DTU Library

Performance of low pressure mechanical ventilation concept with diffuse ceiling inlet for renovation of school classrooms

Terkildsen, Søren; Svendsen, Svend

Publication date:
2011

Link back to DTU Orbit

PERFORMANCE OF LOW PRESSURE MECHANICAL VENTILATION CONCEPT WITH DIFFUSE CEILING INLET FOR RENOVATION OF SCHOOL CLASSROOMS

Søren Terkildsen[*1], Svend Svendsen[1],

1 Technical University of Denmark
Department of Civil Engineering, Section of Building
Physics and Services
Brovej, Building 118
2800 Kgs. Lyngby, Denmark
*Corresponding author: sterk@byg.dtu.dk

ABSTRACT

In a great portion of Danish primary schools the mechanical ventilation systems is outdated or simply rely on opening of windows to ventilate the classrooms. This leads to high energy consumption for fans and/or ventilation heat losses and poor indoor environment, as the ventilation systems cannot provide a sufficient ventilation rate. A recent study with 750 Danish classrooms show that 56 % had CO_2-concentrations over a 1000 ppm, which is the recommended limit by the Danish working environment authority and this adversely affects the performance and well being of the pupils. This paper describes a mechanical ventilation concept to lower energy consumption and improve the indoor environment, developed for refurbishment of school classrooms. The performance of the concept is investigated through computer simulations and measurements of energy consumption and indoor environment. The measurements are made at a pilot project at Vallensbæk primary school, where a system is installed in two classrooms used by the 6th grade. The system is designed with an oversized air handling unit and duct system to reduce the pressure loss and thus fan power required to operate the system. The supply air to the rooms is distributed through diffuse ceilings inlets, where the air is supplied over a large part of the ceiling area through small perforations. The flow rate to the rooms is determined by motion and CO_2 sensors and controlled by a new type of flow control dampers increasing the flow rate according to the demand. The measurements and simulation results show that the indoor environment fulfils indoor environment category II in EN 15251 and the CO_2-concentration is kept below 800 ppm. The heat recovery efficiency is 85 % and the SFP-value of the system is measured to 495 J/m^3 at the design flow rate, lower than 1/4 of the maximum requirement in the Danish building code. This result in a yearly fan power consumption of 4.0 kWh/m^2, included a primary energy factor of 2.5. The results show that the indoor environment is improved to an acceptable level with little energy use, making the concept applicable for implementation in future energy renovation project of school classrooms.

KEYWORDS

Low pressure, diffuse ceiling, mechanical ventilation, energy renovation, performance, school children.

INTRODUCTION

Large parts of suburban Copenhagen was developed and build through the 1960-70. The schools build in those years rely on opening of windows or mechanical ventilation systems that are now outdated to provide fresh air. The recommended maximum CO_2-concentration by the Danish working environment authority is 1000 ppm [1], but a recent study with 750 Danish classrooms showed that 56 % had CO_2-concentrations above that [2]. This shows poor indoor air quality in the classrooms which is due to an insufficient ventilation rate and this adversely affects the school children learning ability and health. Wargocki *et al* (2007) [3] has shown that school children performance can be increased up to 15 % by improving the indoor air quality. Solutions on how to renovate and improve the ventilation systems in existing schools and thereby improve the indoor environment is therefore needed. However, this must be done without excessive energy use, due to the increasing climate concerns. Traditional ventilation system can have specific fan power (SFP) values of 5.5-13 kJ/m^3 while new systems have SFP-values of 2-2.5 kJ/m^3 [4]. The heat recovery in traditional ventilation systems is typically cross flow heat exchangers with efficiencies around 50 % if any heat recovery at all, while new systems have efficiencies of 80-85 %. The energy requirements on buildings in Denmark will be lowered by 75 % in the following years up to 2020 [5]. Current ventilation systems cannot comply with these requirements and new solutions that have minimal fan power consumption and heat loss are therefore needed, although without compromising the indoor environment. This paper describes a pilot mechanical ventilation system that is installed in two classrooms at Vallensbæk primary school, as part of an overall renovation of the ventilation system at the school. The system design is based on a low pressure concept and the objective was to determine the performance of different design solutions and components, and investigate how a conventional oversized air handling unit operates at low pressure. The system has high efficient heat recovery, diffuse ceiling inlet and demand controlled flow rate controlled by a new type of flow control damper. The goal is to keep the indoor CO_2-concentration below the recommended 1000 ppm by the Danish Working Environment Authority and reach a SFP-value of 0.65 kJ/m^3, equalling 1/3 of the current requirement of 2.1 kJ/m^3 in the Danish building code.

