Air flow rates and energy saving potential in schools with demand controlled displacement ventilation

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Abstract

Two Norwegian schools with demand controlled displacement ventilation (DCDV)are analyzed and compared with more traditional constant air volume (CAV) solutions. The effective supplied air volume pr pupil in schools with DCDV displacement ventilation was about 1/3 of the corresponding supplied air volume in schools with CAV. This shows that there it a considerable potential for reducing energy use for ventilation purposes without compromising the indoor air quality with demand controlled dicplacement ventilation.

Keywords: Schools; Demand controlled ventilation; Displacement ventilation; Indoor air quality; Airflow rates

1 Introduction

Displacement ventilation means supplying ventilation air with relatively low air temperature at a low level in the ventilated room, and extract the used air at a high level. This creates a lower zone of fresh and quite unpolluted air, while the contaminants from humans and other convection sources are mainly displaced to a higher region preferably above the humans breathing zone. It is essential that the horizontal air movements are small in displacement ventilated rooms, making the air flow patterns dominated by free-convection currents. This conduces a thermal stratification that stabilizes air movements [1].

The heat sources will make a buoyant plume. The vertical flow rate of the plume will increase rapidly with height. This will continue until the plumes have consumed all the supply air. This happens at a level above floor called the concentration interface. The clean zone is below the concentration interface and the contaminated mixed zone is above. The clean zone will probably have better air quality than a room with mixed ventilation. Displacement ventilation has therefore a potential to improve the air quality in the breathing zone compared to mixed ventilation if the supply air volume ensures that the interface between the clean and the mixed zone is above the breathing zone. An air quality sensor placed at a desired interface height can do this. The air quality sensor controls the supply air volume to the room. The unanswered question is: What ventilation air volumes can we expect in a typical classroom with displacement DCV compared to mixed Constant Air Volume (CAV), and what are the corresponding energy saving potential with displacement DVC compared to CAV. To answer this the actual ventilation air volumes in two Norwegian schools, Jaer Scool and Mediaa School, with demand controlled displacement ventilation (DCDV) have been measured and compared with predicted air volumes with a typical CAV ventilation strategy. Corresponding energy use for DCDV and CAV is predicted for Mediaa School.

2 Methods

2.1 Ventilating air volumes with CAV

Modern Norwegian schools usually have a constant air volume (CAV) ventilation system, for which the ventilation rate is dimensioned for the maximum pollutant load expected in the ventilated space. The Norwegian building regulations require at least 2 m² for each occupant, or a maximum occupancy density of 0.5 pupils/m² [2]. Classrooms in Norway are traditionally sized for a maximum of 28 pupils and two teachers, which implies a required area of 60 m². Further, the building regulations suggest a ventilation rate of 7 ℓ/s for each occupant, with an additional 0.7 to 2.0 ℓ/s·m² depending on the expected emissions from the building materials and fittings [3]. Normal practice for CAV is to provide a classroom with 270 ℓ/s or 330 ℓ/s fresh air depending on the building materials. This airflow rate is kept constant during the operational hours of the air-handling unit.

2.2 Measurements of ventilating air volumes at Jaer School

The Jaer School, see Figure 2, is situated south east of Norway (59.9°N; 10.7°E). The 850 m^2 two-storey school building for 6-13 year old pupils was completed in 1999. The maximum number of pupils is 196, but the actual numbers was 150 during school year 2001-2002 and additional 10 teachers in average [9] and it was about the same number the year before.

The school has CO_2-sensor based demand controlled displacement ventilation (DCDV-CO_2), with sensors placed about 1.1 meter above the floor. The CO_2-sensors controls the airflow so that the CO_2-level does not exceed 1000 ppm at this height.

Air flow rate (by means of anemometer), have been logged for extended periods between January 2000 and April 2002. Measurements during Tuesday 16th of May 2000 are chosen for further analysis. Schild [11, 12] has described the measurements, methods and results. The airflow rate has been logged each five minute during the measurement period.

2.3 Measurements of ventilating air volumes at Mediaa School

The *Mediaa School*, see Figure 3, is situated in the relatively cold climate of Grong, Norway (64.5 N; 12.5 E). The 1000 m^2 one-storey school building for 6-13 year old pupils was completed in 1998. The maximum number of pupils is 196, but the actual number was 140 in 2002 and additional 8 teachers in average [6].

