What should the minimum ventilation rate be in a Demand-Controlled Ventilation strategy?

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Abstract
Demand-Controlled Ventilation is emerging as a dominant ventilation strategy in non-residential buildings in Norway. The ventilation airflow rate is controlled between pre-set minimum (V_{min}) and maximum (V_{max}) values, based on the signal from room-sensors. The choice of V_{max} is based on current knowledge about necessary airflow rate to reach an acceptable IAQ (indoor air quality) with maximum likely personal load and emission load from building materials.

The choice of V_{min} has an obvious impact on energy use, but there are few studies about its impact on IAQ. V_{min} varies typically from 0.7 to above 2 (l/s)/m² in Norway. In several buildings, V_{min} is set to the upper range of this interval due to technical limitations of the specific equipment used.

We have performed blind cross over intervention-studies with an untrained test panel to evaluate PAQ (perceived air quality) when entering 20 *PAQ-rooms*. All the rooms have low-emitting building materials, but extra pollution sources were introduced in some of the rooms for this study. Supplementary, intervention studies were performed in a dedicated *test room* to assess the impact of airflow rate on PAQ, performance and well-being during the first 20 minutes of occupation.

We found that increasing V_{min} has a significant positive impact on PAQ in rooms with extra pollution sources. This effect was not consistently present in the low-emitting rooms. Airflow rates did not noticeably affect PAQ, performance and well-being during the first 20 minutes of occupation. This indicates that V_{min} above 1 (l/s)/m² has limited benefit to IAQ in low emitting rooms.

Keywords: Demand-controlled ventilation, Indoor air quality, Performance test, Low-emitting materials, Pollution level, Ventilation strategy.

1 Introduction

1.1 The scope of this paper

The amount of ventilation necessary to maintain good IAQ (indoor air quality) in a room depends on the strength of the pollution from interior surfaces, furniture and occupants. These pollution sources are either stationary or variable. The variable sources

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are mainly users and user-related activities. The purpose of demand-controlled ventilation (DCV) is to continuously follow these changes in ventilation requirement.

DCV achieves the greatest energy savings in buildings with rooms that are unoccupied for a significant part of the operating hours [1] and when the ventilation rates are significantly reduced in unoccupied rooms [2]. DCV has thus emerged as a dominant ventilation strategy for such non-residential buildings in Norway.

The ventilation airflow rate in modern DCV systems is controlled between pre-set minimum (V_{min}) and maximum (V_{max}) limit values, based on the signal from one or more room sensors (Figure 1). The V_{min} and V_{max} limit values that can be set to account for changes in, for example, pollutant load from materials, room size, or the maximum likely number of occupants [3].

