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The effect of positive pressure on indoor air quality in a deeply renovated school building – a case study

Camilla Vornanen-Winqvist[a,*], Sander Toomla[a], Kaiser Ahmed[a], Jarek Kurnitski[a,b], Raimo Mikkola[a], Heidi Salonen[a]

[a]*Aalto University, Department of Civil Engineering, Rakentajanaukio 4, 02150 Espoo, Finland*
[b]*Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia*

Abstract

This paper is a case study of ventilation and indoor air quality (IAQ) investigations in an extensively repaired comprehensive school in Finland. Our main hypothesis is that positive pressure between air indoors and outdoors can be used for decreasing the concentration of harmful chemical and microbiological agents in indoor air, as well as occupants´ complaints about IAQ, in a building waiting for new repairs or with unsolved IAQ problems. Research was undertaken on a building consisting of 12 classrooms, and served by one air handling unit. It found that the ventilation system was crucially unbalanced. However, IAQ measurements did not explain occupants´ symptoms, which were suspected to be related to the impurities leaked through the building envelope caused by the high negative pressure. To eliminate the potential harmful effects of the building related sources and infiltration airflows, the air handling unit was adjusted to generate a 5-7 Pa positive pressure for a period of 4 months. In the next planned phase of the study, moisture content of the structures during the heating season will be measured, as well as potential changes in perceived IAQ and microbial contamination.

Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics.

Keywords: Positive pressure; mechanical ventilation; indoor air quality; school building

* Corresponding author. Tel.: +358-50-3472755.
E-mail address: camilla.vornanen@aalto.fi

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1. Introduction

According to the National Building Code of Finland [1], buildings should be maintained at negative pressure, especially in a cold climate countries where keeping structures dry is one of the main issues. A moderate 5-10 Pa negative pressure (negative difference between indoor and outdoor pressure) is achieved by the ventilation design of buildings, and it prevents exfiltration of the moist indoor air into the structures. However, preventing infiltration of the possible impurities from the structures or surroundings, caused by high negative pressure, is crucial for maintaining a good indoor air quality (IAQ). In the worst case, unbalanced ventilation can lead to a continuous pressure fluctuation. Moist air exfiltration could cause microbial growth and material deterioration inside structures, and infiltrations through the damaged structures could bring in harmful compounds. In air tight buildings with a mechanical ventilation system, the balancing and controlling of the ventilation system and pressure differences is essential [2]. While improving energy efficiency is of high importance in new buildings or renovation processes, the role of the well-balanced ventilation should not be forgotten. Pressure difference measurements are found to be important when evaluating the effect of improving energy efficiency on the perceived IAQ [3]. Using the common IAQ measurements alone to determine occupants´ circumstances indoors can lead to misinterpretations and leave unsolved problems in the building. Proper ventilation measurements should be an essential part of every IAQ investigation [4].

The aim of our research project was to find out whether occupants´ complaints and symptoms could be decreased with positive pressure in a multi-problematic building, which have been under extensive repairs, yet where the IAQ is still poor. The research project includes two parts: (1) Ventilation and IAQ measurements before and after ventilation balancing and generating positive pressure, and moisture excess calculations; (2) Microbial samples from extract air filter, occupants´ symptom questionnaire and moisture behaviour inside the structures. The first part will be presented in this paper, and the second part will be published in a separate journal paper.

2. Materials and methods

2.1. Study design, location and building characteristics

This study is a two-step intervention study, in which the first part was carried out between April and September 2016, and the second part will continue until April 2017. The study was carried out in a comprehensive school in Vantaa, Southern Finland. The school was selected in co-operation with Vantaa Real Estate Centre in the spring of 2016, based on its repair history, and the fact that a reasonable and controllable part of the building could be separated for implementing the positive pressure intervention without major ventilation system changes in the building.

The school was built in 1968 and fully renovated 2003-2005. It has a mechanical supply and exhaust ventilation system with heat recovery. The mechanical ventilation system in all classrooms and corridors was installed in 2002. Each classroom has 2-3 supply air duct diffusers and 1-2 extract air grilles. Air flow rates are adjusted by dampers in the main air handling unit and with regulation and measuring devices connected to each terminal device. The studied section of the building as seen from the outside, and the typical supply and extract terminal units of a classroom in the section are shown in Fig. 1a and 1b.

Almost 700 students aged 11-15 years, and over 50 teachers and other staff work daily in the school. Occupants have had IAQ related symptoms and discomfort since the renovation, and several microbial and structural investigations have been made since 2004. Moisture and mould damage have been observed and repaired in some parts of the building. Ventilation problems have been one of the main concerns of the occupants, and ventilation adjustments have been made several times in different parts of the building over the past years. Also air leakages, especially of the structures in contact with the ground, have been widely sealed. Even so, the school has many classrooms and other spaces where occupants have complained of IAQ related symptoms and discomfort. At the time of this research project, investigations were ongoing in the building and some microbial growth and major air leakages were found. Repairs in the whole building will take place during 2017.