CASE

General description of pilot system

The pilot system is installed in class room 42 and 44 in a wing of Vallensbæk primary school, see Figure 1 left. The rooms are presently occupied by the 6th grade (age 11-12) and there are 24 pupils in each class. Room 42 is 80 m^2 and room 44 is 60 m^2, with a floor height of 2.5 m in the main part of the rooms.
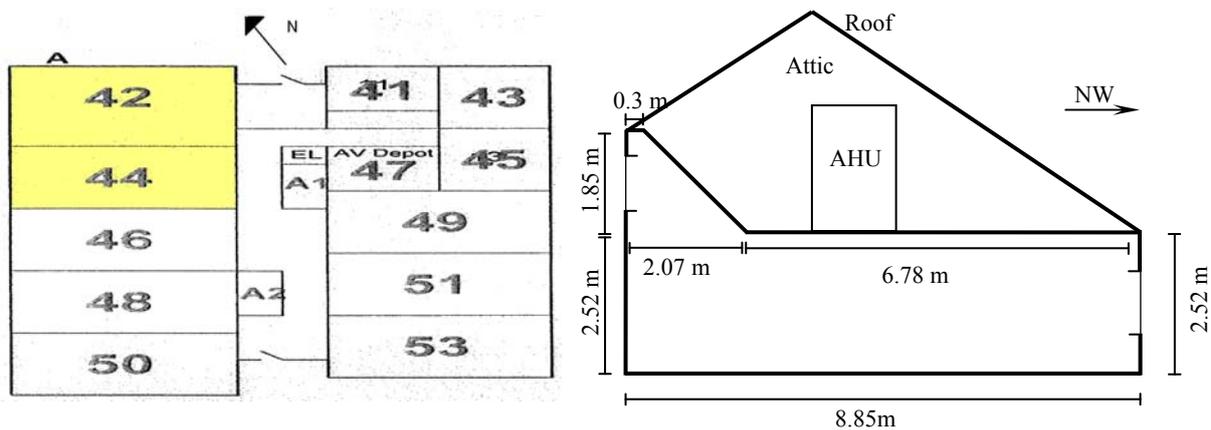
Figure 1. Plan of rooms used for pilot project (left) and section of the rooms (right)

The main facade with windows is oriented North-West. Therefore is the solar gain during the occupied hours limited and only fabric curtains are installed as shading device. The air handling unit (AHU) is placed in the attic above room 42 to reduce duct lengths, see Figure 1 (right). The fresh air to the rooms is supplied through a diffuse ceiling in the horizontal part of the ceiling and the extract is placed in the sloped part of the ceiling.

Indoor environment requirements

The main purpose of the new ventilation system was to improve the indoor air quality, and maintain the CO_2-concentration below 1000 ppm, which is the recommended limit by the Danish working environment authority. The system was only designed to provide fresh air and not cool the air, as the need for cooling is expected to be limited. This is due to the orientation of the windows, limited internal heat loads and varying occupancy during the day. The rooms are used for maximum 1.5 hours at the time before a break of at least 20 minutes, where most of the pupils leave the room, which is providing a break to recondition the room. The room temperature should however comply with the recommended temperature range in EN 15251 category II of 20-24 ^{o}C in the winter and 23-26 ^{o}C in the summer [6]. The heating demand is to be covered by the heating system, but the supply air is preheated in the heat recovery to decrease ventilation heat loss and avoid draught problems. The design flow rate for the system is set to 5 l/s per person resulting in a flow rate of 450 m^3/h for one room with 24 pupils and one teacher. This corresponds to an air change rate of 2.0 h^{-1} and 2.6 h^{-1} for room 42 and 44, respectively.

Air handling unit

The AHU is a conventional unit with a heat exchanger radial fan and filters. The unit is oversized compared to standard dimensioning to reduce pressure losses in filters and heat exchanger. The unit has a minimum flow of 450 m^3/h in order to function properly according to the producer, this correspond to the design flow rate for one room and will therefore be tested if only one room is occupied. The maximum flow rate is 2500 m^3/h which is well above the expected demand of 900 m^3/h for the two rooms. The fan will therefore operate at low speeds the entire time, minimizing the fan power consumption. The heat recovery is a counter flow exchanger and has a design efficiency of 85 %. Higher efficiency is not expected to provide further energy savings as the ventilation heat loss will be covered by internal gains

from occupants, lighting system and equipment [7]. A heating coil has been omitted as studies of diffuse ceiling inlets show that it is possible to supply cold air ($\Delta T > 8$ ^oC) without causing draught problems [8]. The heat recovery will therefore be sufficient to preheat the air making a heating coil dispensable and an easy way to reduce cost. The unit has compact filters on both the supply- and extract side with efficiencies EU7 and EU5, respectively.

