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The Effects of Nightly Shutdown of Ventilation on Indoor Air Pressure Difference Conditions and TVOC and radon concentrations in Finnish Schools and Day-care Centres

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Abstract. In the Future Spaces research project, the impact of completely shutting down night-time ventilation on measured and experienced indoor air quality was examined in 11 Finnish day-care or school buildings. The study compared a normal situation comparison period defined by measurements during early winter to a consecutive altered situation comparison period defined by measurements during late winter. The effect was evaluated by comparing daily hourly mean values measured during the comparison periods. Modern ventilation systems in new buildings generally keep pressure differentials at a moderate level when properly adjusted and in most cases and the night-time ventilation shutdown does not have a big impact on the air pressure difference conditions over the building envelope. TVOC (Total Volatile Organic Compounds) and radon concentrations increased as expected at night when ventilation was stopped, but this had no significant impact on concentrations during occupied hours when ventilation was restarted 2–3 hours before the arrival of the first building users to ensure clean indoor air. Therefore, the effects on indoor air quality during occupied hours are not an obstacle to stopping ventilation during absence periods for example for energy saving reasons.

1 Introduction

Mechanical ventilation, wind and the temperature difference between indoor and outdoor air cause a pressure difference across the building envelope. This can often be noticed especially in high buildings, when walking through the front door or when opening a window. Mechanical ventilation has traditionally been adjusted to a slightly negative pressure difference [1]. In cold climate, overpressure of the indoor air can cause condensation of moisture in the envelope structures at an air leakage point which may lead to microbial and moisture damage. However, excessive negative pressure in buildings is also not desired, as it causes air infiltration through the leakage points in the building envelope. In such case pollutants can be transported into the indoor air from possible microbial damage points in the building envelope structures or from the crawl space. Therefore, the ventilation should be adjusted so that the air pressure difference during building operation is as small as possible. According to current Finnish national guidelines, ventilation should be designed and adjusted in such a way that neither underpressure nor overpressure causes problems.

Indoor air problems in schools and day-care centres have been a significant topic of conversation for a long time. Poor quality of the indoor environment has been found to have a greater effect on children than on adults. Because of this, close attention must be paid to the working environment of day-care and school-aged children. [2] There are approximately 500,000 students studying in Finnish primary schools and there are about 200,000 children in early childhood education. In addition to this, about 30 % of people of working age work in the public sector in Finland. [3] Clean and fresh indoor air has positive effects on people's ability to learn, ability to work and on health. According to a report by the Institute of Health and Welfare, people of working age spend about 90 % of their time indoors. Small children and the elderly may stay indoors even more than this. [4]

In the field studies of the previous research project COMBI (Comprehensive development of nearly zero-energy municipal service buildings) in 2016–2018, it was found that the night-time ventilation of day-care centres and schools causes negative pressure over the outer envelope in the investigated buildings. [5] In the field studies of the current Future Spaces project 2021–2022, the effect of eliminating night-time negative pressures on indoor air quality was investigated by stopping night-time ventilation completely, including the separate exhausts from toilets and similar spaces. The effect of stopping ventilation at night on the indoor air quality of buildings was evaluated based on two comparable measurement periods. The physical conditions of the indoor air and pollutant concentrations were measured in the examined buildings. The effects of stopping the ventilation were then evaluated based on the changes in these period-specific measurement results.

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2 Methods and materials

2.1 Field measurements

2.1.1 Studied buildings

The buildings studied in the field research included 12 school or day-care buildings from the Tampere Region in Finland, as well as one office building in Tampere and another in Helsinki. Ventilation was not stopped in two buildings due to air heating and these buildings are not included in this paper. Table 1 presents basic information of the 11 school and day-care buildings that were included in the ventilation shutdown phase of the research. All buildings had mechanical supply and exhaust ventilation with multiple ventilation units.

Table 1. Basic information on the studied buildings.

