanced mechanical ventilation system (Building C) 6500 Euro/year, assuming that the price of electricity is 0.11 Euro/kWh and of district heating 0.06 Euro/kWh. This may be compared with the investment cost of 224 kEuro for Building B and 95 kEuro for Building C. However, as this is a retrofit situation, the installation of new ventilation systems would have been carried out in any case. This means that, to do a real cost-benefit analysis, the marginal costs should be compared with a retrofit to the original standard of the building.

CONCLUSION

The Tånga School has been retrofitted with a hybrid ventilation system controlled with a building energy monitoring system (BEMS).

The requirements of thermal comfort, relative humidity, and air velocity conditions are fulfilled on the first floor of the hybrid ventilated building, while the air flow rates on the ground floor are not sufficient. The occupants are satisfied with the hybrid system, in particular with the fact that the system is quiet. Teachers frequently took advantage of the ability to manually control the system to increase the ventilation rate.

The hybrid system manages to maintain a good indoor environment except for short periods of about ten minutes when the carbon dioxide concentration can rise above 1000 ppm. This could probably be improved if the control system's setpoint for regulating the local dampers was reduced to 800 ppm instead of 1000 ppm.

The design criteria for the ducts need to be reconsidered since the first floor does not reach the design air flow rates, whether with natural ventilation or with fan-assisted ventilation.

The BEMS system should be reprogrammed, e.g., by including a timer on the manual control of the hybrid ventilation or an automatic reset. This will avoid high ventilation rates in classrooms without occupants and thus unnecessary energy losses.

The evaluation of the energy savings associated with the retrofit shows that electricity consumption for the hybrid ventilation system has decreased 55%. The saving can be further improved if the settings for the balanced heat recovery ventilation system for the restrooms are adjusted to work only in daytime. The energy saving evaluation also shows that energy used for space heating has been reduced by 32%. This saving can also be further improved by adjustment of the night and weekend airing by the timer or resetting to override manual control.

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