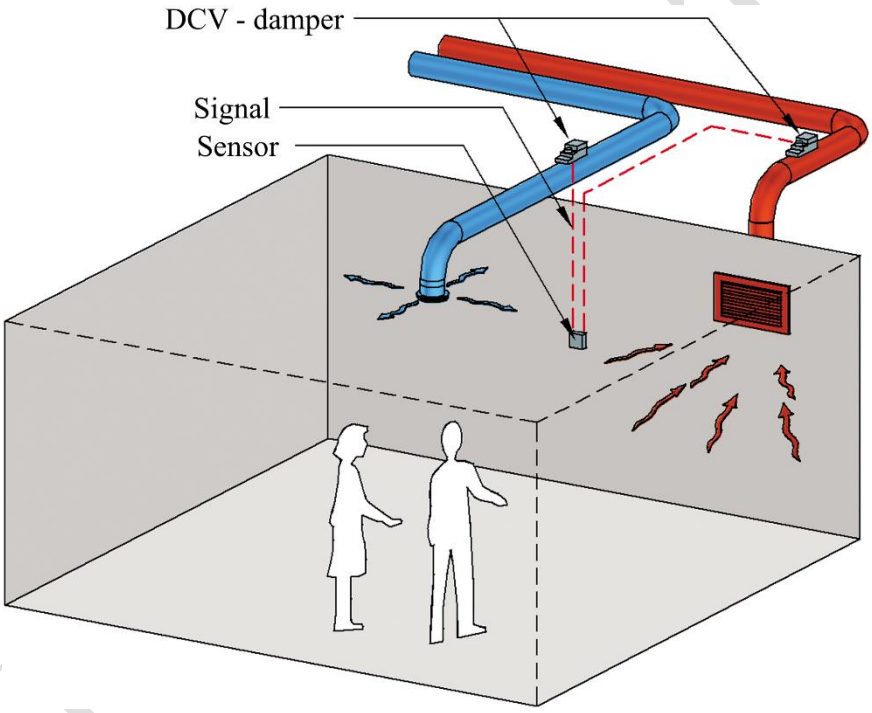

Fig. 1. DCV-controlled room. A sensor picks up the pollution level and signals DCV-dampers about a corresponding ventilation volume to maintain IAQ (Illustration SINTEF).

The choice of V_{max} is based on current knowledge about necessary airflow rate to reach an acceptable IAQ taking into account maximum likely personal load, cooling load, and the total emission load from materials in the room. Recommendations about necessary airflow rates, e.g. HealthVent review report [4], are mainly based on studies with constant ventilation rates per person. These recommendations are not fitted differences in emission sources or DCV-system dynamics.

The choice of V_{min} has an obvious impact on energy use, but there are few studies on the impact on IAQ. Thus, there are no scientifically-based optimal guidelines for V_{min}.

The present rationale for choosing V_{min} is to maintain a constant IAQ in accordance with Fanger's olf-based "addition principle" [5]. This implies that V_{min} is set to achieve an acceptable olfactory concentration accounting for the total pollutant load from materials plus occupants in the room. For unoccupied rooms, this minimum ventilation demand varies typically from 0.7 to over 2 (l/s)/m^2_{floor} in Norway. V_{min} is often set to the upper end of this range due to risk off high emitting furniture, or technical limitations in the equipment such as flow-measurement. However, we should depart from this practice, and instead acknowledge that unoccupied rooms do not need to be intensively ventilated primarily for olfactory comfort. The remaining question is whether reducing V_{min} has any negative impact on PAQ (perceived air quality), indoor-air related symptoms, health, or human performance, when an occupant enters the empty room. This has been investigated in the R&D project BEST VENT. In this paper, we report the results from the first experiments carried out in 2016. BEST VENT will continue experimentation for two more years.

2 Methods

2.1 Experimental design overview

The experimental design in BEST VENT consists of five major steps:

1. Identify a test school with dedicated test room with controllable ventilation and close to project partners' laboratory facilities
2. Establish a test panel (occupants)
3. Develop sensitive and reliable surveys and performance tests
4. Perform adequate measurements
5. Rational data collection and analysis

Each step is briefly reported in this paper.

2.2 Selection of test school and test panel

DCV-systems in 5 schools were audited. Fernanda Nissen School in Oslo was chosen as our field laboratory, as it has all the required features, including easily adjustable airflow rates, and temperature and CO_2-control. The interior surfaces in this passivhaus-standard school was completed in 2016, approx.6-8 months before the experiments. The school has concrete floor slabs covered with linoleum, walls are timber frame, 300 mm mineral wool insulation, and are generally clad with 13 mm plasterboard with acrylic paint. Materials and paint are either M1-certified or implicitly low-emitting. The use of sealants was limited, with no sealants visibly exposed to rooms. All classrooms have balanced supply and exhaust mechanical ventilation. The ventilation system has bag air filters of class F7 in accordance with EN 779:2012.

One 60 m^2 classroom, denoted the *Test room*, was loaned for research purposes year-round. Other rooms were available for research during holidays, including week 40 (autumn holiday). 20 un-occupied rooms were carefully selected for week 40, and are

denoted *PAQ-rooms* in this paper. All of the education rooms at Fernanda Nisses school have mixing ventilation with well distributed ceiling-integrated air supply devices (Figure 2).

30 students from Oslo and Akershus University college of Applied Science, were recruited as an untrained test panel. It was on a voluntary basis, with book gifts for those who attended 6 or more experiments. The number of students each test day varied between 15 and 22. 10 of them participated in all 8 experiments.

