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A Field Study of the Indoor Climate in an Energy Efficient Building in Norway

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Abstract

In our modern society, people spend as much as 90% of their time indoors. The objective of this study is to investigate the indoor climate in an energy efficient building with balanced mechanical ventilation system placed in Norway. Field measurements have been performed in an energy efficient office building in November 2015. Parameters such as temperature, air velocity, relative humidity, particulate matter (PM) and CO₂ concentration were measured and analysed. The results showed that the thermal environment was within satisfactory limits and the measured rooms achieved categories A and B according to the international standard ISO 7730. The relative humidity was found to be slightly low and varied between 20 and 25%. The PM_{2.5} and PM₁₀ values in the breathing zone were below the recommended maximum limits according to the Norwegian Institute of Public Health. However higher concentration of PM₁₀ was found at floor level in one office room. The high concentration of PM₁₀ at floor level might cause increased PM₁₀ in the breathing zone due to re-suspension of particles in the air. The low levels of relative humidity might contribute to lower performance among the office workers in addition to development of SBS symptoms, asthma and respiratory infections. Increasing the relative humidity may improve the performance of workers in the office. It must be noted that the study is not representative for the whole building as only five rooms on the third floor were evaluated.

Keywords – Indoor Air Quality; Human Health; Energy Efficient Buildings; Atmospheric Environment; Thermal Environment

1. Introduction

The world's energy consumption is constantly increasing with globalization and new technology. According to the United Nation's Environmental Program, 40% of the energy used in the world is linked to energy use in buildings and as a result, buildings contribute to 30% of global annual greenhouse gas emissions^[1]. Human beings spend as much as 90% of their time indoors; either at home, at school or in their work place^[2].

Studies confirm that indoor surroundings have an effect on human health. A study by Skyberg and Skuleberg et al. (2003) in Norway established that frequently reported health problems by office workers were feelings of fatigue or heavy-headedness, eye irritation and dry facial skin^[3]. Wyon stated in 2004 that poor indoor air quality (IAQ) could reduce the performance of office workers with 6-9%^[4].

Several studies discuss how the thermal environment can affect perceived IAQ and the performance of office workers. Seppänen et al. collected literature regarding the relationship between temperature and work performance. They established an average 2% decrease in work performance per degree Celsius that exceeded 25°C^[5]. An experiment involving 30 female subjects exposed to three levels of air temperature and humidity (20°C/40%, 23°C/50%, 26°C/60% and 20°C/40%) and two levels of ventilation rate (10 l/s/p and 3.5 l/s/p) concluded that several Sick Building Syndrome (SBS) symptoms were improved when the workers were exposed to low levels of air temperature and humidity. This implies that low levels of air temperature and humidity might be beneficial for the productivity rate^[6].

Egawa et al., suggests that a dry environment in our daily life influences the skin surface patterns^[7]. Relative humidity (RH) directly influences the indoor size of allergenic mites and VOCs as explained by Arundel et al. in 1986^[8]. The off – gassing from indoor building materials and the amount of fungi in the building is also influenced by RH. A majority of adverse health effects triggered by either too high or too low RH are minimized by keeping indoor RH levels between 40% and 60%^[10]. Fang et al. states that levels of RH around 40% are beneficial for the performance of office work^[6]. Moreover, Wiik concluded that experience of dry air and the associated SBS symptoms influenced the reduction in indoor productivity most during winter months^[10].

Epidemiological studies consistently show an association between particulate air pollution and mortality from cardiovascular and respiratory disease^[11]. According to Brunekreef et al. in 2002, effects of particulate matter (PM) on human health have been seen at very low levels of exposure^[12]. The World Health Organization recommends a mean annual indoor particle concentration of 10 µg/m³ and 8 µg/m³ for PM₁₀ and PM_{2.5} respectively^[13]. Sources of indoor PM include cooking, heating, building materials, house dust and outdoor particle infiltration^[14].

Findings show that maintaining the indoor CO₂ concentration beneath 1000 ppm is beneficial for the productivity of office workers. An increase in SBS symptoms has been seen at CO₂ levels above 800 ppm, especially upper respiratory symptoms and eye irritation, according to Tsai et al. and Satish et al.^[15,16]. The Norwegian Work and Environment Act recommends an upper indoor limit for CO₂ concentration of 1000 ppm^[17].

The objective of this study is to examine the indoor climate in an energy efficient building and the potential health risks the indoor climate might expose to human occupants. Field measurements were conducted in an office building in Norway. Two single office rooms, two open office rooms and one meeting room were investigated in this survey. Both the thermal and atmospheric environment was assessed.