Use	Construction year	q_{50} value [m^3/hm^2]
Day-care	2019	0.9
Day-care	1986	2.7
Day-care & school	2018	0.9
Day-care & school	2014	1.0
Day-care & school	2014	0.86
Day-care	1904	2.34
School	1952, 2006	3.8
Day-care & school	2012	0.8
Day-care	2012	0.5
School	1964, 1990	4.25
Day-care & school	2013, 2019	1.0

There was a total of 52 spaces studied in field measurements, with a total of 9 measured variables in continuous measurements.

2.1.2 Measurement devices

The air pressure difference ($\Delta P = P_i - P_e$) over the outer envelope, and the indoor air conditions of temperature (T), relative humidity, carbon dioxide concentration, TVOC concentration, radon concentration and small particle concentrations PM1, PM2.5 & PM10 were continuously measured in the field study case buildings. Table 2 shows the data of the measuring devices with which the obtained measurement results are discussed in this article.

Table 2. The measurement devices used in the study.

Variable	Measure-ment device	Unit	Accu-racy	Range
Pressure difference	In-house built (Honeywell)	Pa	±0.25%	±250 Pa
Tempera-ture	Rotronic CL11	°C	±0.3°C	-20–+60 °C
TVOC	AirWits IAQ R1.1	ppb		0–50°C <95% RH
Radon	RadonEye Plus2	Bq/m³	< ±10%	10–40°C <80 % RH

Outdoor air temperature, relative humidity and fine particle concentration data were obtained from the nearest observation station of the Finnish Meteorological Institute [6] and the observed values were used in the calculation of the indoor air vapour excess and in the studies of fine particle concentrations.

The time resolution for measurements was 5 min for indoor air conditions and 10 min for outdoor air conditions. The data was collected monthly from the on-site measurement devices.

2.2 Effects of nightly shutdown of ventilation on indoor air conditions and quality

2.2.1 Comparison periods of normal situation and altered situation

The impact of night-time ventilation shutdown on indoor air quality was assessed based on two consecutive comparable measurement periods. These comparison periods were scheduled during the winter season, and efforts were made to select periods of similar length and average outdoor conditions. The indoor air conditions in normal situations were determined based on measurements conducted between October 25, 2021, and January 9, 2022. Night-time ventilation was stopped from January 10, 2022 to March 28, 2022. The duration of the comparison periods was 11 weeks, and the average outdoor temperature was practically identical. The outdoor conditions during the comparison periods are presented in Fig. 1.

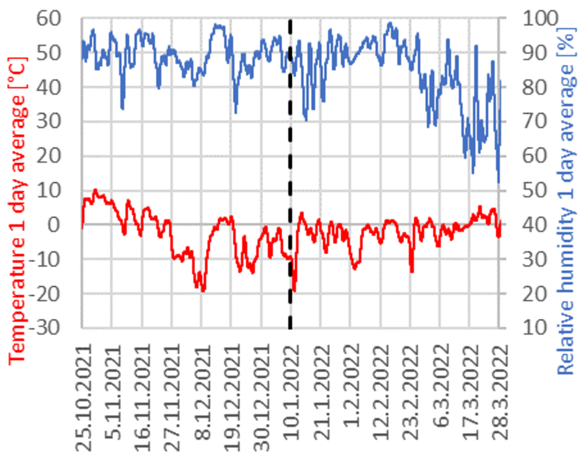

Fig. 1. Outdoor conditions during the comparison periods.

2.2.2 Data analysis

Due to the substantial amount of measurement data, raw data was processed and compiled using Python code to manage the large dataset. The processed data was further analyzed using Excel tables and Python code. The primary tool for evaluating the impact of stopping night-time ventilation was a box plot, which compared the mean values of individual hours during the comparison periods. By examining the hourly mean values over a 24-hour period, increases and decreases in measured night-time values could be observed returning to normal levels when ventilation resumed. The per-hour box plots also allowed consideration of different operation situations and building usage throughout the day and week.

