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Comparison of air pressure difference, air change rates, and CO_2 concentrations in apartment buildings before and after energy retrofits

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Abstract

Impacts of energy retrofits on air pressure differences across building envelope, air change rate (ACR), and indoor carbon dioxide (CO_2) concentrations were studied. Measurements were performed before and after the retrofits of multi-family buildings during heating season in two Northern European countries: Finland and Lithuania. In the Finnish case buildings (N=128), pressure differences against outdoor were within national guideline values before the retrofits in 52% and after the retrofits in 42% of the buildings with mechanical exhaust ventilation system. The values were within the guidelines before the retrofits in 33% and after the retrofits in 20% in buildings with natural ventilation, correspondingly. In the Lithuanian case buildings (N=31), pressure differences against outdoor were within the same guideline values before the retrofits in 77% and after the retrofits in 52% of the buildings. After the retrofits, higher air pressure differences and ACR, as well as lower CO_2 concentrations, were observed in Finnish buildings with mechanical ventilation. On the contrary, lower air pressure differences and ACR, as well as higher CO_2 concentrations, were observed in Lithuanian buildings with natural ventilation.

Keywords: Air change rate, CO_2 concentration, pressure difference, energy retrofit, apartment building

1. Introduction

Ventilation is needed to maintain adequate indoor environmental quality (IEQ) in occupied spaces, by evacuating heat, moisture, contaminants, or odours generated indoors and bringing in fresh (outdoor) air. In terms of heating energy consumption, it is also important to keep the ventilation at a sustainable rate, in order to maintain the resulting heat loss as low as possible. Airflow through the building envelope is also an important factor influencing heat loss and also moisture behaviour of the structure, as well as transfer of air pollutants indoors.

Total ventilation rate is a sum of the airflow through ventilation system and additional airflow induced by wind and stack (buoyancy) effects through openings and cracks. Measuring actual infiltration in buildings poses many challenges, which limits the experimental database available [1]. Several methods have been developed to estimate the total ventilation rate [2], which can be divided into the direct measurement techniques (generally using tracer gas [3]) and calculation techniques such as isothermal Computational Fluid Dynamics (CFD) simulation [4], simplified models based on the physical knowledge (iterative model COMIS [5] and standard [6] rough estimations [7]).

The input of the rough estimation is a result of the airtightness measurement (usually air infiltration rate in 50 Pa pressure difference), which is divided by coefficient (10 to 30, usually 20) in order to get air infiltration rate in normally prevailing pressure difference conditions. For standard EN 15242 [6], calculation inputs are the measured pressure difference, facade information (wall and roof areas, building height) and weather and terrain information. The estimation methods, for which primary input is the airtightness measurement or fan pressurization, are estimating the air filtration rate, not the total ventilation rate. All intentional openings (inlets/outlets) are sealed and the ventilation system turned off during the airtightness measurement. Therefore the total ventilation rate should include the measurement of air flows through the ventilation outlets and estimation of the air infiltration based on the airtightness value (using applicable models).

Tracer gas methods, such as concentration decay method, continuous dose method, and constant concentration method, described in standard EN 12569 [3], can be used to measure the ventilation rate or the specific air flow rate. The concentration decay method has a limited measurement period, a couple of hours, while the continuous dose and constant concentration methods can provide a longer measurement period, up to several weeks. Also tracer gas measurement gives a value for air flows only under prevailing (during measurement) leakage and weather conditions. It is suggested that the air flow through ventilation outlets/inlets should be measured, using techniques for volume and mass flow rate measurements, separately without tracer gas [8]. Mathematical models can determine infiltration values for all air leakage paths and different weather conditions.

In a previous study, the average airtightness of 56 apartments in Finnish multifamily buildings was measured [9]. The average n_{50}-value was 1.6 h^{-1} (ranging from 0.3 to 5.3 h^{-1}), and it was below 1 h^{-1} in 49% of these apartments. In Lithuania, measurements of the airtightness of blocks of flats revealed an average air change rate of 6.7 h^{-1} at ± 50 Pa, whereas in a set of new single-family detached houses (built in 2005–2011) with energy efficiency classes B or C, the airtightness ($n50 = 3\ h^{-1}$) was two times higher than the normative value [10][11].

