Demand controlled ventilation in school and office buildings: lessons learnt from case studies

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ABSTRACT

Demand controlled ventilation (DCV) refers to a ventilation system with air flow rates that are controlled based on a measurement of an indoor air quality (IAQ) and/or thermal comfort parameter. DCV operates at reduced air flow rates during a large amount of the operation time. Due to this decrease, less energy is needed for fan operation and heating/cooling the supply air. However, uncertainty still exists about the IAQ performance and ventilation efficiency in the room, especially at lower air flow rates. Aim of this paper is to evaluate the IAQ performance, ventilation efficiency, operation and energy efficiency of DCV in school and office buildings based on measurement results. This research was done in cooperation with Flemish manufacturers of ventilation components, engineering offices designing HVAC and industrial federations.

Four case studies with large and varying occupancy and with different use and ventilation systems are selected. First case study is a school building with natural air supply and mechanical extraction controlled by measured indoor CO_2 concentration. Second study consist of an educational building with lecture rooms. In this building balanced mechanical ventilation is controlled by CO_2 and temperature measured at the extract air grill. Finally, in two different office buildings, three landscaped offices are evaluated. Here the balanced mechanical ventilation is controlled by CO_2 concentration and temperature.

To evaluate IAQ, ventilation efficiency and the energy savings of the system, the following parameters are monitored: CO_2 concentrations and air? temperatures at different positions in the room and at the extract air grill, position of the variable air volume (VAV) boxes, supply and extract air flow rates and the occupancy of the room. Measurements lasted for at least two typical weeks in autumn and winter 2015-2016.

The results show that a DCV system is able to guarantee a good IAQ in all the studied cases even at reduced air flow rates. The VAV boxes react well to predefined set points for CO_2 concentration The effect of the reduced air flow on the ventilation efficiency is negligible. Moreover, during the measurement period, the reduction of the fan energy ranges from 25-55% compared to a constant air volume system (CAV). For the heat losses, the reduction was 25-32% compared to a CAV during the measurement period. Energy reductions of both the fan and heat losses are calculated according to a design airflow rate of 29 m^3/h.pers, i.e., IDA3 in EN 13779. However, commissioning of the DCV is necessary to maintain these high energy reductions and good IAQ and ventilation efficiency. To conclude, DCV is an interesting ventilation system in rooms with a large and varying occupancy such as lecture rooms and landscaped offices.

KEYWORDS

Demand controlled ventilation, energy savings, IAQ, ventilation efficiency, office and school buildings

1 INTRODUCTION

Demand controlled ventilation (DCV) can reduce the energy use significantly compared to a constant air volume (CAV) system. DCV operates at reduced air flow rates during a large amount of the operation time. Due to this decrease, less energy is needed for fan operation and heating/cooling the supply air. Mysen et al. (2005) showed that the energy demand in school buildings was reduced by 38% for a CO_2-DCV compared to a CAV. In addition, Wachenfeldt et al. (2007) showed with measurements and simulations of a school building that the energy demand for respectively heating and fan use was reduced by 21% and 87% compared to a CAV. Maripuu (2009) showed that by implementing a DCV system in a university building the energy use for the fans was decreased by 50%. Ahmed (2015) showed for the implementation of DCV a decrease of 33-41% for the energy needed for heating, cooling and fans in an office building. In addition, measurements of the CO_2 concentration inside the office indicated a good indoor air quality (IAQ) with values below 900 ppm.

The air flow pattern is affected due to the lower air flow rates and velocities and might not cover the whole occupied zone. Fisk et al. (2012) measured the spatial variability of CO_2 concentration in occupied meeting rooms. In a crowded conference room the CO_2 concentration varied among different measurement positions up to approximately 300 ppm and fluctuated substantially with time for the measurement positions. Measurements for ventilation efficiency in a landscaped office by (Martínez et al., 2015) showed values between 0,55 and 0,66. The efficiency was affected by supply air that was mixed with extract air resulting in a higher CO_2 concentration at the supply.

However, there is still uncertainty about the indoor air quality (IAQ) and the ventilation efficiency of the room. The aim of this paper is to assess the IAQ, ventilation efficiency and energy efficiency of real DCV systems. Five rooms with large and varying occupancy in four school and office buildings in Belgium are selected. Overall lessons from these case studies are discussed. This measurement campaign is part of an applied research project about DCV in school and office buildings in cooperation with Flemish manufacturers of ventilation components, engineering offices HVAC and industrial federations.