The air pressure difference ΔP [Pa] over the building envelope was studied separately to find out if the night-time shutdown of mechanical ventilation reduced the absolute air pressure difference values. This was done by first plotting the air pressure difference as a function of various other available parameters. From these it was noticed that there was a linear correlation to the temperature difference between indoor and outdoor air ($\Delta T = T_i - T_e$). This was utilised by fitting a straight line ($\Delta P = \beta_0 + \beta_1 \cdot \Delta T$) to the results, tabulating the coefficients and then comparing the coefficients between the normal and altered situations with the t-test. In the following text, weekdays mean those times, when the day of the week is between Monday and Friday, and the hour is between 10 and 14. Weeknights means the same days, but the hours are between 22 and 02. Weekends mean times when the day is either Saturday or Sunday.

3 Results

3.1 Indoor air pressure differences

3.1.1 Measurement results

Contrary to the previous COMBI project, no significant night-time negative pressures were observed in the buildings based on the field measurements in this study. Apparently, between the research projects, building ventilation has been successfully adjusted to be more balanced. Thus, the change in night-time pressure differences due to completely shutting down ventilation was smaller than assumed. Fig. 2 shows the pressure difference data for a single week in a studied space.

The building was selected for inclusion in the Future Spaces project because of the pressure difference values observed in the COMBI project. Based on the measurements made in the Future Spaces project, ventilation has been balanced between the research projects. The building envelope is very airtight (q50=0.50 m^3/hm^2), making ventilation adjustment challenging. However, based on Fig. 2, the pressure difference is currently relatively moderate. Individual spikes are presumed to be caused by building occupants. The graph forms a staggered two-level pattern for weeknight values and for weekday values. During weeknights, the values were mostly between -5…-10 Pa. During weekdays, the pressure difference values stayed mostly between 0…-5 Pa.

The differences in night-time hourly averages between the normal situation and the altered situation in the same space are presented in Fig. 3. Overall, the impact of stopping ventilation on pressure differences was very small. However, in a few other cases a more noticeable difference between the comparison periods was observed. In general, the pressure difference values during the altered situation often settled at a moderate level of underpressure.

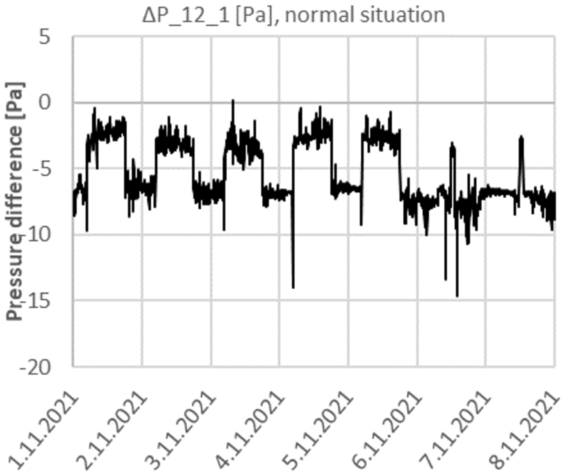

Fig. 2. Pressure difference data from a single week during the normal situation measured in studied space 12_1.

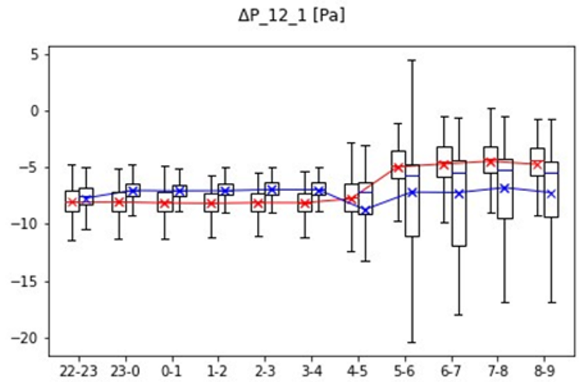

Fig. 3. Nightly averages of pressure differences measured in the same space as in Fig. 2. The line connecting averages during altered conditions (blue line) is slightly above the corresponding line during normal conditions (red line) between 22 and 04 in the night.