Diffuse ceiling inlet

The supply air is blown into the room via a suspended ceiling with porous plates. The ceiling consists of passive and active plates, where only the active plates are permeable. Above the plates is a 15 cm cavity that functions as a pressure chamber making the supply air distribute evenly through the active plates, see Figure 2.
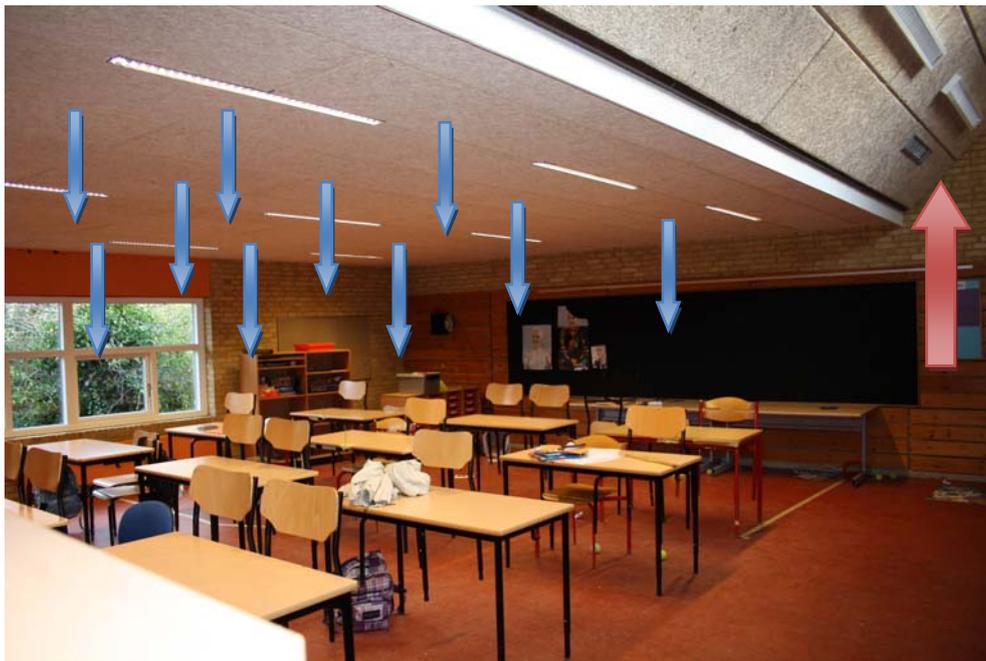

Figure 2. Picture of room 42 with principel airflow pattern of the diffuse ceiling inlet indicated with arrows.

There are eight active plates of 0.6x2.4 m giving a total inlet area of 11.5 m^2 in each room. This large inlet area reduces the inlet air velocity to a minimum, thereby preventing draught in the occupant zone. The low air velocities also allow for lower inlet temperatures, in [8] there was found no lower temperature limit that caused draught. Another advantage of diffuse ceiling inlet is the low pressure loss induced. In Hviid et al (2010) [9] pressure losses of 1.5-2.5 Pa was recorded and for the product used the producer states 2 Pa. The extract diffusers are the existing from the old ventilation system, which are placed on the sloped part of the ceiling. This was done to lower cost as the original diffusers had reasonable size and pressure loss. The placement of the extract diffusers high in the room is also favourable to remove warm and polluted air.

Duct system

Reducing the pressure loss in the duct system is an essential and relatively easy part in reducing the total pressure loss and thereby fan power needed. By increasing the dimension by one size, the pressure loss in straight duct can be reduced by 35 % and larger reductions can be achieved on single losses like bends, enlargements etc. In the design of the duct system

a pressure gradient of 0.1 Pa/m was aimed for, resulting in air velocities of 1-2 m/s, at the design flow rate of 450 m³/h to each room.

Control system

The air flow to the rooms is controlled by a new type of dampers (LeanVent®) see Figure 3, the damper has an aerodynamic design that minimize turbulence generation and thereby pressure and it can operate at low air velocities.
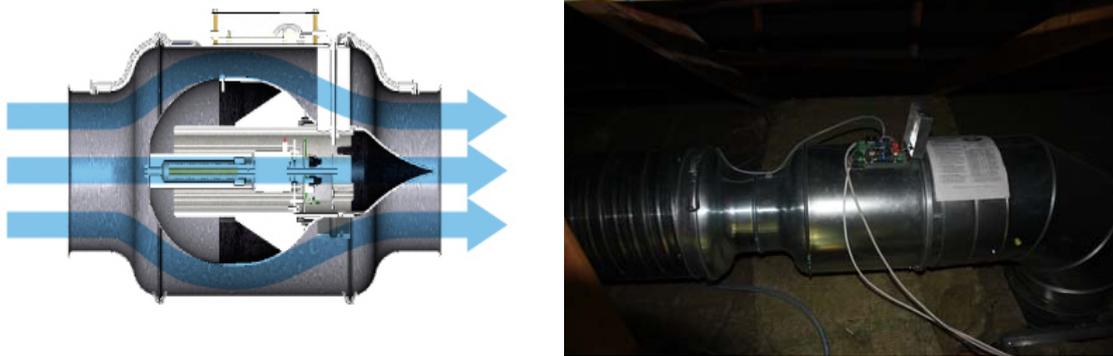

Figure 3. Principle sketch of airflow pattern in LeanVent® dampers (left) and picture a damper installed at Vallensbæk school (right).