2 METHOD

First, a description of the case study buildings and the systems is presented. All the case studies analysed are located in Belgium. Afterwards, the measurement setup for the evaluation of IAQ, ventilation efficiency and energy efficiency is shown.

2.1 Case studies

Table 1 summarizes the building, use, ventilation system and control properties of the case studies. Four different case studies are analysed with 3 different types of rooms:

- a classroom
- a lecture room
- three landscaped offices.

In all the case studies the DCV system is controlled by measured CO_2 concentrations in the zone. With exception of the kindergarten the ventilation system is also temperature controlled. For all the case studies a brief description is given with the important details.

Table 1; building, use, system and control properties for all case studies

Case study	Measurement period	Room type (floor area)	Ventilation system	DCV	Air flow (m^3/h)	Design occupancy (person/m^2)	Setpoint system
Kindergarten De Boomhut	16-27 November 2015	Classroom (66m^2)	Natural air supply and mechanical extraction	CO_2	200-600	20 (3,3)	1100 ppm?
Infrax	14 February – 2 March 2016	Landscaped office (200m^2)	Balanced mechanical ventilation	CO_2+T	550-1400	20 (10)	700 ppm
Test lecture room	8-19 February 2016	Lecture room (140m^2)	Balanced mechanical ventilation (displacement)	CO_2+T	400-2200	80 (1,75)	1000 ppm (21°C)
KU Leuven office	25 November - 8 December 2016	2 Landscaped offices (70m^2 and 72m^2)	Balanced mechanical ventilation	CO_2+T	70-420 70-500	12 12 (6)	800 ppm (23,8°C)

Kindergarten De Boomhut

This kindergarten includes four rectangular classrooms of each 66 m^2 and is used for pupils from the age of 3-6. An impression of this building is shown in Figure 1. The classroom is used by approximately 15 pupils during the measurement period.

Figure 1. left) View of south-east façade of the kindergarten "De Boomhut", right) interior of the classroom measured

The classrooms used for measurements are located at the north-west side. Fresh air is supplied in each classroom through self-regulating grills integrated in the windows with a maximum supply of 550 m^3/h. The air is mechanically extracted by one centrifugal duct fan per two neighbouring classrooms with a capacity of 400-1200 m^3/h. The extract air grill in the classroom is located at the mezzanine, just below the ceiling. The extraction air flow rate is controlled by the highest indoor CO_2 concentration of the two classrooms, with the setpoint at 1100 ppm?. In each classroom a CO_2 sensor is placed near the extraction air grill. A more detailed description of this case study is given in the study of (Merema et al., 2016).

Test lecture rooms KU Leuven

Figure 2 shows the plan and cross section of the test lecture rooms at the Technology Campus Ghent of KU Leuven (Belgium). This case study building contains 2 large lecture rooms with 140 m^2 floor area and a maximum occupancy of 80 students each. The building is built according to the Passive House standard. Balanced mechanical ventilation is provided with a total supply airflow of 4400 m^3/h. The AHU regulates the VAV boxes by sending a request signal to control the airflow based on CO_2 concentrations and operative temperature in the classrooms. Each classroom is a single zone with a supply and return VAV. Setpoint for CO_2 and indoor temperature (heating) are set at respectively 1000 ppm and 21°C. A more detailed description of this case study can be found in (Merema et al., 2015).