The test panel left the Test room for minimum 30 minutes between experiments (Table 1). Figure 2 shows the test room prior to experiment.

Fig. 2. The test room at Fernanda Nissen School, Oslo. All of the education rooms have mixing ventilation with similar air inlet and outlet as the test room. (Photo: SINTEF).

2.3 Experimental design, surveys, performance tests and measurements in the *Test room*

Intervention-studies with the test panel present, were performed in the *Test room* to assess the impact of airflow rate on PAQ, performance and well-being during the first 20 minutes of occupancy. These experiments were repeated 8 times with different airflow rates from 3 to 16 (l/s)/person when the room was occupied. V_{min} was set to 1 or 2 (l/s)/m² before the test panel entered the room, hence they were blind to the intervention. The physical lower limit of the DCV-damper was 1 (l/s)/m².

The eight experiments in the *Test room* were performed without any obvious negative acoustic, actinic or mechanical factors that may confound the results. Indoor temperature varied within limits of ±1 °C during experiments. Tables 1 and 2 show the time schedule for the test week and for each experiment, respectively. Only results from the first 20 minutes are reported in this paper. The colour codes show ventilation periods before each experiment. The room was empty between the experiments, expect for necessary time to read or adjust instruments and ventilation settings.

Table 1. Time schedule for testing in the dedicated *test room*. V_{min} varied between1 (l/s)/m² [yellow and orange] and 2 (l/s)/m² [blue]. Eight experiments were conducted. White hatched area means ventilation off (Wednesday night and Thursday night).

Day	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
00:00 -07:00					
7:00-8:45					
8:45-9:45		(1)Testing with panel		(3)Testing with panel	(7)Testing with panel
9:45-10:15					
10:15 - 11:15		(2)Testing with panel		(4)Testing with panel	(8) Testing with panel
11:30 - 12:30					
13:00 - 14:00				(5)Testing with panel	
14:00- 14:30					
14:30 - 15:30				(6)Testing with panel	Removing
15:15 - 16:30					
16:30 - 17:30					
17:30-00:00:00					

Table 2. Time schedule for testing in the dedicated *test room* after test panel entrance. The test panel was in the *test room* for 60 minutes.

Minutes after entrance	Activity
0-5	PAQ, IAQ-survey
5-20	Performance test
15-45	Lecture
44-55	Performance test
55-60	PAQ, IAQ-survey

PAQ and building-related symptoms were reported by the test panel and scored using digital tablets. The survey questions are based on the Ørebro questionnaire [6]. The score was on a continuous-scale slider. For PAQ the extremes were "clearly unacceptable" to "clearly acceptable". For SBS-related questions like "Do you have headache", the extremes were "Yes, very" to "Not at all". It was not allowed to score at the midpoint. The scores were stored in the Microsoft cloud solution, prepared for data-analysis performed with statistical program R.

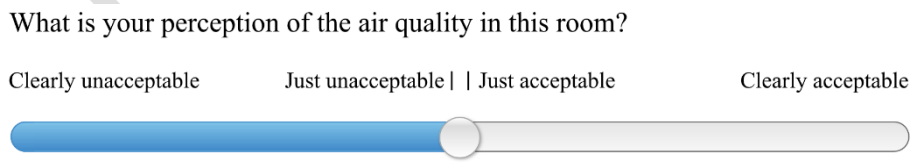

Fig. 3. Scores were reported on digital tablet. The figure shows the PAQ score slider.

The *OK Tick-off Test* ("OK-Tekstkryss" in Norwegian) measured sustained human performance. The test is a visual detection task designed to assess the ability of individuals to maintain visuo-cognitive alertness for an extended period of time. The test

contains meaningless, but readable, words. The task is to tick off as many Os and Ks as possible in 10 minutes (Figure 1). The paper-version of the OK Tick-off Test has shown satisfactory reliability [7]. A digital version for the digital tablet was developed and used in the BEST VENT-project.