The dampers calculate the flow rate by measuring the pressure across the damper and regulate it by adjusting the position of droplet shaped head in the flow direction. The ventilation demand is determined by a CO_2-sensor in each room. The sensor transmits a 0-10 V signal to the inlet dampers corresponding to CO_2-concentrations of 0-2000 ppm. The damper then regulate the flow rate according to the diagram shown in Figure 4.
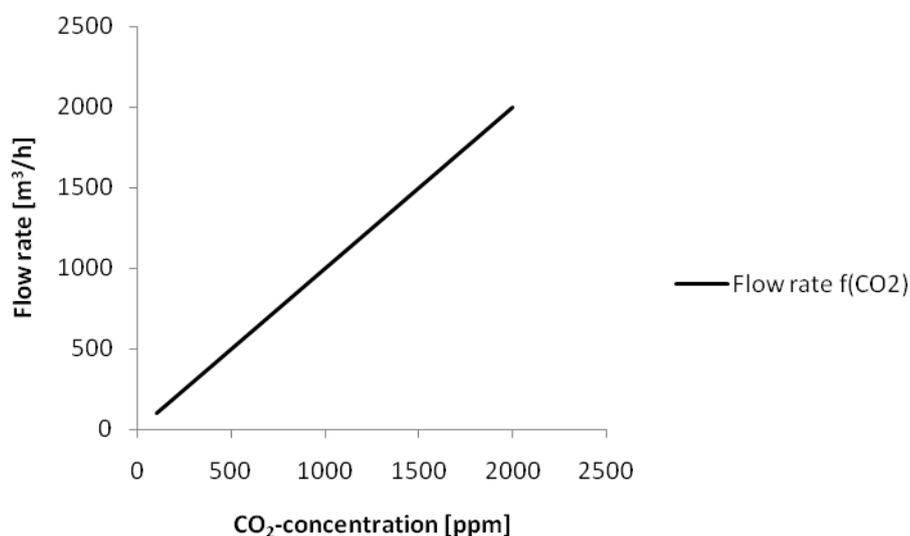

Figure 4. Theoretical ventilation flow rate to one room as a function of the CO_2-concentration.

The CO_2-concentration in the rooms in the morning and after breaks is expected to be close to the outside concentration of 360-400 ppm, and the flow rate will therefore be lower than the design value. However as the CO_2-concentration build up the flow will increase and maintain the concentration below 1000 ppm. The AHU has a time control, and motion sensors are installed in each room. The time control is set to start the system at 7.30 and shut down at 15.30, to avoid unnecessary ventilation outside occupied hours. The use of the classrooms is

highly irregular as the pupils have classes at other locations, therefore motion sensors was installed to shut down the flow rate to the room if it was not occupied. This does however not function correctly yet, as motion in one room will start the ventilation in both rooms. The fan is set to maintain a constant static pressure in the duct system that is controlled by a static pressure sensor placed in midway in the supply duct. The optimal set point for static pressure was determined through the setup process of the system and the aim was to lower it as much as possible to reduce fan power.

Measurements and calculations

A series of measurements and calculations was carried out to determine the performance of the new ventilation system and individual components or design solutions. The performance is evaluated based on the indoor environment, energy consumption, pressure loss and general applicability. The following measurements and calculations were carried out.

- Measurements and theoretical calculation of the pressure loss in the entire system and individual components, to determine the pressure loss characteristic of the system.
- Measurements and theoretical calculation of energy consumption to determine SFP-value of the system.
- Measurements of CO_2-concentration, temperature and relative humidity in the classrooms before and after installation.
- Calculations of indoor environment and annual fan power consumption in the simulation tool BSim [10].

RESULTS AND DISCUSSION

Pressure loss characteristics and fan power consumption

In Table 1 is listed the design- and measured pressure loss for the different components in the ventilation system at a flow rate of 900 m^3/h (corresponding to the design flow rate of the two rooms).

Component	Design pressure loss – supply system	Design pressure loss – exhaust system	Measured pressure loss – supply system	Measured pressure loss – exhaust system
Intake/exhaust	5	5	-	-
Heat exchanger	55	55	32	32
Filter	14	3	0	1
Duct system	32	39	12	21
Leanvent damper	20	20	19	23
Diffuse ceiling/ extract diffuser	2	10	1	8
Sum	128	132	64	85

Table 1. Design and measured pressure losses for components in pilot ventilation system at a flow rate of 900 m^3/h.