When the airtightness of the building envelope is changed, for example, as a result of energy retrofits, both ventilation rate (primary air infiltration rate) and pressure differences across the building envelope are likely to change. An un-balanced ventilation can increase pressure difference across the building envelope, increasing uncontrolled air leakages (infiltration) and possible air pollutants entering indoors from outside and building structures [12].

Stack effect (buoyancy), wind, and ventilation all affect the pressure difference over the building envelope. Infiltration airflow is driven by the pressure gradient across the envelope. The stack pressure is a function of the building height and ambient air temperatures (indoor and outdoor), while the wind pressure is mainly affected by the wind (velocity and direction), local terrain and topography, and building shape characteristics [1].

Also the distribution of air leakage sites across the building envelope influences the air pressure difference. Pressure difference is a driving force for the airflows transporting water vapour and different gaseous contaminants. In the cold climate, if the air pressure is higher indoors, exfiltration of water vapour through the building envelope may increase risks of moisture accumulation, condensation, changes in the (moisture depended) properties of the materials, increased risk of microbial growth in building materials, and even structural deterioration [12]. If the air pressure is lower indoors, different impurities from outdoors, structures, ground or crawl-space (for instance radon), can infiltrate indoors through cracks, resulting in deterioration of IEQ [12] [13]. Special attention should be paid to the floor-wall, wall-roof, and other joints, which are typically “weak spots” pertaining to the airtightness of the envelope.

According to the National Building Code of Finland [14], buildings should be maintained under negative pressure conditions related to outdoors, in order to avoid moisture damage to the building envelope. Despite of this common design assumption, it has been concluded, based on measurements and simulations in detached and apartment buildings in Finland [12], that there are almost always both negative (at the floor level) and positive (on the ceiling level) air pressure differences across the building envelope.

The Ministry of Social Affairs and Health of Finland [15] has given guidelines for the pressure difference between indoor and outdoor, as well as between indoor and staircase depending on ventilation systems (Table 1).

Table 1. Guidelines for pressure difference [15].

Ventilation system	Pressure difference	Notes
Natural	0…-5 Pa against outdoor 0 Pa against staircase	Pressure differences vary a lot enclosed to weather
Mechanical exhaust	-5…-20 Pa against outdoor 0…-5 Pa against staircase	Pressure differences vary a lot enclosed to weather
Mechanical supply and exhaust	0…-2 Pa against outdoor 0 Pa against staircase	Pressure differences vary a lot enclosed to weather

Based on 685 single pressure difference measurements in 176 Finnish buildings, the average indoor – outdoor pressure difference was -8 Pa, ranging from -80 Pa to +12 Pa [16]. These 176 buildings included sixteen multifamily apartment buildings (183 apartments). The average pressure difference in the multifamily buildings was -19 Pa, ranging from -38 Pa to -4 Pa. Two of the multifamily buildings had natural ventilation with an average pressure difference of -5 Pa. Nine buildings had mechanical exhaust ventilation with the average pressure difference of -21 Pa. Six buildings had mechanical supply and exhaust (i.e. balanced ventilation) with the average pressure difference of -15 Pa.

Kalamees [12] reported long-term (about one month) pressure difference measurements in two apartment buildings, two apartments each. The pressure differences of all the measured apartments were negative (pressure lower indoors than outdoors) almost throughout the whole measurement period. Daily average pressure differences at the first floor were -11 Pa and -7 Pa. At the fourth floor, the average pressure difference was -2 Pa in both buildings, respectively. Based on the moisture simulation it was suggested that air pressure difference across the building envelope should be close to ±10 Pa, in order to avoid harmful moisture convection. If the energy efficiency of the building is improved, especially by improving airtightness without balancing ventilation or designing routes of compensation air for the exhaust ventilation, the air pressure difference may increase up to ±30 Pa [12].

In our previous paper (Leivo et al. submitted manuscript), we assessed impacts of energy retrofits on indoor thermal environment, i.e. temperature (T) and relative humidity (RH), as well as ventilation rates and carbon dioxide (CO_2) concentrations based on the data collected as a part of INSULAtE project (www.insulateproject.eu). This paper presents additional data and analyses focused on the impact of energy retrofits on air pressure differences across the building envelope, as well as ventilation rates and indoor CO_2 concentrations. The purpose of the whole project was to develop a common protocol for assessment of the effects of energy retrofits on IEQ, and occupant health and wellbeing, and to demonstrate the potential effects on the building and national levels.