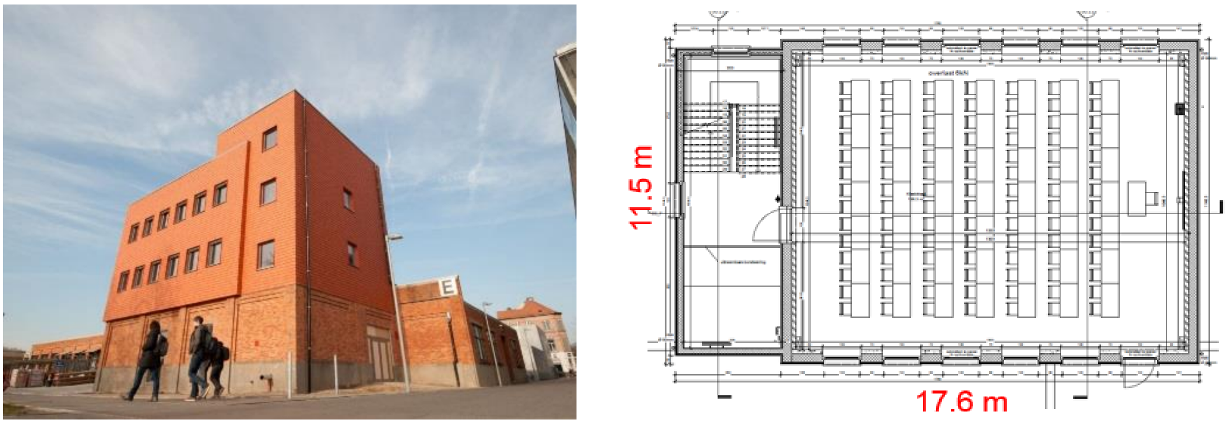

Figure 2; Plan and outside view of the test building

Office building Infrax

The office building, shown in Figure 3, includes 2 landscaped offices per floor. In one large landscaped office of 200 m^2 measurements have been carried out. Balanced mechanical ventilation is provided in which air is supplied by grills in the floor. Each landscaped office is a single zone with a supply VAV. The supply VAV controls the Air flow rate varies between 550 and1400 m^3/h based on the measurement of the CO_2 concentration and the operative temperature at the extract air grill. Setpoint for the DCV system is set at 700 ppm and 21°C.

Figure 3; Impression of the Infrax office building and landscaped office

Office building KU Leuven

The office building for the administration and logistics, shown in Figure 4, consists of two upper floors with open landscaped offices and, two floors for the servers and a supercomputer. Two landscaped offices with a design occupancy of 12 persons (both approximately 70 m^2), each with a different orientation (north and southeast), are studied in detail. Balanced mechanical ventilation is provided, fresh air is supplied through air grills in the ceiling. Each landscaped office is a single zone with a supply VAV. The supply VAV controls the air flow rate (70-420 in office 1 and 75-500 m^3/h in office 2) based on the CO_2 concentration and the temperature measured inside the extract air grill. Setpoints for the DCV system are set at 800 ppm and 23.8°C. A more detailed description of this case study is given in the study of (De Klerck and Massagé, 2017).

 

Figure 4; Impression of the KU Leuven office building and landscaped office 2

2.2 Measurement setup

Measurements are carried out during occupied hours for a period of at least two consecutive weeks for each case study during autumn/winter between November 2015 and December 2016. In all the case studies a minimum of 2 CO_2 sensors are installed in the occupied zone and 1 at the extract air grill for measurements of the IAQ and ventilation efficiency. The ventilation efficiency is defined by (1) according to EN 13779 (2010).

$$\varepsilon_v = \frac{C_{ETA} - C_{SUP}}{C_{IDA} - C_{SUP}} \tag{1}$$

In which ε_v is the ventilation efficiency, C_{ETA} CO_2 concentration of the extraction air, C_{IDA} CO_2 concentration in the occupancy area and C_{SUP} CO_2 concentration of the supply air. For a good operating and well-designed ventilation system the efficiency is between 0,70 and 1,10.

Properties of the sensors used for these measurements are listed in Table 2. Time interval used for the IAQ and ventilation efficiency measurements in all case studies is 1 minute. The measurement height used for the CO_2 sensors inside the occupied zone is 1m high. Occupancy of the rooms is measured during the measurement period by counting the number of people or with use of counting cameras (Test lecture room).

Table 2; Properties of the sensors used for measurements

Parameter	**Type sensor**	**Accuracy**
Air temperature	Omega PT100	±0,10°C
CO_2 concentration	VAISALA GMW 94	±30 ppm + 2% of reading
	Telaire 700LI	±50 ppm + 5% of reading

3 RESULTS

3.1 IAQ

Figure 5 presents the results of the CO_2 measurements during operating hours for the both the sensor installed in the occupied zone (sensor with highest values) and the sensor located at the extraction air.

In all the case studies measured the 75% quartile value both in the zone and at the extraction is below the CO2 setpoint of the ventilation system. This indicates that the ventilation system is able to maintain the CO2 concentrations below the predefined CO2 setpoint. Only the results for the kindergarten “De Boomhut” shows that values inside the occupied zone are above the predefined setpoint. Here the data is used of the sensor which was installed beneath the mezzanine, which is a semi-enclosed space.