The total measured pressure loss was lower than the design values, more than 100 Pa for supply and exhaust combined. The difference is mainly due to lower pressure loss in the heat exchanger and duct system. The lower pressure losses in the duct system are due to lower pressure losses in both the fire dampers and silencers than calculated. The Leanvent® dampers are the key to this low operating static pressure as they can regulate the air flow by inducing pressure losses of only 14-30 Pa depending on the flow rate. The static pressure setpoint to

control the fan speed was set to 25 Pa, well below the standard values of 150-200 Pa recommended by the AHU manufacturer. In Figure 5 is shown the pressure loss characteristic for system along with the SFP-value characteristic depending on the flow rate.
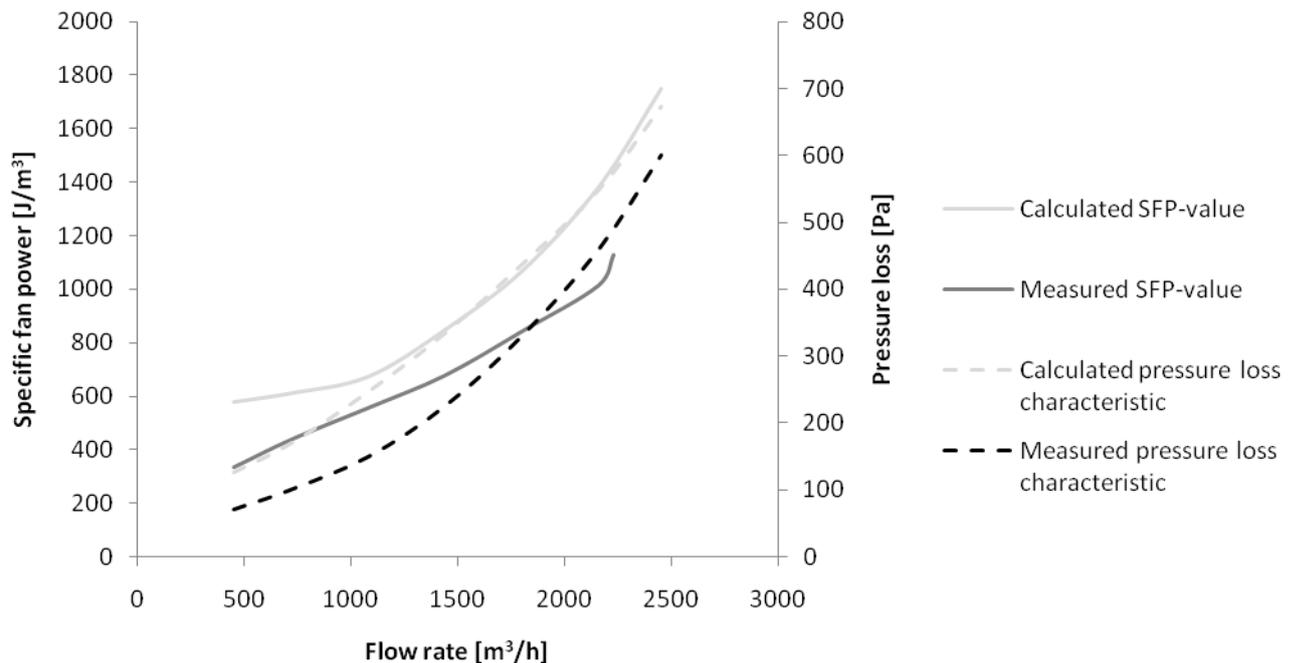

Figure 5. Calculated and measured SFP-values for the new ventilation system along the measured and calculated pressure loss Characteristics of the system.

The measured pressure loss characteristic is 100-150 Pa lower than the calculated. This is due to higher calculated pressure losses in the producers' software tool, compared to the measured values. The difference in pressure loss affects the SFP-values, where the measured value is lower than the calculated value. For the design flow rate of 900 m^3/h, the measured SFP value is 495 J/m^3. The maximum flow rate provided by the AHU during the measurements was 2230 m^3/h, which is 200 m^3/h lower than the producer specification. The yearly fan power consumption was calculated to 219 kWh in the simulation tool, equalling 4.0 kWh/m^2 including a primary energy factor of 2.5. In the simulation model the system was operating eight hours per day, five days a week and the system was turned off during school holidays.