Fig. 3 illustrates typical effects observed from the box plot figures. In normal situation, the indoor and outdoor air pressures were in most cases already well balanced as the air pressure difference values settled at a modest underpressure level through the night. In most cases, the ventilation shutdown at 10 PM had virtually no effect on the nightly hourly mean values in the altered situation. In a few case buildings, the difference was more notable. However, the reasons were not thoroughly analysed in this study.

3.1.2 Correlation to outdoor air temperature

Fig. 4 shows the measured air pressure difference as a function of the temperature difference between the indoor and outdoor air temperature from a single zone. The different operating situations are marked with different colours.

In Fig. 4, the correlation between the air pressure difference and temperature difference was quite linear, although some variation existed around the fitted line. The RMSE of the residuals in Fig. 4 was 2.7 Pa for weekdays (R^2 = 0.36), 1.6 Pa for weekends (R^2 = 0.59) and 1.5 Pa for weeknights (R^2 = 0.72). Fig. 5 shows the intercepts β_0 of fitted lines for all the zones and operating situations, in both the normal situation and in the altered situations.

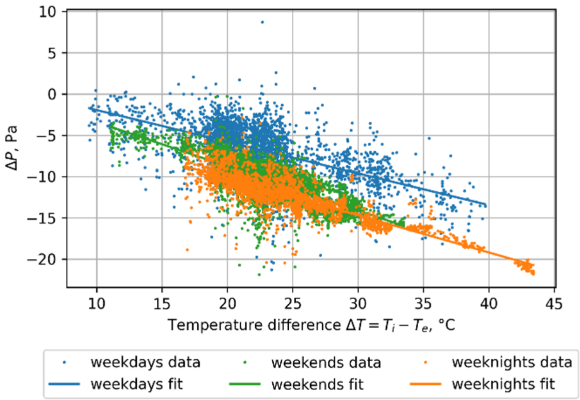

Fig. 4. Air pressure difference as a function of temperature difference between the indoor and outdoor air for a single zone in the altered situation. Different operating situations are marked with different colours (weekdays, weeknights and weekends).

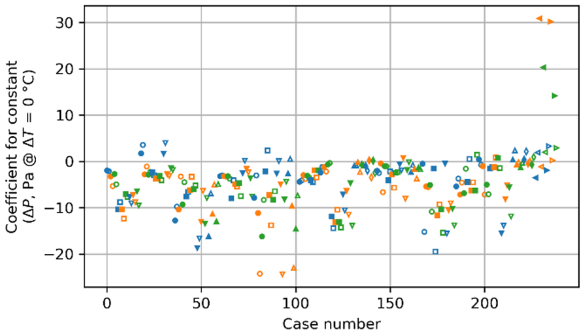

Fig. 5. Intercepts of the regression lines for all the zones and operating situations, for both the normal situation (filled marker) and the altered situation (next adjacent empty marker).

Fig. 6 shows the slopes β_1 of the fitted lines for all the zones and operating situations, for both the normal and altered situations.

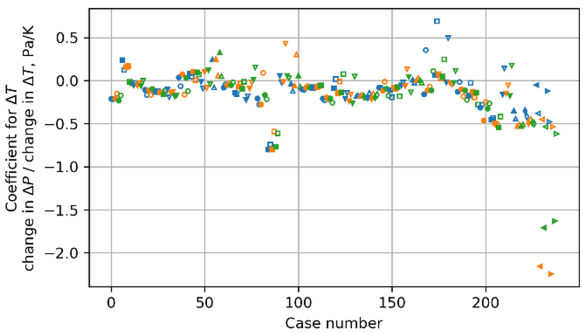

Fig. 6. Slopes of the regression lines for all the zones and operating situations, for both the normal situation (filled marker) and the altered situation (next adjacent empty marker).