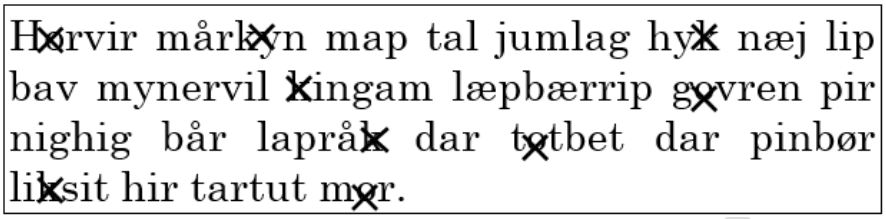

Fig. 4. Example taken from the OK Tick-off Test.

Measurements: Air temperature, relative humidity, CO_2, Ozone, NO_x (NO_2+NO), volatile organic compounds (total VOC and specific compounds), formaldehyde and particulate matter (PM) at different size fractions from 3 nm to 32 µm, were measured during the test week with calibrated instruments. Supply and exhaust air rates were measured by a differential pressure sensor in the DCV-damper with sufficient straight duct length upstream to have a distributed airflow stream throughout the duct cross-section. The values were continuously logged by the BMS (building management system). The accuracy of the measurements was controlled prior to the experiments with calibrated funnels. Only measurements result with scope relevance are reported in this paper.

Table 3 shows V_{min} and average ventilation rate per person during the first 20 minutes. In experiments 1, 2, 3, 7 & 8 the ventilation rate was maintained at V_{min} for the first 20 minutes.

Table 3. The 8 *test room* experiments. $V_{pers20min}$ is average suppled airflow the first 20 minutes of occupancy divided by the number of room occupants.

Expt. no:	V_{min} (l/s)/m²	$V_{pers20min}$ (l/s)/person	Number of persons present
1	1	3	22
2	2	6	21
3	1	3	21
4	1	13	21
5	2	8	15
6	1	16	15
7	1	3	22
8	2	6	22

Test hypotheses: Before the experiments, it was believed that low V_{min} has negative impact on immediate PAQ when entering, and on SBS-symptoms and performance during the first minutes of occupancy. To falsify the test-hypothesis: *"V_{min} of 1 or 2*

(l/s)/m² has no impact on PAQ, SBS-symptoms or performance", V_{min} was set to 1 or 2 (l/s)/m² before entering the room, and then increased to between 3 and 16 (l/s)/person for the first 20 minutes of occupancy.

2.4 PAQ in 20 rooms

The test panel assessed PAQ when entering the 20 un-occupied *PAQ-rooms* with mixing ventilation similar with the test room. Room 13, 16 and 19 had a floor area of 30 m². The rest of had a floor area of 60 m². All rooms were built with certified low-emitting materials. Extra pollution sources were introduced to some of the rooms — i.e. old shoes were hidden in rooms 5 and 9. Room 7 had initially a peculiar smell from an unidentified source. The rooms were ventilated with V_{min} of 0, 1, 1.5 or 2 (l/s)/m² before entering. The last three are typical V_{min}-values. Individuals in the test panel entered the rooms one by one with at least 30 second intervals. Air temperatures were steady at 21.5 ±1°C. The test panel were blind to the different ventilation rates and pollution sources. Airflow rates, air temperature, relative humidity and CO_2 were logged during the test week.

Test hypotheses: Before the experiments, it was believed that low V_{min} has a negative impact on immediate PAQ when entering, and this impact is enhanced with additional pollution load in the room. To falsify the test-hypothesis *"V_{min} of 1, 1.5 or 2 (l/s)/m² has no impact on PAQ immediately after entering"*, V_{min} was set to 1, 1.5 or 2 (l/s)/m² before entering. The ventilation rates were crossed between the experiments in randomly chosen rooms. Some rooms were kept unchanged to reliability test the test panel and experimental design.

3 Results

3.1 *Test room* results

Before the experiments, it was believed that low V_{min} negatively affects PAQ, SBS-symptoms and performance. Table 3 shows V_{min} and average ventilation rate per person the first 20 minutes. The test-hypotheses was not falsified. The result analysis revealed no consistent tendency of ventilation impact during this first period of occupancy. The detailed results are not given in this paper since the data material is vast and shows no pattern.