Indoor environment

Figure 6 show the temperature and CO_2-concentration readings for week 6 in january and february before the new ventilation system was installed.
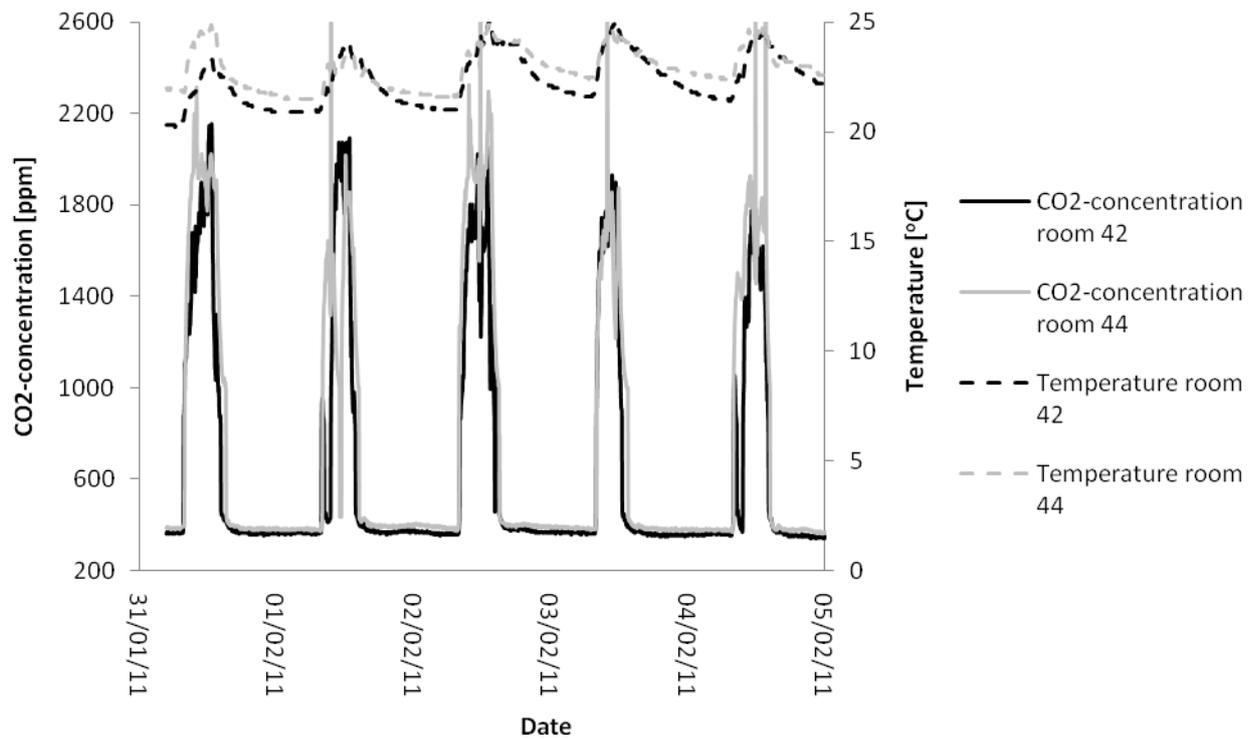
Figure 6. Indoor environment measurements in the two classrooms used in the study, before installation of the new ventilation system.

The figure show that the temperature varied between 21-25 ^{o}C in the two rooms, which is 1 ^{o}C higher than the design temperature range for the winter period. The maximum temperature will probably be decreased when the ventilation rate is increased with the new ventilation system. Otherwise it should be fixed by optimizing the heating system in the classrooms, to improve comfort and lower energy use. Figure 6 also shows that the CO_2-concentration increased from below 400 ppm at night to around 1800 ppm during occupied hours every day with maksimum values of 2600 ppm in room 44, values well above the recommended value by the Danish working environment authority of 1000 ppm. In Figure 7 is shown the temperature and CO2-concentration readings after installation.
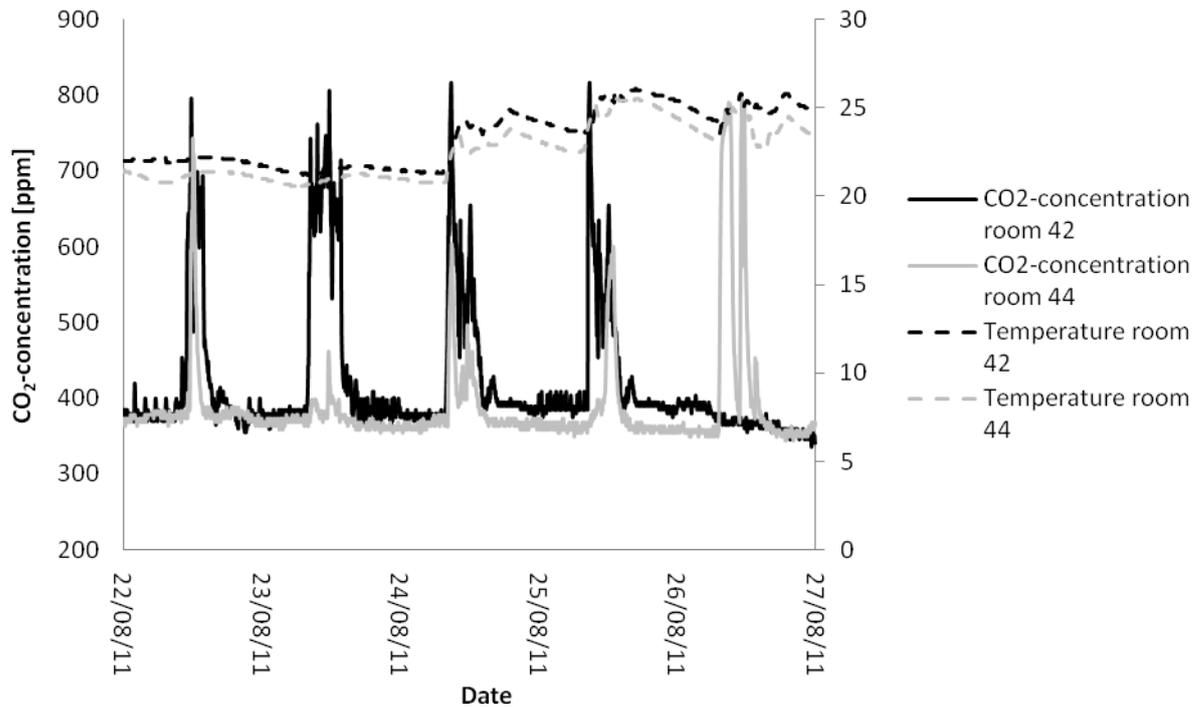
Figure 7. Indoor environment measurements in the two classrooms after installation of the new ventilation system.