A bit surprisingly, in Fig. 5 the air pressure difference at zero temperature difference was not zero in most of the cases. The exact reason for this was not thoroughly analysed in this study, but possible reasons are at least measurement uncertainties, statistical confidence intervals, persistent wind directions, the filtered times not properly aligning with ventilation unit schedules, and some of the mechanical ventilation units not being shut down or causing an impact to the measurement location through another zone.

The impact of varying mechanical ventilation on air pressure difference was identified from figures similar to Fig. 4 by them having distinct clusters of data points within a single operating situation. After removing these cases and analysing only weeknight data, paired t-tests (n = 29) were done to test if the sample means of the intercept or slope were different between the normal and altered situations. According to the calculations, the intercepts did not have statistically significant differences (p = 0.13) between the two samples, whereas the slopes did have (p = 0.026). However, the change in intercept (mean = –0.8 Pa, SD = 2.7 Pa) and slope (mean = 0.029 Pa/K, SD = 0.067 Pa/K) are quite small and for a temperature difference of 30 K, the change in air pressure difference would be (-5.0 Pa - 0.12 Pa/K x 30 K) - (-4.2 Pa - 0.15 Pa/K x 30 K) = -8.7 Pa - (-8.8 Pa) = 0.1 Pa, that is the difference would be insignificant on average. It can be said that the small change was also expected, because the situations with strange performance were cleaned out before the statistical test. If all the weeknight cases were included in the comparison (n = 40), then the changes in both the intercept and the slope were statistically significant (changes in intercept: mean = -3.0 Pa, SD = 8.4 Pa, p = 0.028; changes in slope: mean = 0.13 Pa/K, SD = 0.4 Pa/K, p = 0.049).

3.2 Indoor air quality variables

The effect of stopping night-time ventilation on indoor gas and particulate concentrations was investigated as a part of a master's thesis [7]. The spaces included in the study were grouped based on whether there were supply and exhaust air vents in the examined space or if exhaust ventilation was centralized to a nearby corridor or a sanitary unit. This article presents results of TVOC and radon concentrations, as the night-time concentrations were noticeably affected and thus they function well as indicators of the ventilation operation. Regarding the other measured variables, no significant effect was found in the study.

The most significant differences in TVOC and radon concentrations between normal and altered ventilation comparison periods were observed during the night in spaces where both inlet and exhaust ventilation operated at partial capacity during normal period maintaining steady and low concentrations throughout the night. Other ventilation cases involved supply and exhaust ventilation only in "dirty" spaces and cases with only exhaust ventilation used in the building.

Indoor VOC (Volatile Organic Compounds) sources include building materials, interior materials, textiles, cleaning agents, cosmetics, and people [8]. Therefore, indoor VOC sources are present even when the occupants are not present. The difference in TVOC concentrations during the comparison periods is illustrated in Fig. 7.

Night-time TVOC concentrations increased as expected when ventilation was stopped. However, it was noted from the measurements that when ventilation started at 4:00 AM, the TVOC concentration decreased and returned to normal levels by 7–8 AM. The situation had normalized by the beginning of the operating hours of the buildings at 8 AM. User activities have a significant impact on concentrations during daytime. Thus, concentrations during operating hours may differ from comparison periods. If space usage was consistent, concentrations in normal and modified ventilation scenarios behaved similarly during operating hours.

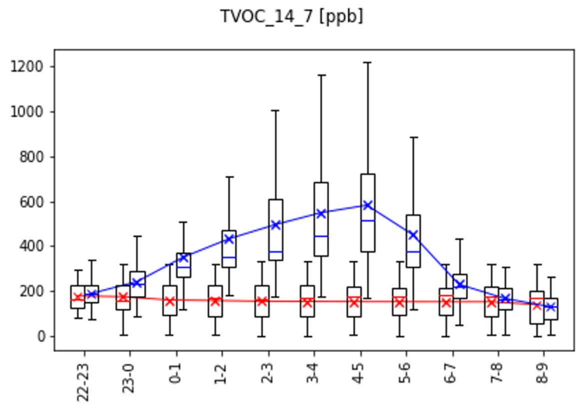

Fig. 7. Nightly averages of TVOC concentrations measured in Room 14_7. The line connecting averages during altered situation (blue line) is above the corresponding line during normal situation (red line).