3.2 20 PAQ-rooms results

PAQ-results were linearly scored from −1 (clearly unacceptable) to +1 (clearly acceptable). Fig. 5 shows the average score for the different air flow rates used in the specific PAQ-rooms. Table 4 highlights significant differences.

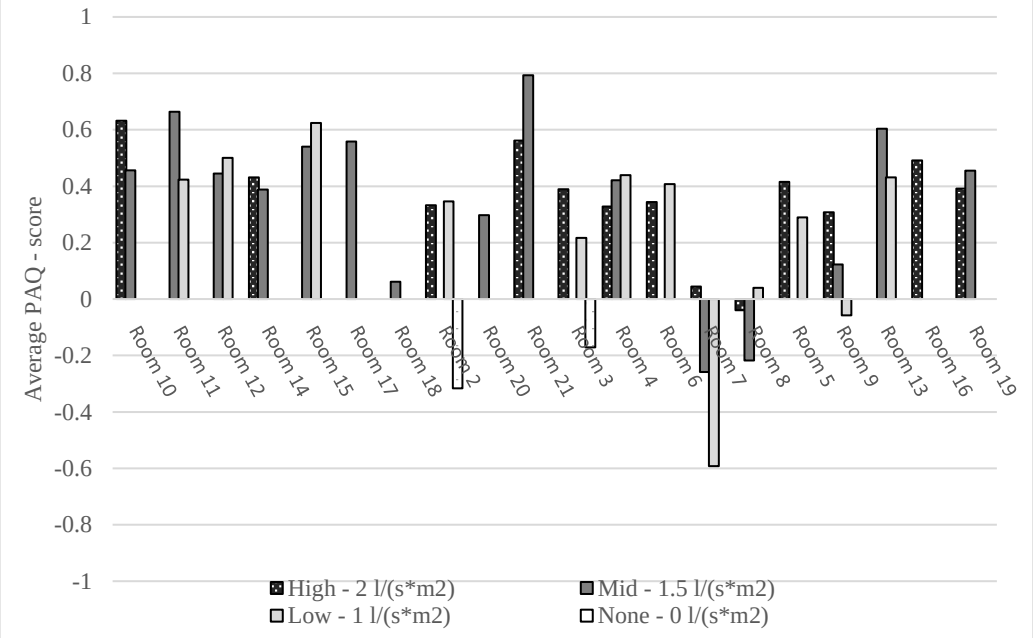

Fig. 5. Average PAQ-score by the test panel for test room nr 3 - 21. PAQ-results were linearly scored from −1 (clearly unacceptable) to +1 (clearly acceptable).

Table 4. Paired sample *t*-test of the differences in PAQ with different V_{min}-values. *P*-values and confidence intervals are shown. Significant differences are in bold and red.

	High – mid 2 – 1.5 (l/s)/m²	**High – low 2 – 1 (l/s)/m²**	**Mid – low 1.5 – 1 (l/s)/m²**	**High – none 2 – 0 (l/s)/m²**
Rom 2:	-	0.113, (-0.145, 0.561)	-	**0, (0.307, 0.96)**
Rom 3:	-	**0.037, (-0.017, 0.329)**	-	**0.002, (0.189, 0.765)**
Rom 4:	0.854, (-0.405, 0.13)	0.927, (-0.408, 0.067)	0.54, (-0.203, 0.184)	-
Rom 5:	-	**0.035, (-0.015, 0.349)**	-	-
Rom 6:	-	0.798, (-0.289, 0.121)	-	-
Rom 7:	**0.02, (0.016, 0.608)**	**0, (0.277, 0.745)**	0.157, (-0.152, 0.443)	-
Rom 8:	0.078, (-0.061, 0.351)	0.567, (-0.429, 0.365)	0.97, (-0.548, 0.013)	-
Rom 9:	**0.02, (0.013, 0.455)**	**0.027, (-0.005, 0.492)**	0.353, (-0.236, 0.342)	-
Rom 10:	0.473, (-0.19, 0.203)	-	-	-
Rom 11:	-	-	**0.004, (0.078, 0.403)**	-
Rom 12:	-	-	0.496, (-0.264, 0.266)	-
Rom 13:	-	-	0.168, (-0.168, 0.452)	-
Rom 14:	0.365, (-0.236, 0.328)	-	-	-
Rom 15:	-	-	0.91, (-0.273, 0.057)	-
Rom 19:	0.663, (-0.411, 0.274)	-	-	-
Rom 21:	0.96, (-0.436, 0.028)	-	-	-

