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Indoor Air Quality in a Zero Emission Building

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Abstract

The objective of this paper is to evaluate the indoor air quality in a renovated zero emission office building. Zero emission buildings should replace fossil fuels with renewable clean energy so that the saved emissions equals the emissions caused by the building's construction, operation and materials. The building energy use has to be minimized, and for ventilation, the airflow rates should be just large enough to maintain good and healthy indoor air quality.

The studied building is Powerhouse Kjørbo, the first Norwegian zero emission office building. It has a high efficiency heat recovery wheel, demand-controlled (CO_2 concentration and/or indoor temperature) displacement ventilation, and low velocities in ducts. Inlet diffusers supply slightly below room temperature air from the central part of the floor towards the facades in the open landscapes, where the workstations are located. The stairway is used as an extraction duct. In this paper, the air distribution in the open office area is studied.

The methods applied in this study are a literature survey on displacement ventilation in large enclosures, measurements involving tracer gas to analyze ventilation effectiveness and smoke to detect shortcuts on the ventilation, and parts of a survey conducted among the occupants.

Tracer gas measurements indicate stagnant zones in some parts of the office landscape, especially corners where bookshelves obstruct the flow. Further, there might be a short circuit between some of the air inlets and the exhaust. Possible alternatives for improving the ventilation effectiveness will be discussed.

The conclusion of the paper is that the occupants are generally satisfied with the indoor air quality, but if the ventilation effectiveness had been improved less air could have been used to maintain the air quality.

Keywords – Displacement ventilation, field measurements

1. Introduction

This paper discusses the indoor air quality in terms of the ventilation efficiency and the perceived indoor climate in the zero emission office building [1] Powerhouse Kjørbo, located just outside of the Norwegian capital, Oslo. Powerhouse Kjørbo is the first energy-positive office building in Norway. It was initially built in 1979, renovation commenced in 2012, and operation started in April 2014. It consists of two building blocks, 4 and 5, and is part of a building complex of nine blocks in total. Powerhouse Kjørbo received the highest grade, "Outstanding", by BREEAM-NOR, the Norwegian adaption of an environmental assessment method and rating system for buildings, originally launched by the "Building Research Establishment" (BRE) in 1990.

The powerhouse concept derives from the passive house concept, but it comes with the possibility to produce energy as well. It is common to do so with solar energy by the use of photovoltaic panels and solar thermal collectors. Definitions may vary from country to country, but for Powerhouse the Powerhouse Alliance in Norway use the definition: "A Powerhouse shall during its lifetime produce more energy than it uses for materials, production, operation, renovation and demolition." [2].

The world energy demand is expected to increase by over 50 % for the coming 25 years [3], and the building sector makes up a substantial part of the world energy budget. It is estimated that it represents 40 % of the energy consumption, in addition to the claim of 40 % of the material resources and produces 40 % of the waste produced worldwide [4]. Both from an environmental and energy-saving point of view it is important to take certain measures to reduce the waste and energy demand of both existing and future buildings. When such actions are implemented into the building industry (e.g. passive house, low-energy buildings etc.), it is important to fully understand its effects on the indoor climate, and how one can achieve more optimal solutions that benefits all parties.

The main objects of ventilation is to supply fresh air to the zone of occupancy and extract used air along with its contaminants and excess heat. This should happen at a quick enough rate to ensure the quality of the air. From an economic perspective, it is lucrative to keep the employees healthy and productive. According to Wargocki et al. [5] it is estimated that the work performance in an office increases by 1.5 % for every 10 % decrease in persons dissatisfied with the indoor air quality. Another study by Wargocki et al. [11] states that higher ventilation rates and/or lower pollution loads could increase the productivity of the occupants. According to a study by Mundt [6] on the air quality "the particle concentration in the convection flows are much higher with displacement than with mixing ventilation indicating a higher exposure risk", but displacement ventilation is, in theory, more efficient regarding air exchange and need less air than mixing ventilation to do the same job, thus using less energy.

A study performed by De Carli et al. [12] about the placement of air inlet and air outlet diffusers in offices concluded that “displacement ventilation performance was very sensitive to the position of exhaust grilles”, but “the location of the exhaust on the ceiling results in higher air quality levels regardless of the position of the inlet diffusers. It also stated, “Displacement ventilation does not always result in better air quality than mixing ventilation”, in their case. Positioning of the diffusers play a part for the ventilation efficiency, and should be studied.

Achieving a low-energy system while containing an acceptable indoor climate is an ongoing challenge. The building ventilation system affects both the indoor air quality and the energy use, and therefore it needs proper design and planning to achieve the goals of a low-energy building. The goal of this paper is to evaluate the indoor air quality of Powerhouse Kjørbo through a fieldwork experiment with tracer gas, and a survey presented to the building’s users about the perceived indoor climate.