Fig. 1. (a) Studied building part; (b) A typical supply air duct diffuser and an extract air grille in a classroom.

2.2. Measurement strategy and measurement methods

In the set up a small 5-7 Pa positive pressure was generated to prevent both a potential infiltration of harmful agents and a strong exfiltration of indoor air. The studied part of the building consisted of 12 classrooms, 1 corridor, 6 toilets and a cleaning storage area, and was served by one air handling unit. Most of the classrooms are occupied by approx. 20-25 humans for a few hours per day during the normal school week. It was possible to establish positive pressure in this building by a simple fan speed control frequency adjustment in the air handling unit. The layout of the studied part of the building and orientation are presented in Fig. 2.

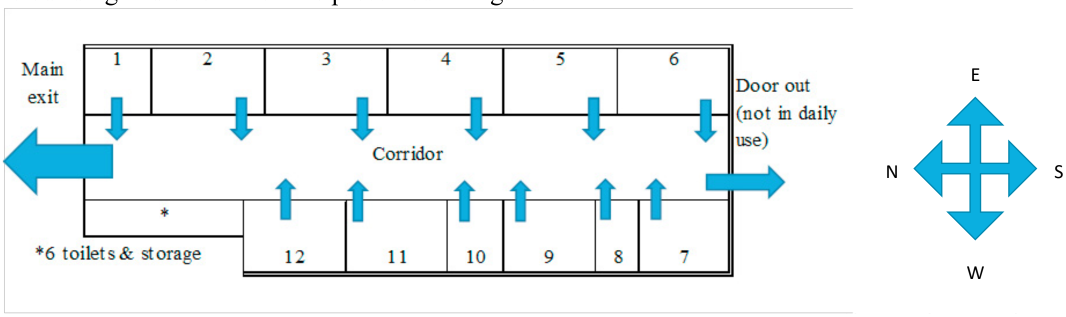

Fig. 2. Layout of the studied building part, exits and orientation. Outer walls are marked with double line.

The ventilation of the studied part of the building was measured and adjusted in four phases: (a) air flow rates of the rooms were measured to determine the initial state of the ventilation; (b) the air distribution ductwork was fully balanced; (c) air handling unit´s supply and extract fans speed were adjusted to generate the desired 5-7 Pa positive pressure over the building envelope in each classroom; and, (d) air flow rates of the rooms were re-measured after a setting period. The ventilation balancing work was conducted by an authorized company.

Corresponding measurements were conducted before and after the ventilation balancing and the generation of positive pressure. Some of the measurements were conducted in the whole of the studied building section, and some in only the two classrooms with the most significant IAQ related complaints from the occupants: classrooms 3 and 9. The following factors were measured: extract and supply air flow rates, long term pressure differences from two classrooms, moisture excess, IAQ related formaldehyde, particulate matter size 2,5 µm ($PM_{2,5}$), volatile organic compounds (VOCs) and total VOCs (TVOC), temperature (T), relative humidity (RH) and carbon dioxide (CO_2). Moisture excess in these two classrooms was calculated in order to evaluate the risk of moisture condensation inside the structures before the positive pressure period was begun.

Positive pressure in the studied building section and pressure difference measurements across the building envelope in the two classrooms will be continued over the winter season. In addition, in order to monitor the possible moisture condensation risk in the structures of the building, T and RH probes were installed inside the structures at elevated risk areas. As described in part 2 of the research project, microbial samples from the extract air filter of the air handling unit of the studied building section and outside air were collected, and IAQ related symptoms were recorded with a questionnaire before ventilation adjustment. This will be repeated after 5 months of positive pressure and these results will be published separately.

2.3. Measurement devices

The ventilation air flow rates of the classrooms were measured from the adjustment and measurement units when possible. The pressure differences across these units were measured with SWEMA 3000md. Air flow rates of the corridor and toilets were measured with air flow hood Swemaflow 125D. The pressure differences across the building envelope were measured with both SWEMA 3000md and KIMO CP101 for instant and long term measurements respectively. T and RH outdoors were measured with ThermaData-loggers.

Indoor T, RH and CO_2 from classrooms 3 and 9 were recorded as continuous measurements using Rotronic CL11 meters. $PM_{2,5}$ and formaldehyde were recorded as continuous measurements from classroom 3 with PM meter MiePDR1500 and formaldehyde meter FM-801. VOCs were determined from 8 liter air samples collected with Tenax TA –tubes from classrooms 3 and 9 and the corridor, and analyzed with GC-MS.