4 Discussion

4.1 Test room

PAQ, SBS and performance was assessed by a joint test panel in accordance with the time schedule in table 2. The statistical analysis reveals no consistent tendency of the impact of V_{min} during the first 20 minutes of occupancy, with neither significant impact on PAQ, SBS nor performance.

We believe that the *test room* is a low-emitting room. Material emissions are probably diluted below our sensory threshold level by 1 (l/s)/m² or more of supply air. This explains why V_{min} above 1 (l/s)/m² had no impact on PAQ. Keep also in mind that the temperature was kept approximately constant in these experiments.

Another explanation of the PAQ results is that this room was taken into use by the complete test panel counting from 15 to 22 persons and it took a few minutes before PAQ was scored on the digital tablet. PAQ could have been dominated by human bioeffluents or the influence of a few minutes of higher ventilation rate. However, experiments 1, 2, 3, 7 and 8 do not support this explanation, since the ventilation rate was not increased from V_{min} in these experiments.

SBS-symptoms and performance were not influenced by ventilation rate the first 20 minutes. This indicates that human beings need more than 20 minutes' exposure to be influenced by the ventilation differences in these experiments. This implies that it is not necessary for DCV-systems to respond quickly to olfactory pollution load changes.

A field laboratory experiment might always be influenced by factors not controlled for. These experiments must be repeated before any final conclusions can be made.

4.2 PAQ-rooms

PAQ was assessed in the PAQ-room by individuals from the test panel one at the time. We found that ventilating with 2,0 (l/s)/m² significantly improved immediate PAQ compared to no ventilation (Table 4). This was expected.

We found that increased V_{min} above 1 (l/s)/m² significantly improved PAQ in rooms 5, 7 & 9, all of which had additional pollution sources (Table 4).

We did 17 comparisons between different V_{min}'s in 13 rooms with two significant outcomes in room 3 and 11 (Table 4). In five of the rooms (2, 4, 6, 8, 12 & 15) the average PAQ-score was elevated with V_{min}=1 (l/s)/m² compared to V_{min}=2 (l/s)/m² (Figure 4). This indicates that the positive impact of V_{min} above 1 (l/s)/m² was not present in the low-emitting rooms without additional pollution sources. These indications are supported by the results from the *Test-room*.

However, the results are not consistent. Further experimentation on pollution loads from interior and user activity is required.

5 Recommendations for V_{min}

We found that increasing V_{min} had a significant positive impact on PAQ in rooms with extra pollution sources. This effect was not present in the low-emitting rooms with temperatures at 21.5 ±1ºC. We could not see that different airflow rates had an impact on PAQ, performance or well-being in the dedicated *test room* during the first 20 minutes of occupation. This indicates that V_{min} above 1 (l/s)/m² has limited impact on IAQ in real low-emitting rooms. Our preliminary recommendation is to restrict V_{min} to 1 (l/s)/m² in rooms designed to be low-emitting. Additional ventilation due to uncertain pollution load from materials or equipment should be included in the choice of V_{max}.

This preliminary recommendation is based on the prerequisite that a DCV-system has easily adjustable V_{min} and V_{max}. This means that V_{min} can be easily adjusted in the case of rooms not successfully fitted as a low-emitting room, if the pollution load is changed by different use of the room or changes in room size.

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Compliance with ethical standards

Formal consent was given by the volunteers who participated in this study. Permission was given by the school where this study was conducted. We did not collect any identifiable or sensitive information that would require ethical approval. The research has been conducted in compliance with the ethical standards at OsloMet – Oslo Metropolitan University (formerly Oslo and Akershus University College of Applied Science) and Norwegian Law.

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