The school has CO_2-sensor based demand controlled displacement ventilation (DCDV-CO_2), see Figure 4 and Figure 5, with sensors placed about 1.2 meter above the floor. The CO_2-sensors controls the airflow so that the CO_2-level does not exceed 1000 ppm at this height.

At this school, the logged measurements included air temperature before and after the culvert, as well as estimated airflow rates (by means of pressure drop over the filter). Measurements during Thursday 23th of August 2001 are presented for further analysis. Tjelflaat [4,5] has described the measurements, methods and results. The airflow rate has been measured to 2890 m³/h when the filter pressure drop (p) is 20.9 Pa. The air volume (Q) is calculated at other pressure drops from the well-known relationship $Q = k\sqrt{p}$, where k is an empirically derived constant. The pressure drop were logged each minute during the measurement period.

2.4 Prediction of energy performance for alternative ventilation system configurations at Mediaa school

The school building has been further analysed throughout the year 2002 [7]. A detailed simulation model for the building has been developed using the simulation tool ESP-r, see Figure 6. The characterisation of the ventilation system with all its components was derived from a detailed field experiment [7,8]. The high accuracy of the measurements enabled very reliable modelling of the airflow network in the ESP-r model.

All the remaining parts of the model were also critically evaluated, including the modelling of solar radiation, the control of heat injection, internal heat gains, the predicted infiltration/exfiltration rates and the heat exchange mechanisms in the embedded ducts and all the other rooms and construction elements in the building. Meteorological data were measured on site. Through comparison with data from a closely located meteorological station and regionally adapted theoretical models, detailed calibration algorithms were developed, assuring high accuracy on the meteorological input data. The thermal bridges in the building envelope were taken into account through calibration of the insulation levels until the predicted energy consumption matched the monitored energy consumption.

Results from the ESP-r simulation model reflected the monitored data from the Building Energy Monitoring System (BEMS) well throughout the whole year under variable climatic conditions, use and airflow rates [7]. The model is therefore suitable for studying the effect of alternative building and system design options.

Due to the high complexity of the simulation model, and that simulations had to be carried out with one minute time steps (or less) to reflect the control system properly, simulations and results analysis were relatively time consuming. It was therefore chosen to focus on only one typical school week for the present analysis.

The week from Monday November 11 to Sunday November 17, 2002, was chosen. It represents an ordinary school week during which the measured energy consumption is very close to the yearly average. The detailed field experiment [8] for characterisation of the ventilation system was undertaken only two weeks earlier.

For the chosen week, simulation models for four different ventilation system configurations were made. The chosen configurations are:

1. CO_2-based demand controlled displacement ventilation (DCDV-CO_2) without heat recovery during unoccupied hours. This is the way the building was operating in reality. The pump operating the heat recovery circuit was programmed to shut down from 17h00 to 06h00 weekends and 20h00 and 06h00 weekdays, possibly because it was believed that night time ventilation was to low for heat recovery to be significant.
2. DCDV-CO_2 with continuous heat recovery. This is chosen as the base-case for comparative studies since alternative 3 described below involves higher ventilation rates during unoccupied hours.
3. Constant air volume (CAV) ventilation with ventilation rates set according to the airflow rates recommended in the guide to the Norwegian building regulations for a standard case, which are 7 l/s per person and 1 l/s per m^2 of floor area in order to handle emissions from materials. It the present case the ventilation rate during non-occupancy is based on the 1 l/s per m^2 of floor area, giving relatively high rates also at night.
4. In order to compare differences only in the daytime ventilation mode, configuration 4 involves CAV ventilation during occupancy and natural ventilation with heat recovery outside occupied hours as in case 2. Actually, it is not unusual that CAV systems are shut off outside school hours Configuration 4 is a realistic middle course between configuration 3 and shutting the ventilation completely off during non occupancy.

Due to the energy storage and lag effects related to the embedded duct, 40 days of pre-simulation were carried out prior to the chosen week for all configurations. In all cases the ventilation system were operating in the hybrid ventilation mode during the pre-simulation, as is the case in reality. While configuration 1 reflects reality, configurations 2 to 4 differs only in that the heat recovery system runs continuously in the simulation model. However, this difference does not affect the start-up conditions significantly, so that they can be taken as identical for all configurations.