3. Results and discussion

3.1. Air flow rate measurements

Total air flow rates before and after the ventilation system balancing are shown in Table 1. Before balancing, the air flow rates were found to be heavily unbalanced in most classrooms, as well as in the corridor and the toilets. According to the Finnish regulations, the acceptable deviation at room level is 20 % and 10 % at system level [1]. At classroom level the supply air flow rates were within +/- 20 % of the designed values with two significant exceptions of -36 % and +57 %. Almost all the classrooms had extract air flow rates over 20 % higher than the designed values. The corridor extract was 18 % lower than the designed values. The extracts from the toilet and storage units were 55 % lower than the designed values, which was found to be caused by the wrong rotation direction of the fan. At a system level, the total extract air flow rate was 18 % higher than the designed values. After generating the positive pressure all classrooms received more supply than extract air.

Table 1. Air flow rates before and after ventilation system balancing.

Total air flow rates	Designed [L/s]		Measured before ventilation balancing [L/s]		Measured after positive pressure [L/s]	
	Supply	Extract	Supply	Extract	Supply	Extract
Classrooms	2585	2585	2655	3230	2636	2479
Corridor	320	110	330	90	303	79
Toilets and storage	-	210*	-	95	-	223
TOTAL	2905	2905	2984	3415	2939	2781

*Estimated air flow rate (420 L/s) of TK07PF02 divided for two identical units

3.2. Pressure difference across the building envelope and moisture excess

Pressure difference across the building envelope was measured continuously for one week before the ventilation system balancing and after generating the positive pressure in classrooms 3 and 9. Results are shown in Fig. 3. Before the ventilation balancing, pressure differences fluctuated within a large range during a one week period, and both measured rooms were at a significant level of negative pressure. It should be noted that the prolonged readings of -50 Pa could also be caused by mistreating the measurement devices in classroom 3. After balancing, the pressure differences across the envelope were stable and moderately positive.

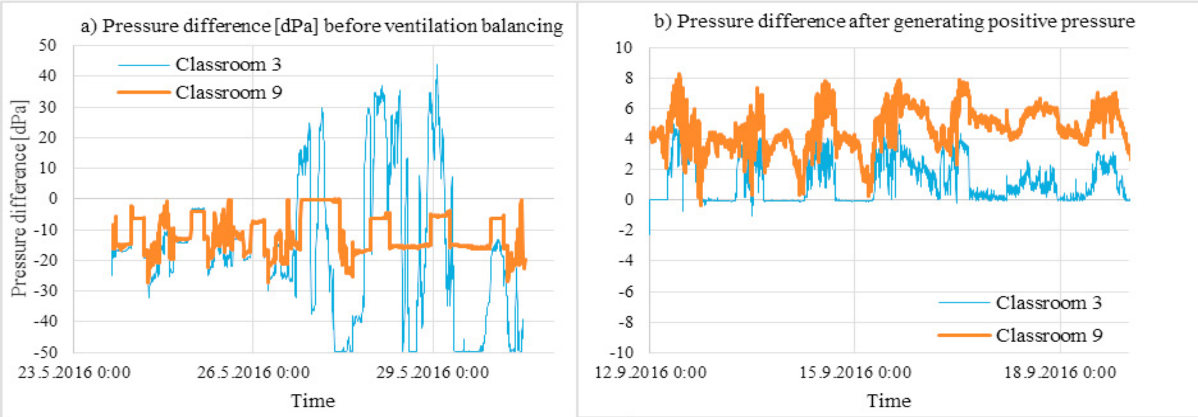

Fig. 3. Pressure differences (indoor-outdoor) in classrooms 3 and 9: (a) before ventilation system balancing and (b) after ventilation system balancing and generating positive pressure.

Indoor air moisture excess was studied via the humidity of indoor and outdoor air (Fig. 4). Humidity was calculated based on the measured T and RH [5]. The total atmospheric pressure was assumed to be 101325 Pa. Fluctuations were minimal and even slightly negative moisture excess values were measured. Based on these results, humidity generation by occupants was not substantial and no risk of moisture condensation during positive pressure was shown. A longer measurement period is needed to determine typical moisture excess values to assess the condensation risk.