2. Building Ventilation Strategy

Powerhouse Kjørbo utilizes a displacement ventilation strategy. The open landscape and larger meeting rooms have demand-controlled variable air volume (VAV), and cell offices and small meeting rooms have constant air volume (CAV). The ventilation system has a very low-pressure drop through the components and ducts, with air supplied to the room at a very low velocity. The system is designed with overflow from cell offices to landscape. The constant airflow supplied in the cell offices makes up the base ventilation for the floor. When the CO_2 emissions from people increase in the landscape, or the temperature rise, the VAV dampers starts to open. A small amount of air flows into secondary functions such as toilets and is extracted from these. The main extract is through a centrally positioned open staircase reaching from entrance floor to the top floor where the air-handling unit (AHU) is placed. It is possible to open the windows at each workstation allowing some self-controlled ventilation if necessary.

The AHU has twin fans for both supply and main exhaust (an additional fan for other exhaust such as toilet rooms), a rotary heat exchanger with a bypass function, and a combined waterborne heating and cooling coil for the supply air.

Both indoor CO_2 concentration levels and indoor temperature control the supplied air volume in areas with VAV. The set point for the CO_2 concentration is 650 ppm in the open landscapes and 550 ppm in meeting rooms. When the set point is surpassed the dampers in the ducts will start to open, and at 200 ppm above the set point, the dampers will be fully open, allowing for maximum air volume supply to the zone in question.

Experience has shown that the air supply regulation reacts too slowly in meeting rooms with large load; therefore, these meeting rooms have a lower set point.

The supply air temperature is regulated by the exhaust air temperature. When the outdoor temperature is equal to the desired supply air temperature, the AHU is run without heating/cooling and heat recovery. A bypass damper on both supply and exhaust is open when there is no need for heat recovery.

3. Method

The methods described here are from the tracer-gas field measurements, and the survey on the perceived indoor climate by the users of Powerhouse Kjørbo.

3.1 Tracer-gas Measurements

The main objective of ventilation is to ensure good indoor air quality. The effectiveness varies among the different ventilation strategies. One of the methods to measure the effectiveness is to use a tracer gas method. The method used in this paper is described by the REHVA "Ventilation Effectiveness" guidebook [7]. However, since the measurements were done in occupied premises with possible disturbances, and without a constant airflow rate, the ventilation effectiveness has not been calculated. Instead, there are drawn some conclusions from observing the progress of the tracer-gas decay curves.

The procedures involved adding a tracer gas (in this case nitrous oxide, N_2O) to the supply air and measuring its concentration in the zone of occupancy over time, thus using the step-up and step-down method for the tracer-gas method.

The fieldwork experiments were conducted on the 2nd floor in block 4 with a realistic scenario with normal temperature and load of users. The 2nd floor was chosen on the basis of having a normal load of occupants and being an "average floor" between two similar floors, 1st and 3rd. The drawback of measuring in an occupied building is that several parameters that might influence on the airflow pattern changes during the day.

The floor height is approximately three meters and each floor in the building is around 625 m^2. Only the open landscape was used in this fieldwork, and the 2nd floor has around 450 m^2 of area which supposed to be ventilated by the VAV air supply in the open landscape. The rest are cell offices, meeting rooms and staircases.

The equipment used was the Multipoint Sampler and Doser - Type 1303 and the Multi-gas monitor -Type 1302, both made by Brüel and Kjær. The equipment is remote-controlled from a computer with the LumaSense

Technologies Application Software - Type 7620, which again logs the measured data. The Multi-gas monitor measured the gas concentration of N_2O and the concentration of water vapor to compensate for water vapor's influence while measuring. The planned level of nitrous oxide in the fieldwork environment was set to 25 ppm. The range drift of the Type 1302 is ± 2.5% of measured value per 3 months. The equipment can measure up to six different sample points, where each point is measured approximately every eight minutes (80 seconds per sample). [8]

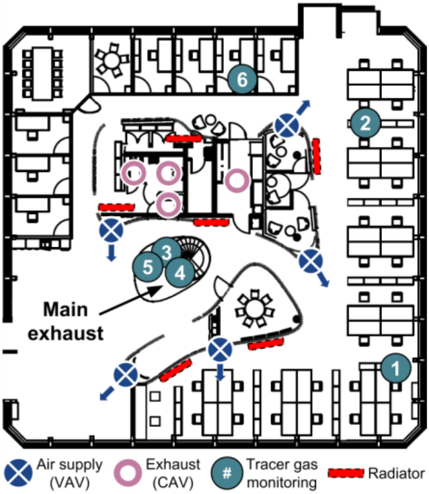
The tracer gas sampling points were in different areas on the 2nd floor of block 4 as seen in Figure 1 in the next chapter. The tracer gas (N_2O) was injected directly into the supply air of the AHU in block 4, and from there it was distributed to all the four floors in the building. It was decided to keep the supply concentration of the tracer gas at 25 ppm, which is within the safe concentration levels and is suitable for the tracer gas in this experiment [7]. The measurements reflect the increase and decrease of the tracer gas as it is injected into (step up) and shut off from the air supply (step down). The experiments were conducted for two days, making it four experiments. The duration for each experiment is shown in their respective graphs in the results chapter.