3 Results

3.1 Ventilating air volumes with CAV

Table 1 shows typical ventilating air volumes with a traditional designed CAV-system during the operation time of the air-handling unit.

Table 1. Typical design criteria's and ventilating air volumes with a CAV-system.

School	Max. number of persons	Ventilating air volume per person [l/s*persons]	Area [m^2]	Ventilating air volume per because of emissions [l/s*m^2]	Total ventilating air volume with CAV [l/s]
Jaer	206	7	850	1	2300
Mediaa	204	7	1000	1	2400

3.2 Measured ventilating air volumes with DCDV

Table 2 shows the measured average and maximum air volumes.

Table 2. Measured air volumes with DCDV.

School	Measurement period	Number of persons associated with the school	Average ventilating air volume between 7 am and 5 pm [l/s]	Average ventilating air volume between 9 am and 3 pm [l/s]	Maximum ventilating air volume in the measurement period [l/s]
Jaer	Tuesday 16th May 2000	160	575	533	897
Mediaa	Thursday 23th August 2001	148	407	445	918

3.3 Predicted ventilating air volumes in Mediå School with different ventilating strategies

Figure 7 shows the predicted airflow rate for the alternative airflow configurations in the Mediå School. The actual mode of operation during the simulation period was CO_2-based demand controlled displacement ventilation (DCDV- CO_2), and the resulting airflow rate is given by the red curve.

The supply and exhaust fan were chosen by the ventilation consultant based on the airflow rates recommended in the guide to the Norwegian building regulations. To simulate the constant air volume (CAV) mode of operation, the fans in the simulation model were simply set to operate at their design capacity from 07:00 to 17:00 on weekdays and at 45% of the maximum fan frequency the remaining time.

With maximum 196 pupils, 8 teachers and 1000 m^2 of surface area, the airflow rates recommended in the guide to the Norwegian building regulations can for the Mediå School be predicted to 7 l/s per person*204 persons + 1 l/s per m^2 of floor area * 1000 m^2=2.42 m^3/s or about 12 l/s per person presupposed the maximum number of persons present (204), or 16 l/s per person with the actual number of persons associated with the school during 2002.
The predicted airflow rate, se the thick black curve in Figure 7, shows that the fans were correctly dimensioned in order to fulfil this requirement. The ventilation during non occupancy is in normal CAV-cases dimensioned to handle emissions from materials. Based on the recommended 1 l/s per m^2 of floor area, the ventilation rate should be about 1.0 m^3/s for the Mediå School. As can be seen from Figure 7 this criteria is practically satisfied when running the supply and extract fan in the simulation model at 45 % of their maximum fan frequency. The simulations made for system configuration 3 thus represent the operation of a classical CAV-system correctly designed and operated according to the guide to the Norwegian building regulations.

In configuration 4, the system is operated in CAV-mode during school hours as in configuration 3, and in hybrid mode during non occupancy as in configuration 1 and 2. The predicted airflow rate entering the ventilation air supply duct is given by the thick blue curve in Figure 7.

3.4 Predicted energy performance of Mediå School

In order to compare the energy performance for the different ventilation system configurations described above, the energy loss from the Mediå School has been analysed. The energy loss to the ground via conduction and to the ambient via the airflow or conduction through walls/roof, frames/doors and transparent surfaces are presented in Figure 8.

4 Discussion and conclusions

A traditional designed CAV ventilation system would provide Mediaa and Jaer School with about 2300 l/s (Table 1) during the operational hours of the air-handling units. Such a ventilation system is designed for the maximum possible pollution load from persons in the school. The number of persons associated with the school will in practice be less than the design maximum and was about 75% of the maximum at both schools. Sick leave and other errands would reduce the actual person load even further. It has been shown in Swedish schools that DCV with a present detector can reduce the ventilation energy requirements by approximately 50% [20].

The measured airflow rates at Jaer and Mediaa was only 20-25% of the corresponding airflow for a mixed CAV-system (Table 2), showing that DCDV have a considerable potential of reducing the air flow beyond the effect of demand control ventilation only.