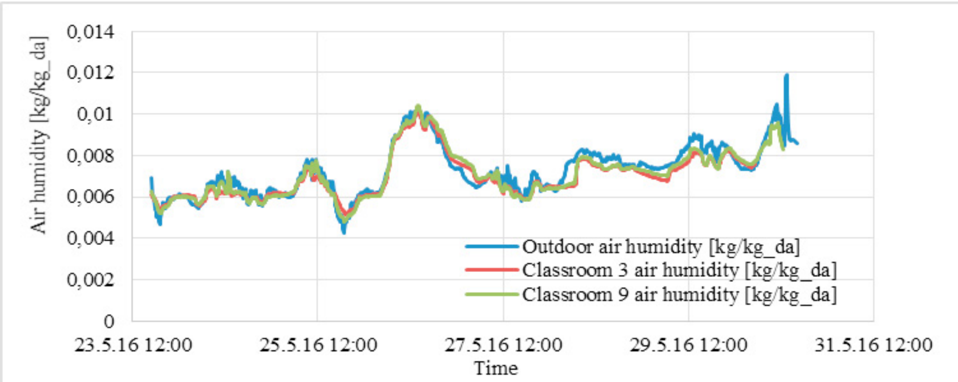

Fig. 4. Air humidity (kg per kg of dry air) in classrooms 3 and 9 and outdoors.

3.3. Indoor air quality

Measured IAQ parameters are shown in Table 3. Formaldehyde concentration before and after the ventilation balancing was below 10 ppb (equivalent to approx. 13 µg/m^3), which is the detection limit of the meter. After balancing there was a concentration of 12-26 ppb during two hours on one day, which was probably due to some specific action in the classroom, e.g. art lecture. Single VOCs that had concentration over 1 µg/m^3 were analyzed; concentrations were 1-4 µg/m^3, which is fairly below action limits.

According to the Finnish Decree on housing health [6], the $PM_{2,5}$ mean concentration following 24 hours in indoor air has to be below 25 µg/m^3, and the formaldehyde average concentration below 50 (annual) or 100 µg/m^3 (30 min). The action limit value for TVOC is 400 µg/m^3. The Finnish classification for indoor climate [7] limits CO_2 concentration in Class 1 “Individual indoor climate” to a maximum of 750 ppm. The levels of measured factors were clearly below the national thresholds. Temperatures were slightly higher in classroom 9, which can be explained by the room location on the western side of the building and the summer season. TVOC and $PM_{2,5}$ values were decreased by the ventilation balancing and the positive pressure. The decrease in TVOC values is significant, but the concentrations are very low in general and consist mainly of compounds with a concentration below 1 µg/m^3. In addition to positive pressure, no other changes were undertaken; therefore, the only known explanation for the decreased concentrations is the positive pressure and infiltration turned to exfiltration.

Table 2. Temperature, relative humidity CO_2, TVOC and $PM_{2,5}$-concentration before and after ventilation adjustment.

		Temperature [°C][1]			Relative humidity [%][1]			CO_2 concentration [ppm][1]			TVOC [µg/m^3][2]	$PM_{2,5}$ [µg/m^3][2]		
		Average	Min	Max	Average	Min	Max	Average	Min	Max		Average	Min	Max
Classroom 3	Before	19,9	18,6	22,8	48,4	32,2	71,9	424	399	597	31	1,7	0	5,1
	After	20,4	18,3	24,2	50,5	31,5	78,7	448	389	862	19	1,2	0	5,8
Classroom 9	Before	22,5	20,2	29,3	42,4	22,6	60,7	433	397	894	42	-	-	-
	After	20,4	19,4	23,9	49,8	31,0	77,1	443	381	1046	19	-	-	-
Corridor	Before	-	-	-	-	-	-	-	-	-	34	-	-	-
	After	-	-	-	-	-	-	-	-	-	27	-	-	-
Outdoor air	Before	16,6	8,4	30,2	66,2	21,0	94,0	-	-	-	-	-	-	-
	After	13,3	3,6	24,0	78,5	44,3	95,4	-	-	-	-	-	-	-

[1] One month measurement period, [2] One week measurement period

4. Conclusions

If the ventilation system performance had been evaluated only using the air change rate and CO_2 concentration of the indoor air, ventilation might have been claimed to be sufficient. However, the ventilation system of the studied building section was shown to be significantly unbalanced, and fluctuation of large negative and positive pressures occurred. TVOC concentration decreased after ventilation balancing and positive pressure, yet was initially very low. In the wide structural investigation that was conducted in the school by a consultant, signs of microbial growth as well as air leakage points were found in the outer wall structure of the studied building section. Results indicate that the unbalanced ventilation system and the possible impurities infiltrated by the large negative pressure are potential causes for the complaints from the occupants using this building. The usefulness of positive pressure in reducing the symptoms of occupants can be assessed based on the questionnaire analyzed in the second phase of the study.

Moisture performance of structures during positive pressure will be determined with structural follow-up measurements. Results so far have indicated that humidity generation in well-ventilated classrooms is not an issue. Finally, possible changes in the microbial profile of the indoor air will be of great interest.

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