In the office buildings the IAQ is equal to IDA class 1 (EN 13779, 2010), which indicates that the IAQ is the highest possible that can be achieved. This shows that the DCV system is able to deliver a good IAQ. The IAQ in the school buildings is comparable to IDA class 3 which is the basis level for an acceptable IAQ. In all the case studies for the outdoor CO2 concentration a default value of 430 ppm is assumed for the calculations of the IDA class.

The highest CO_2 concentrations are found for the kindergarten "De Boomhut". Here the median value in the occupied zone is 950 ppm. Lowest values are found in the KU Leuven building (zone 10) with a median value of just 500 ppm in the occupied zone. A remark is that in this zone the occupancy density was low, most of the time the occupancy rate was below 50%. Furthermore, it is noticed that in most (3 out of 5) case studies the CO_2 concentration in the occupied zone is at least 100 ppm lower than at the extraction air grill, which indicates a good operation of the ventilation system. In all the cases measured the 75% quartile is below the set point of the ventilation system. This has an impact on the ventilation efficiency (see next paragraph). CO_2 concentration in the landscaped offices is approximately 200 ppm lower, Because the controlling Set points are lower (800 ppm vs 1000 ppm) and the occupancy density is lower compared to classrooms (lecture rooms), as shown in table 1.

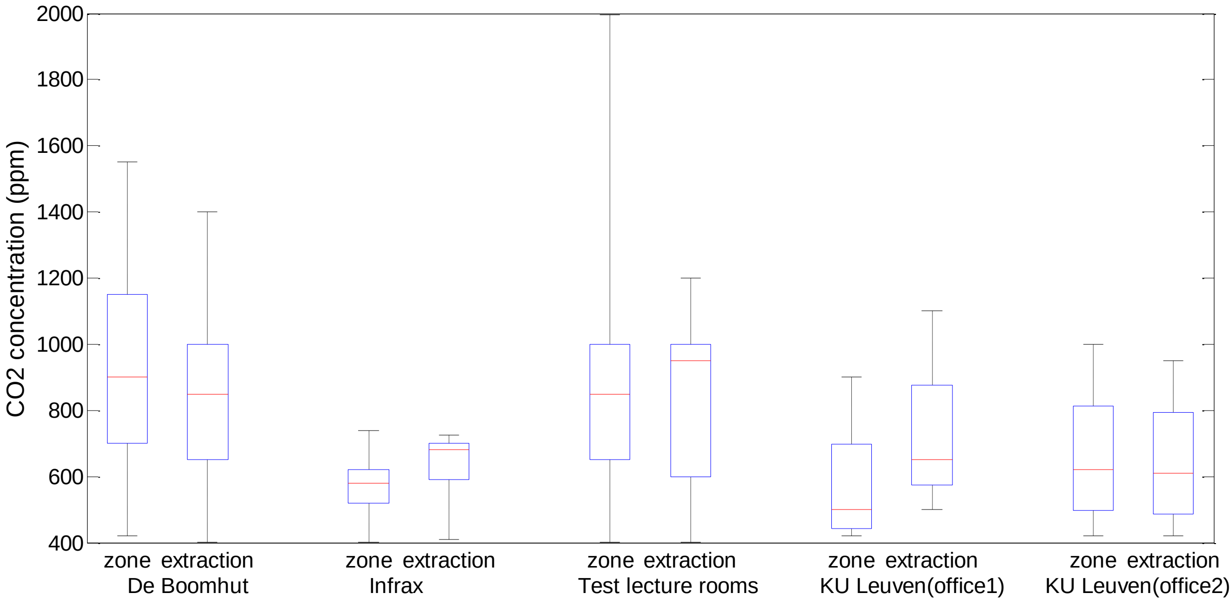

Figure 5; CO_2 concentrations during operating hours for all case studies

3.1 Ventilation efficiency

Additionally, the ventilation efficiency of the system is determined based on the CO_2 data of the sensor installed in the occupied zone and the sensor at the extract air by using equation 1. Table 3, shows the results for ventilation efficiency for all the case studies during operating hours and how the fresch air is supplied. A ventilation effectiveness of 1 means that there is a complete mixture of air and pollutants (EN 13779, 2010) between the occupied zone and the extraction air. A good operating and well-designed ventilation system should show values of 0,70-1,10 for the ventilation efficiency. For systems with displacement ventilation values between 1-2 are more typical.