The predicted airflow rates (Figure 7) with DCDV are somehow higher than the measured values (600 – 1000 l/s in average between 7 am and 5 pm). This analyse does not fully take into account sick leave, errands and how practical use of the of the school space influence the actual occupancy density, and this analyse could be considered as a careful estimate of the potential to reduce the airflow with DCDV compared with CAV.

Use of DCDV-CO_2 reduces the overall energy loss with about 20% compared with CAV, presupposed comparable ventilation airflows outside the operational time of the air-handling unit (Figure 8).

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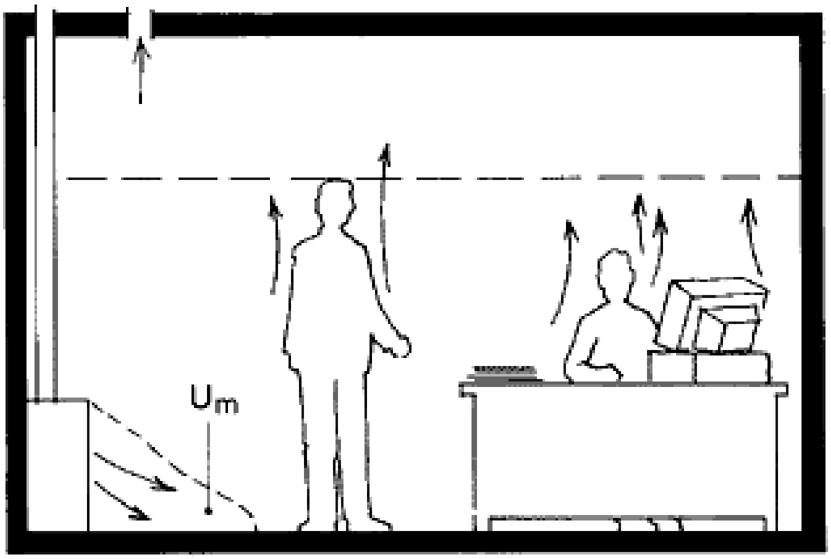

Figure 1 Displacement ventilation (byttes med bilde som viser clean zone, concetration interface and mixed zone).

Figure 2. View of facade and air-intake tower of Jaer School, Norway

Figure 3 View of the south façade of the Mediå School, Norway.

Figure 4 The ventilation air is distributed into the occupied zones via grilles in the floor or under benches (left and middle). In order to achieve efficient displacement ventilation in the classrooms, the supply air temperature is controlled to be about 19^0C in the heating season, which is slightly below the room temperature set point at 20^0C. The exhaust air is extracted through hatches situated about three metres above the floor (right).

Figure 5 CO_2 sensors placed 1.2 metres above the floor level on the classroom walls (left and middle) control the opening and closing of the exhaust ventilation hatches (right) as well as the fans. Temperature sensors are placed just above the CO_2 sensors, in order to control the heating system.

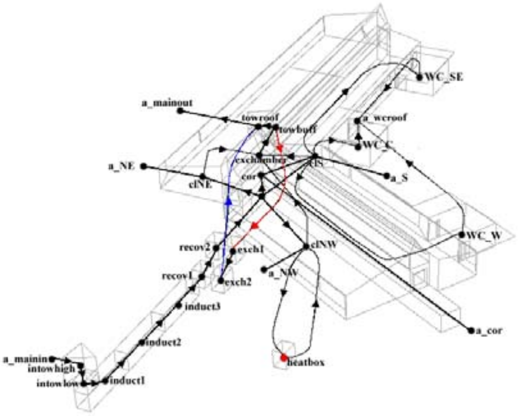

Figure 6 The Mediå School simulation model as seen in ESP-r's project manager, with an imposed illustration of the airflow network.