A smoke test was also conducted to understand the airflow in certain parts of the studied floor. A standard airflow test tube was used to observe how the air moved from a certain air supply diffuser towards the open landscape and eventually to the main exhaust.

3.2 The Perceived Indoor Air Quality

The perception of the indoor climate is essential for the understanding of how an occupant experiences a building. A survey was delivered to all of the permanent users of Powerhouse Kjørbo, and the response rate was 48 % (74/154 users). The survey was conducted in May 2015, approximately one year after the renovated building started operation. The utilized survey is based on the Örebro model and a web-based survey from the Center for the Built Environment (CBE). The Örebro model is part of the MM Questionnaires, developed in 1985 at the Department of Occupational and Environmental Medicine at the University Hospital in Örebro, Sweden [9] (Andersson et al., 2015). The user could select the following categories when rating the air quality: *very poor*, *poor*, *acceptable*, *good* and *very good.* Gunnarsen and Fanger [10] used a rating system of ten points (-5 to 5) where zero is the neutral point between dissatisfied (negative) and satisfied (positive) regarding the air quality. Since this study does not include equally many rating points, a direct comparison cannot be made. However, this paper will regard *acceptable*, *good* and *very good* as being a rating of being satisfied with the air quality.

4. Results and Discussion



4.1 Tracer-gas measurements

The tracer gas measurements were done during March 12 and 13 in 2015 on sunny days with an outdoor temperature ranging from zero °C to 10 °C. Figure 1 illustrates the six different sample points used during the tracer-gas experiments.

Figure 2 - Building plan of the 2nd floor in block 4. The placing of the tracer-gas sampling points are ***1.*** *East corner* ***2.*** *North corner* ***3.*** *2nd floor staircase* ***4.*** *3rd floor staircase* ***5.*** *Main exhaust* ***6.*** *Air supply inlet*

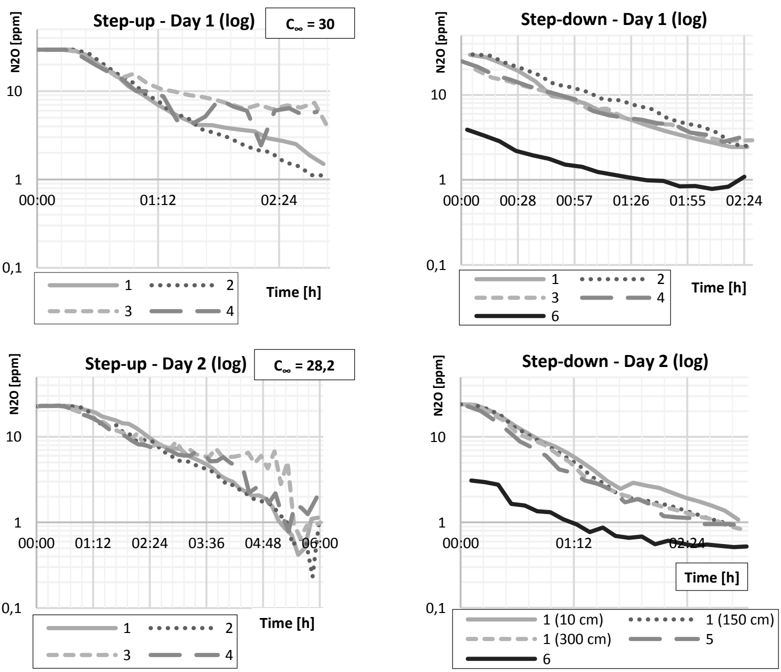


Figure 1 – Step-up and step-down measurements during the two days of experiments. The numbers represent the sampling point from figure 1.

The results from the tracer-gas measurements are presented in four logarithmic graphs in Figure 2, representing the step-up and step-down results from the two different days. The air supply concentration is included only in the step-down graphs, which will be discussed later. The step-up results have also been rearranged to resemble the step-down results. This is done to show a better comparison between the two methods.

The sample points in the step-up period for both days increases (graphically decreases) at different rates. The sample points in the staircase (point 3 and 4), fluctuate more throughout the concentration increase. They do also increase faster in the beginning than the corner points 1 and 2 (which is not so clear in the presented graphs). This could mean that the air moves towards the exhaust in the staircase at a higher rate than the two corners, thus indicating a short circuit between the air supply and the exhaust. This increases the chances of areas where the air is stagnant or exchanged in a much slower rate. The increase near the exhaust does not reflect the characteristics of displacement ventilation, but rather mixing ventilation. The concentration should increase in the open landscape before the sample points near the exhaust.