2. Method

2.1 Measurement Setup

The fieldwork was conducted from 17.11.15 to 19.11.15 in a three-story office building in Trondheim in the middle part of Norway. The building is newly constructed and was first in use in 2011. Three different companies share the building, however only the third floor is evaluated in this study. This floor is used as an office space for the consultant and entrepreneur company Caverion. Approximately 50 people work in the office space regularly, and each employee has a permanent work desk. The building has mechanical demand-control ventilation systems. The larger rooms, such as meeting rooms, are controlled by CO₂ concentration and temperature, whereas presence detectors control the ventilation rate for smaller rooms. The ventilation systems are divided into three parts covering different vertical sections of the building. In this study, only one ventilation system was considered. The heating system consists of wall radiators combined with heated air from the ventilation system. The majority of the office floors are covered with carpets. The properties of the evaluated rooms are shown in Table 1.

Table 1. Room properties

	Area [m ²]	Height [m]	Window area [m ²]	People
SingleOff1	12	3	2.1	1
SingleOff2	12	3	2.1	1
OpenOff1	64	3	6.2	6
OpenOff2	26.8	3	3.2	4
Meeting Room	27	3	7.5	7

2.2 Measurement Conditions

ASHRAE's definition of breathing zone as the region between 0.75 and 1.8 meters above the floor^[18] is used in the performed measurements. All measurements were made at a representative work desk in each room. In the larger rooms, i.e. Open Office 1 and Meeting Room, three different desks in the room were evaluated and the average values were found. The clothing insulation is assumed to be normal indoor winter clothing, i.e. 1 clo, and the metabolic rate is assumed to be 1.2 met for the office workers.

The air velocity was measured at head, hips and ankle level. The mean radiant temperature for a seated person was calculated according to ISO 7726^[19]. The PD due to radiant asymmetry, vertical air temperature difference and warm/cool floors in addition to the draught rate was calculated according to ISO 7730^[20]. The PMV and PPD values were calculated using CBE Thermal Comfort Tool^[21]. The input parameters were air temperature, plane radiant temperature, RH, air velocity, clothing insulation and metabolic rate. The input parameters for CBE Thermal Comfort Tool are shown in Table 2.

The CO₂ concentration was estimated by recording spot measurements over a period of approximately 30 minutes in each location. The average CO₂ concentration for each room was then estimated. The CO₂ concentration recorder was placed above the workspace to avoid influencing the results through exhalation from the worker. The CO₂ level was also measured outdoors by the air supply inlet. It must be noted that the AQ 200 Air Quality device had not been calibrated for a while, which could influence the results.

Particle concentration was measured at both desk level and floor level, as well as outside, in the ventilation inlet and in the ventilation outlet. The measuring time varied from three to five minutes. Particle concentration was measured at several locations in each room and the average value was calculated. The particle counter was limited to certain size intervals, however the detailed distribution within the size interval was not obtainable. The intervals were: 0.3-0.5; 0.5-1.0; 1.0-3.0; 3.0-5.0; 5.0-10.0; 10.0-25.0 [μm]. The PM_{2.5} value was not possible to obtain due to the interval being defined from 1.0 to 3.0 μm . However, the PM_{3.0} value was obtained and compared with the PM_{2.5} limit value.

2.3 Instrumentation

The dry-bulb air temperature, air velocity, standard deviation and RH were measured using Brül & Kjær Indoor Climate Analyser type 1213 together with a rack for attaching measurement probes. The air velocity, air temperature and RH were measured simultaneously. A Bosch PTD1 Thermo Detector was utilized to measure surrounding surface temperatures, including floor and ceiling. The device has an accuracy of $\pm 1^\circ\text{C}$ for surfaces

with temperatures between 10 °C and 30 °C. The thermo detector was also used to verify the air temperature in the room. To measure the carbon dioxide concentration an AQ 200 Air Quality measurement device was used. The device has a range of 0 to 5000 ppm and an accuracy of $\pm 3\%$ of measuring value, ± 50 ppm. An AeroTrak 9306 was used to measure the number and mass concentration of particles in the building. The measuring range of the device is 0.3-0.25.0 μm and the counting efficiency is 50% for particles with diameters of 0.3 μm and 100% for particles with an aerodynamic diameter of more than 0.45 μm .

3. Results

3.1 Thermal Environment

The measured results of air temperature, mean radiant temperature, RH and air velocity are presented in Table 2. The calculated operative temperature and draught rate are also included in the table.

Table 2. Measured thermal parameters in the office building

	Air temperature [°C]	Mean radiant temperature [°C]	Operative temperature [°C]	Relative humidity [%]	Air velocity [m/s]	Draught Rate [%]
SingleOff1	22.50	21.54	22.02	25.00	0.08	6.44
SingleOff2	21.80	21.05	21.52	22.00	0.07	4.59
OpenOff1	22.30	21.07	21.70	20.33	0.07	4.04
OpenOff2	21.70	21.32	21.37	22.00	0.16	19.27
Meeting Room	21.70	20.76	21.25	24.00	0.04	0.00

Table 3 shows the thermal environment category for each of the rooms in the office building according to ISO 7730^[20]. The calculated PPD, PMV and DR are presented, in addition to the percentage dissatisfied caused by vertical air temperature difference, warm or cool floors and radiant asymmetry.