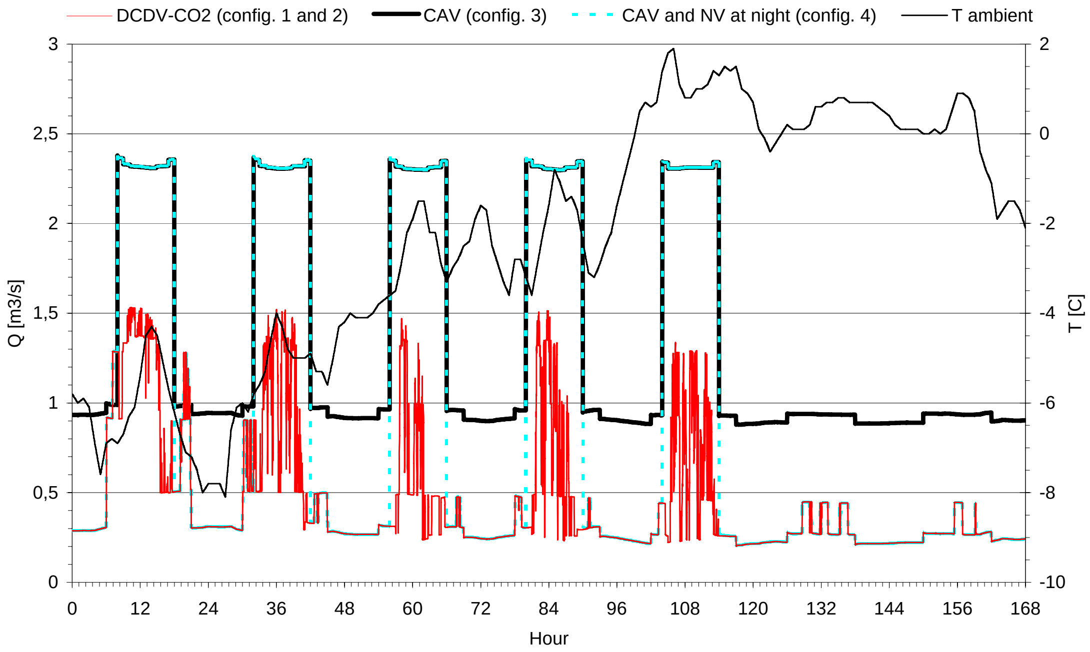

Figure 7 The predicted airflow rate entering the supply duct for the alternative ventilation configurations.

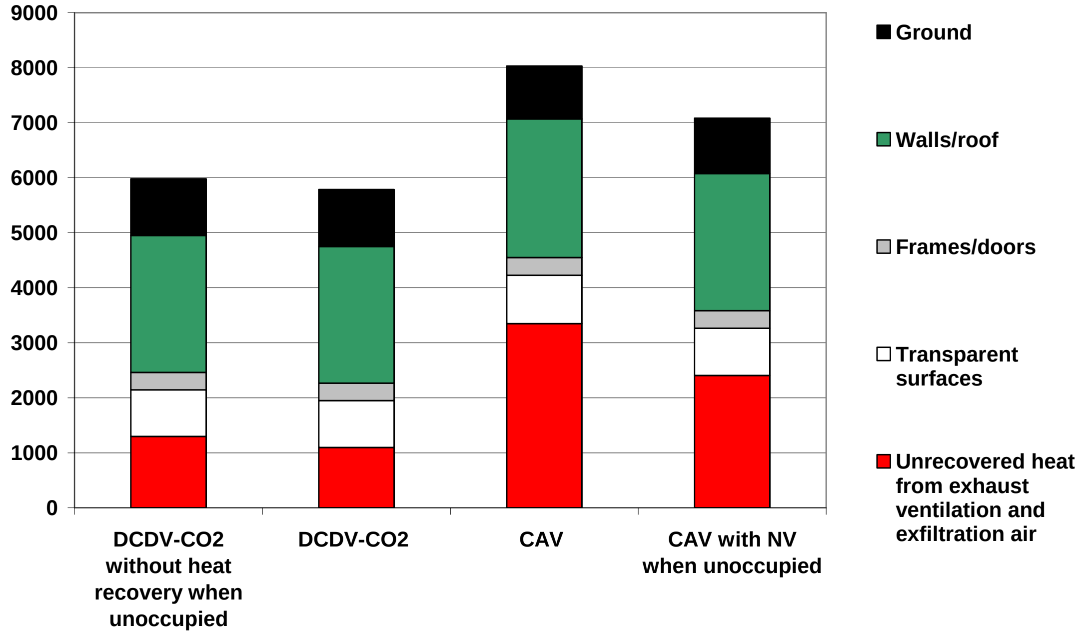

Figure 8 Energy loss from the Mediå School during the simulation period (November 11-17, 2002) for the four different ventilation system configurations.