The measurements after installation show that the temperature readings varied between 21-26 ^{o}C, this is 2 ^{o}C lower than the minimum design temperature. This is however assumed to be acceptable as the pupils should be dressed for colder (>20 ^{o}C) temperatures in the morning. The temperature increase during the day is maximum 3 ^{o}C in the two room, but if needed the pupils can adjust their clothing level during the day. The highest measured CO_2-concentration was around 1000 ppm lower after installation of the new system with peaks around 800 ppm. This is well below the requirement recommended value from the Danish working environment authority. The measured CO_2-concentrations had peaks higher than the results from the simulation model, which has a maximum concentration of 750 ppm, see Figure 8.
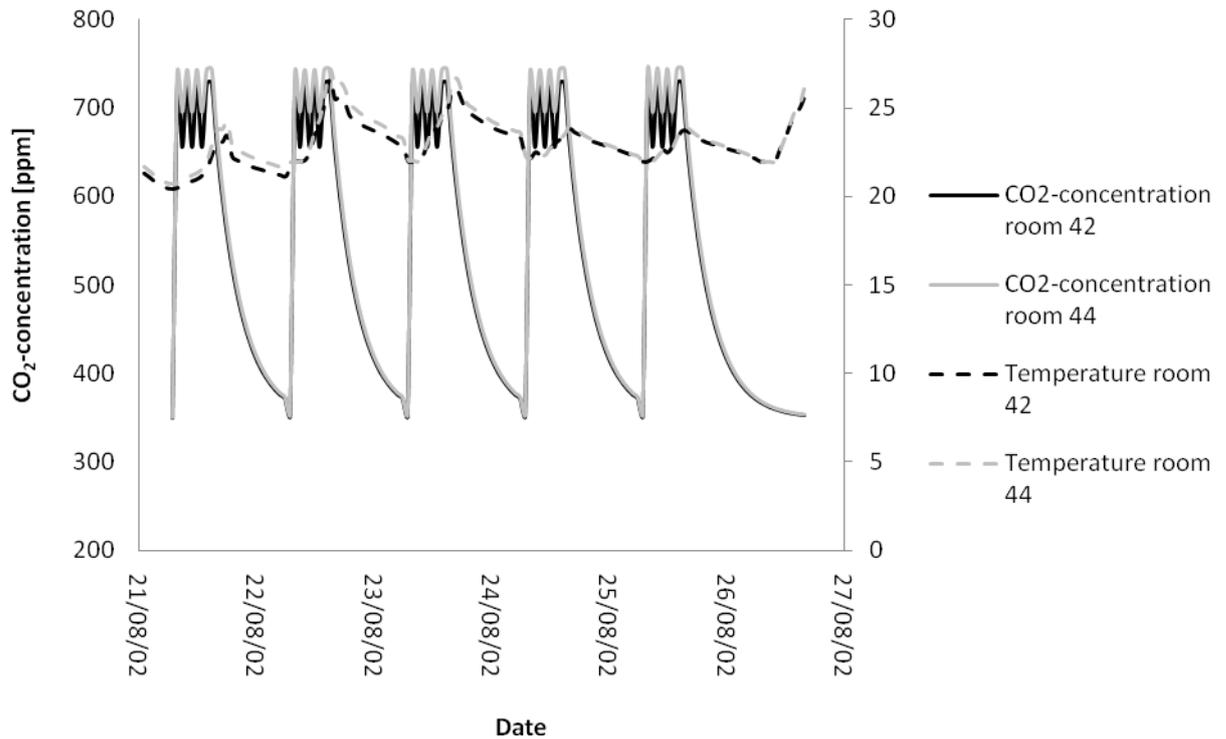
Figure 8. Simulated CO_2-concentrations and air temperatures in the two classrooms

The simulated CO_2-concentrations give the same uniform pattern for each day, that does not correlate with measured results. This is due to the irregular use of the school classrooms that is diffucult to model in a simulation tools occupancy schedule, but overall the results show that the CO_2-concentration fulfills the set requirements.