The main source for radon indoors is the soil, from where radon enters the building through building's foundation [8]. Radon concentrations could vary significantly between operating hours and nights, even during normal situation. Peak concentrations are significantly influenced by ventilation design, foundation type, air leakage, pressure differentials, and the building's regional location. The nightly shutdown of ventilation had the greatest impact on radon concentrations in spaces where both inlet and exhaust ventilation operated at partial capacity during normal period. The difference in indoor radon concentrations during the comparison periods is illustrated in Fig. 8.

As expected, night-time radon concentrations increased when ventilation was shut down. The difference compared to normal conditions was particularly clear in spaces where supply and exhaust ventilation operated at partial capacity during night-time in normal situation. However, it was observed again from the measurements that when ventilation started at 4:00 AM, radon concentrations also decreased and returned to normal levels by the start of operating hours. The concentrations had returned to normal levels by the beginning of the operating hours of the buildings at 8 AM. Concentrations behaved similarly to VOC concentrations during weekdays, although the emission source was the soil and the building's foundation, rather than building materials and furniture. Radon concentrations measured with radon detectors were generally low and remained well below the action level of 300 Bq/m^3 and the Classification of Indoor Environment 2018 [9] S1 target value of 100 Bq/m^3.

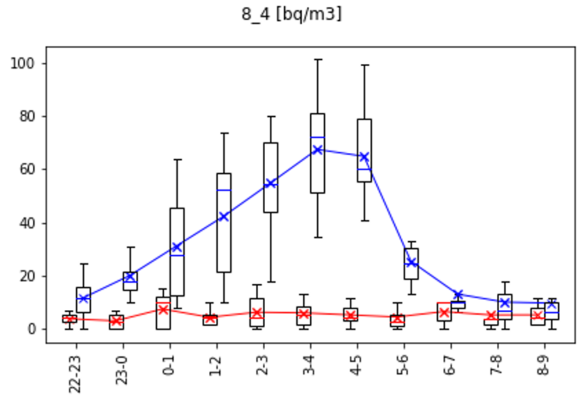

Fig. 8. Nightly averages of radon concentrations measured in room 8_4. The line connecting averages during altered situation (blue line) is above the corresponding line during normal situation (red line).

4 Discussion and conclusions

Temperature differences had an impact on the air pressure differences through the stack effect. The night-time shutdown of the ventilation units however mainly affected the air pressure differences when the mechanical ventilation was not functioning properly in the first place. As a conclusion, it is considered of primary importance to monitor and adjust the behaviour of the mechanical ventilation. After that, the night-time ventilation shutdown does not have a big impact on the air pressure difference conditions over the building envelope. High-rise buildings and other building types in general require their own analysis.

Based on the research results, stopping night-time ventilation has no impact on the indoor air quality during occupied hours when the ventilation is stopped for approximately two hours after users leave the building and restarted 2–3 hours before the start of occupancy to allow ventilation to flush the indoor air before the arrival of the first users to ensure good indoor air quality. However, each building should be treated individually, and measurements should be taken to ensure that indoor pollutant levels return to normal before occupancy begins. When implementing the method, challenges related to the operation of building-specific ventilation systems should also be considered. All ventilation should be connected to operate through an automation system, which can be challenging, especially in older buildings with more primitive ventilation systems. A single remaining exhaust fan can cause significant negative pressure in the building as other exhaust fans stop. When properly implemented, stopping ventilation during the absence of occupants in public buildings can save energy used for heating ventilation.

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