Table 3. Resulting thermal environment category

				PD [%] caused by			Category
	PPD [%]	PMV [%]	DR [%]	Vertical air temperature difference	Warm or cool floor	Radiant asymmetry	
SingleOff1	5.00	0.00	6.44	0.41	6.43	0.20	A
SingleOff2	5.00	-0.15	4.59	0.34	6.17	0.30	A
OpenOff1	5.00	-0.10	4.04	0.37	6.33	0.31	A
OpenOff2	7.00	-0.28	19.27	0.41	6.25	0.14	B
Meeting Room	6.00	-0.18	0.00	0.36	6.30	0.16	B

3.2 Atmospheric Environment

The measured CO₂ concentrations in the Caverion office building are presented in Table 4. The outside concentration was measured to be 466 ppm by the ventilation inlet.

Table 4. Measured carbon dioxide concentrations in the office building

	Single Off1	Single Off2	Open Off1	Open Off2	Meeting Room
CO ₂ [ppm]	644	516	488	554	604

Due to the mentioned limitations in counting intervals for the AeroTrak 9306, the PM_{2.5} concentration was not obtainable in this study. However, the PM_{3.0} concentration was found, and it is assumed that the PM_{3.0} concentration is comparable to the limit values regarding PM_{2.5} concentration. The PM_{3.0} concentration in the office building is shown in Fig. 1. The black and white columns represent the floor and breathing zone concentration respectively. The PM_{3.0} concentration is compared with the recommended maximum values for PM_{2.5} given by the Norwegian Institute of Public Health^[22] and the World Health Organization^[13].

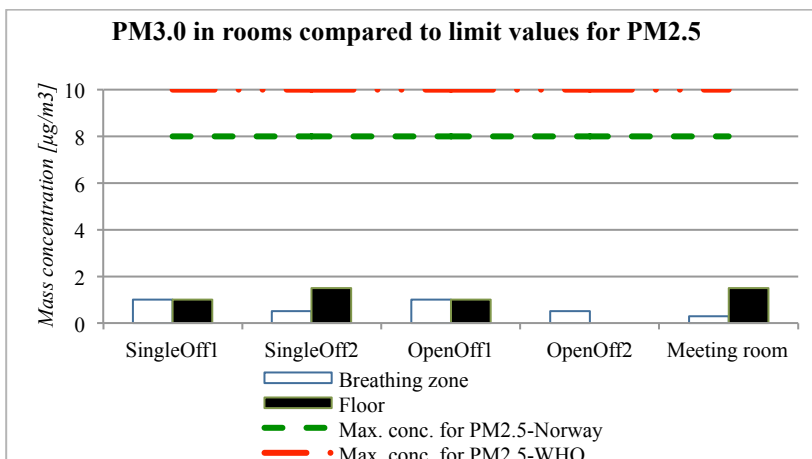


Fig. 1. PM_{3.0} concentration in the office building. PM_{3.0} is compared with limit values for PM_{2.5}

The PM₁₀ concentration in the office building is shown in Fig. 2. The black and white columns represent the floor and breathing zone concentration respectively. The measured concentrations are compared with the guidelines from the Norwegian Institute of Public Health and the World Health Organization.

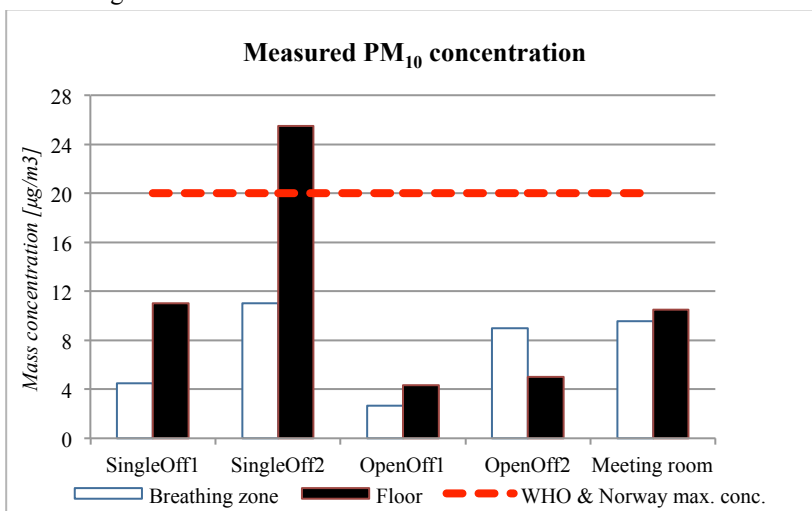


Fig. 2. PM₁₀ concentration in the office building compared with limit values

4. Discussion

4.1 Potential Effects of the Thermal Environment on Human Health

The operative temperatures vary from approximately 21.2 °C to 22.0 °C. This is well below the maximum temperature of 26°C and above the lower limit of 19°C recommended by the Norwegian Work and Environment Act^[17]. The results imply that the experienced temperature in all measured rooms is adequate.