CONCLUSION

The measurements on the pilot ventilation system showed that it is possible to make school renovation that improve the indoor air quality while lowering the energy consumption for ventilation. The average CO_2-concentration was lowered from around 1800 ppm to 800 ppm, which means that the indoor environment now meet the Danish working environment authority requirements. After the new ventilation system was installed the indoor air temperature has only been measured in a part of the summer period that was somewhat mild. In this period the temperature range fulfils EN 15251 category II, but further measurement are necessary to determine thermal indoor environment under warmer conditions and in the winter as well. If further measurement show a need for cooling, the ventilation rate can be increased during occupied hours and/or cool the rooms by ventilating at night. The pressure losses throughout the system was reduced by increasing the size of the AHU and duct components, which was easy on paper, but did make it more complicated to fit the system into the attic. How the installation and manual work can be carried out should therefore always be concidered. The diffuse ceiling inlet has a pressure loss of around 2 Pa. This is a huge reduction compared to standard ceiling diffusers that induce pressure losses of 30 Pa or more, and help to lower the fan power needed to operate the system. Furthermore has Nielsen *et al* (2009) [8] showed that it is an efficient method to supply the fresh air without causing draught. The new type of damper was able to control the air accurately at air velocities of only 1-2 m/s. Therefore was the pressure loss across the damper only 19-23 Pa at the design flow

rate and even lower at smaller flow rates. The SFP-value of the system was measured to 0.5 J/m^3 at the design flow rate, lower than the calculated from the producers' software. The reason is difference in pressure loss and shows the importance of reducing pressure losses to improve energy efficiency. The energy consumption has only been measured for two months but the simulation showed a yearly energy consumption of 4 kWh/m^2 for the system. This makes the concept suitable for use in energy renovations to fulfil the energy requirements for 2020.

Further work

Further measurements, experiments and optimizations on the system are planned to investigate the performance of the components more in depth.

- Trazor gas measurements to determine the ventilation efficiency and mean age of air of the diffuse ceiling inlet.
- Air velocity and temperature measurements in a room to investigate local discomfort by calculating the draught rate.
- Performance test on the pupils under different ventilation flow rates to investigate how improved air quality affect their performance and well being.
- Measurements have only been carried out in the summer, but it is necessary to investigate how the system operates without a heating coil – does the heatexchanger freeze, is the inlet temperature to low and cause discomfort due to low temperature or draught.
- Implementation of a static pressure setpoint reset (SPSR) control agorithm, that ensures one damper is fully open and thereby reduce fan power needed. The energy savings will in this case not be great as the fixed static pressure already is below 25 Pa, it will however be interesting to investigate whether a SPSR control algorithm can operate at such low pressure.

REFERENCES

[1] Danish Working Environment Authority. 2011.
[2] Menå, H.R., and Larsen, E. 2010. *Målinger peger på dårligt indeklima I danske skoler,* HVAC magasinet, 10, 78.
[3] Wargocki, P., and Wyon, D.P. 2007. *The effects of outdoor air supply rate and supply air filter condition in classrooms on the performance of schoolwork by children*, HVAC&R Research. 13(2), 165-191.
[4] Blomsterberg, Å., Delmotte, C.H., Barles, P., Pennycock, K., de Gidds, W., Hardegger, P., and Maldonado, E. 2000. *Design methods for ventilation systems in residential and commercial buildings*, EC JOULE-TIP-Vent project.
[5] Danish Enterprise and Construction Authority. *Danish building code*. 2010.
[6] EN 15251. 2007. *Indoor environmental input parameters for design and assessment of energy performance of buildings addressingindoor air quality, thermal environment, lighting and acoustics, European Standard,* European Committee for Standardization.

[7] Jacobs, P., and Knoll, B. 2009. *Diffuse ceiling ventilation for fresh classrooms*, Proceedings of the 30th AIVC Conference.

[8] Nielsen, P.V., and Jakubowska, E. 2009. *The performance of diffuse ceiling inlet and other room air distribution systems,* Proceedings of cold climate HVAC, Sisimiut.

[9] Hviid, C.A., Svendsen, S., 2010. *Experimental and numerical analysis of perforated suspended ceilings as diffuse ventilation air inlets*, Ph.D. theses, Depertament of civil engineering, Technical University of Denmark.

[10] Aggerholm, S., and Grau, K. 2005. *Buildings energy demand – PC-program and calculation guideline*. Danish Building Research institute. SBI-guideline 213.