It can be seen in Table 3 that for all the case studies analysed the ventilation efficiency is between 0,89 and 1,50. This indicates that in all cases measured the DCV system is working efficiently as designed. The value presented is an average value for the complete measurement period, the standard deviation is also indicated. Both the Test lecture rooms and the Infrax case show an efficiency of around 1,50. This can be explained by the fact that the test lecture rooms uses displacement ventilation while in Infrax air is supplied via the floor at low air speed. For the KU Leuven offices it can be seen that there is a difference 0,35 in ventilation efficiency. This can be explained by the fact that in office 2 the occupancy rate was higher compared to office 1 which resulted in higher CO2 concentrations inside the occupied zone.

Table 3; Ventilation efficiency

Case study	**Ventilation efficiency (std. dev.)**	**Air Supply**
De Boomhut	0,89 (0,32)	Grill above windows
Infrax	1,50 (0,27)	Air supply in floor
Test lecture rooms	1,49 (0,55)	In each corner of the room an air grill (displacement ventilation)
KU Leuven office	1,27 (office 1) 0,92 (office 2)	Air supply in ceiling

3.2 Energy efficiency

The total fan energy demand and ventilation heat losses for the complete measurement period are calculated and shown in Table 4. Energy reductions for both fan and heat losses are compared to the design occupancy with an air flow rate of 29 m^3/h.pers. Heat losses, due to ventilation, are calculated based on the air flow rate and the temperature difference between zone and supply air temperature after heat exchanger (or in case of natural ventilation outdoor temperature). For the energy reduction both on the fan and heat losses the results are compared to a design air flow rate of 29 m^3/h.pers (EN 13779, 2010). Furthermore, the heating degree days are indicated for the complete month during the measurement period.

In all the cases it is shown that significant energy reductions can be achieved by implementing a DCV system. In all case studies reductions on the fans are at least 50% and on heat losses 34%. Highest reductions are found for the fans with a maximum of 55% for the test lecture rooms case. The lowest was found for the office building of KU Leuven with 50%, which still is a significant energy reduction. For heat losses the reductions are minimal 34% (KU Leuven office) and maximal 47% (test lecture rooms).

The test lecture rooms showed the largest reductions for both fan and heat losses. This was mainly attributed by the varying occupancy rate both in time and group size (20-80 persons). The heat losses in the KU Leuven office are the lowest with 34%. Here the heating demand was high since the setpoint used for heating was 23.8°C. This resulted in the fact that the system operated at a high air flow rate to heat up the space for a long time during cold periods.

Table 4; Reduction in fan energy and heat losses for DCV compared to CAV

Case study	**Fan energy (%)**	**Ventilation heat losses(%)**	**Heating degree days**
De Boomhut	50	36	Nov 2015: 192
Infrax *	-	-	-
Test lecture rooms	55	47	Feb 2016: 346
KU Leuven office	50	34	Dec 2016: 365

*Energy consumption and heat losses were not measured in this case study. However, the ventilation system operated 67% of the time during operating hours on a minimum airflow which indicates an energy saving potential.

4 CONCLUSIONS

The measurement results shows that in all the case studies the DCV system was able to deliver and maintain a good IAQ, even at reduced air flow rates. The VAV boxes or extract fans respond well to predefined set points regarding the CO_2 concentration and temperature. Even at low air flow rates it was noticed that the ventilation efficiency was not affected. This shows that demand controlled ventilation is effective in distributing the air at reduced air flow rates. The measurements for ventilation efficiency showed that during the design air flow rate there was a difference of 100 ppm in CO_2 concentration between the occupied zone and the extraction air grill. This shows that the position of the CO_2 sensor is of importance for the performance of the DCV.

Results of the case studies shows that significant reductions in energy consumption are achieved for both the fans and heating system. This means that DCV has a high energy saving potential for rooms with a varying occupancy profile, both in size and time, such as landscaped offices and classrooms.

However, commissioning is necessary for a good energy and IAQ performance of a DCV system. The measurement campaign revealed some problems with the ventilation system. The ventilation system in the Infrax office building was noticed to operate during 67% of the time at the minimum airflow rate. This could indicate that the minimal airflow rate is too high compared to the actual occupancy. Furthermore, the position of the CO_2 sensor has a large impact on the operation of the system. In the Test lecture rooms this position was changed because first results of ventilation efficiency indicated a large difference between CO_2 measured at the extract air grill and the occupied zone.

5 ACKNOWLEDGEMENTS

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