As seen in Table 2, the lowest RH measured in the building is approximately 20%, which indicates that health problems may occur. The literature shows that dry or irritated mucous membranes as well as static electricity or dryness of skin might be health effects caused by too low RH. According to Arundel et al. bacteria, viruses, respiratory infections, allergies and asthma thrive in indoor environments with RH below 30%. Additionally, the results indicate that a decrease in indoor productivity of the office workers may be expected due to low RH, as indicated by Wiik and Fang.

The air velocity is an important factor when deciding thermal comfort. From Table 2 it is noticeable that Open Office 2 experiences higher air velocity than the other rooms. Open Office 2 is placed in the middle of the building with an open hallway through the office. There were numerous people walking by the workspace throughout the period of measurements, as well as large openings for the air to flow freely.

The air velocity in Open Office 2 is 0.1 m/s higher than the recommended maximum air velocity by the Norwegian Work and Environment Act^[17] and gives a draught rate of 19%. This gives reason to believe that the person sitting at this particular office space may experience thermal discomfort due to excessive air speeds.

The overall thermal conditions imply that no severe health effects or reduction in performance will transpire due to a bad thermal environment. Moreover, a possibility for productivity gains can be achieved by reducing the air temperature in the warmest rooms. This complies with a study by Fang et al. in 2004, which states that low levels of air temperature ($\approx 20^{\circ}\text{C}$) might be beneficial for productivity and might reduce SBS symptoms compared to higher air temperatures.

4.2 Potential Effects of IAQ on Human Health

It can be concluded that the CO₂ concentrations are satisfactory. Table 4 shows that the investigated rooms are below the recommended maximum limit of 1000 ppm established by the Norwegian Work and Environment Act. The figure shows that Single Office 1 has the highest value of CO₂, of approximately 650 ppm, followed by Meeting Room. According to Tsai et al. CO₂ concentrations exceeding 800 ppm were linked with an increase in

SBS symptoms compared to concentrations of 500 ppm, which implies satisfactory CO₂ concentrations for productivity in this office.

The results show that the PM_{3,0} level in the investigated rooms are well below the limit of 8 µg/m³ recommended by the Norwegian Institute for Public Health and below the limit of 10 µg/m³ recommended by the World Health Organization for PM_{2,5}. This is valid for both the breathing zone and the floor level. Although the PM_{2,5} value could not be established, it can be assumed that the mass concentration levels for PM_{2,5} would be even lower than that illustrated here for PM_{3,0}.

Fig. 2 shows the PM₁₀ concentration in different rooms. From the results it can be concluded that the concentrations found are well below the requirements from the World Health Organization and the Norwegian Institute for Public Health, except at floor level in Single Office 2. In the Caverion building a majority of the floors are carpeted, which creates good conditions for particles to accumulate. Particles at floor level may re-suspend from the carpet into the breathing zone, thus influencing the particle concentration in the breathing zone. As Fig. 2 shows, the mass concentration of PM₁₀ in Single Office 2 is larger in the breathing zone than other rooms. This may be connected with the high levels of PM₁₀ at floor level.

When comparing with Fig. 1, the PM_{3,0} concentration at Single Office 2 is similar to the concentrations in the other rooms. This suggests that Single Office 2 has a larger concentration of coarse particles ($d > 3 \mu\text{m}$), which can compose of house dust or soil particles. Consequently, the large mass concentration of PM₁₀ in Single Office 2 may be caused by insufficient cleaning procedures. The Caverion office building is vacuumed once a week. The results indicate that the cleaning is not adequate and should be performed more frequently.

5. Conclusion

The thermal environment in the Caverion office building was acceptable with a maximum PPD of 7% and PMV of -0.28. No significant temperature asymmetry or thermal stratification was found in the rooms. The concentration of PM_{2,5} and PM₁₀ were below the recommended maximum limits in the breathing zone. However, the concentration of PM₁₀ was high at floor level, which might cause increased PM₁₀ in the breathing zone due to re-suspension of the particles in the air. Low relative humidity was found in the measured building, which might contribute to lower performance among the office workers in addition to the development of SBS symptoms, asthma and respiratory infections.

It is recommended to examine several energy efficient buildings to get a basis for comparison and to achieve a better understanding of the indoor climate in new, airtight and mechanically ventilated buildings.

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