For the step-down results, the air supply concentration (point 6) has been included, and the graphs start immediately after the tracer gas has been cut from the air supply. Once the gas has been shut off, the concentration measured in the air supply should return to the initial concentration. This is not the case as the concentration drops to around 3 ppm and then slowly decays to the background concentration. This indicates a leakage in the ventilation system where a portion of the exhaust air is recycled into the supply air. It was later, after the fieldwork, confirmed by the supplier of the ventilation unit that the leakage came from the heat exchanger.

Day two has three sample points in the same location (point 1, east corner) at different heights. The concentration is the same at all levels (10 cm, 150 cm and 290 cm above the floor) when the decay begins. In case of displacement ventilation, the decay should happen first at the lowest level, and then the higher levels should follow according to the stratification model. It seems like there are tendencies towards the opposite in this case.

4.2 Smoke Test

Since there is a reason to believe that there is a short-circuiting of the airflow, then there is also reason to believe that there are zones with stagnant air, which could cause lower air quality and risk of excess heat not being removed as efficient as it could have been. During the tracer-gas measurements it was observed that the temperature in the eastern corner of the 2nd floor was higher than other areas on the same floor. A smoke test was conducted and the airflow stream and area of turbulent air is illustrated in Figure 3. The air is distributed from the diffuser, but before it can reach the right corner in the figure, it is drawn towards the main exhaust. It is observed that the furniture used in the open landscape, such as filing cabinets used between the work desks, function as a kind of blockade for the airflow stream. During warmer days, the opposite could be the case, where excess heat is not removed from the corner at a high enough rate, risking too high temperatures.

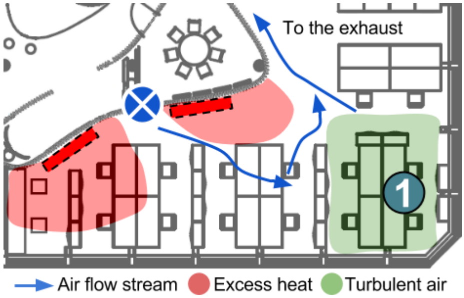


Figure 3 – Illustration of the smoke test flow in the eastern corner with turbulent zones and measured areas of high temperatures.

4.3 Perceived Indoor Air Quality

Regarding the survey for the perceived indoor climate at Powerhouse Kjørbo, the users were asked how they experienced the air quality at their work desk (cell office or open landscape). If considering the rating categories *very good*, *good* and *acceptable* as a form of satisfaction, then there is a satisfaction of air quality of 97 %, and over 70 % perceives the air quality as *very good* or *good*. No users consider the air quality *very poor*, although, 39 % of the same participants state that they sometimes have problems with poor air quality. Since the perception of air quality only regards the work desk it is possible that these problems are experienced elsewhere, such as in meeting rooms. There are additional comments in the survey from the employees, which indicate that this is the case, but it will not be discussed, as it is irrelevant to the study of open landscape ventilation.

4.4 Proposals for Improvements

The tracer gas measurements indicate that there is room for some improvements to the ventilation system at Powerhouse Kjørbo. First, the short-circuiting between the air supply and the exhaust should be avoided. The inlet diffusers supply colder air from the central part of the floor towards the facades in the open landscapes, where the workstations are located. The exhaust duct is centered at each floor through the open staircase. This makes the airflow of the supplied air move in the opposite direction of the extracted air. If the air had been supplied from the external walls towards the exhaust, it might increase the ventilation efficiency and reduce the stagnant zones. This would however not work with the current interior design in the open landscape. It would also require longer ventilation ducts and thus eventually larger energy use. A more appropriate solution could be to reduce the supply from the devices closest to the staircase.

What could decrease the areas of stagnant air is the use of more open furniture that does not obstruct the airflow from the supply diffusers towards the occupants of the open landscape.

5. Conclusion

The ventilation strategy at Powerhouse Kjørbo works in the whole well, and the occupants are highly satisfied with the air quality in the building. However, the tracer-gas measurements and airflow smoke tests indicate that there is room for improvements. Zones of stagnant air is observed and it is suspected a short circuit between the air supply and exhaust from several air supply diffusers. It is important to design the interior of the open landscape with the ventilation strategy in mind so that it does not interfere with the airflow. With the use of displacement ventilation from walls, one should avoid obstructions along the floor, such as filing cabinets and bookshelves. The placement of supply diffusers in a building with a similar ventilation exhaust design should be placed such that the airflow can reach all zones of occupancy before it is extracted. Because of disturbances and variable airflow rate during the measurements, it is recommended to try to confirm these theories by recreating the fieldwork under more stable conditions.

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