2. Material and Methods

2.1.Case study buildings

Selected case study buildings were volunteering multi-family buildings that were planned to be retrofitted during the project, and where average five apartments per building were willing to participate the measurements. Buildings, which were not retrofitted during the project, were included as controls. Majority of the case study buildings were built between 1960 and 1980. More detailed information about the case study buildings is presented by Du et al. [17].

In Finland, a total of 47 multi-family buildings were included, of which 37 were retrofitted (CASE) and ten were not retrofitted (CONTROL). Deep energy retrofits with several retrofit actions were performed only in 11% of the case buildings in Finland. The most common retrofit action in Finland was changing new windows and/or installing heat recovery system into exhaust ventilation system (mechanical ventilation with heat recovery, MVHR). In Lithuania, a total of 20 multi-family buildings were included, of which 15 were retrofitted (CASE) and five were not retrofitted (CONTROL). Deep energy retrofits were performed in about 87% of case study buildings in Lithuania.

Majority of the measured buildings (about 92% of apartments) in Finland had mechanical exhaust ventilation system, with or without heat recovery units, where more efficient exhaust is typically turned on for two hours once or twice a day, in the morning / early afternoon (10 am to 2 pm) and in the late afternoon (4 pm to 6 pm). In Lithuania, majority of the buildings had natural ventilation, which in some apartments was improved with occupant-controlled fan driven exhaust in the kitchen and natural/mechanical exhaust in the bathroom. This kind of mixed ventilation system had been installed afterwards into 44% of the apartments. The occupant operated exhaust fans were usually on during the measurement.

2.2. Measurement methods and statistical analyses

Two rounds of measurement were performed: before and after the retrofits in the CASE buildings (retrofitted), and two corresponding measurements in consecutive years in the CONTROL buildings. Both measurements were performed during the same season (usually heating season). The measurement methods are presented more detailed by Du et al. [17]. Briefly, air pressure differences (Pa), were measured both against outdoor and staircase using differential pressure meter (Testo 512, range of 0 to 2 hPa, resolution 0.001 hPa, and accuracy ±0.5% of fsv). Air change rate (h^{-1}) was calculated based on measured air flows from ventilation outlets and information on the apartment volumes. Apartment volumes (ventilated volume, including furniture) were gauged from the blue prints and other information gathered from the building owners and occupants. A rotating vane anemometer with built-in 100 mm vane and temperature probe (Testo 417, range +0.3 to +20 m/s, accuracy ±(0.1 m/s +1.5% of mv) and resolution 0.01 m/s) was used to measure air flows. Each ventilation outlet was measured, however the measured values were not considered reliable if the outlet was irregular or the air flow was too small. Carbon dioxide (CO_2) concentrations were measured every minute during a 24-hour period using new, factory-calibrated sensors (HD21AB/HD21AB17, Delta OHM, Italy, range 0 - 5000 ppm and accuracy ±50 ppm or ± 3%). For analysing correlations between air pressure difference, ACR, and CO_2 concentrations, the CO_2 concentration during the time of air pressure difference and ACR measurements was used.

Air tightness was measured from three buildings (16 apartments before the retrofits and 12 apartments after the retrofits) in Finland. One apartment in one building had extremely high n_{50}-value (10.8 h^{-1} before the retrofit and 5.9 h^{-1} after the retrofit), which was related to a potential air leakage within suspended ceiling to neighbour apartments or air ducts. Excluding these extreme values, n_{50}-values before the retrofits varied from 1.2 to 2.5 h^{-1} and after the retrofits from 0.6 to 2.3 h^{-1}.

In addition to descriptive statistics, the associations between retrofitting and IEQ (including pressure differences and CO_2 concentrations during the measurements) were studied using paired analyses (including paired samples test and paired correlations) and linear mixed modelling (LMM). Mixed models are used to account for the correlations among observations within the clusters (i.e. apartments within the buildings), which are not independent from each other. The LMM estimation was based on the Restricted Maximum Likelihood (REML) method and the Expected Maximum (EM) algorithm. The building and apartment codes were used as subject variables, and the covariance type was identity (covariance structure for a random effect with only one level). Only main effects were studied, while the factorial design with interaction effects was not used.

Firstly, a null model were studied, which included only the subject and outcome variables without any predictors, in order to examine the variance between country, building and apartment levels, and to calculate the intra class correlation (ICC) (i.e. proportion of the total variance accounted for by the clustering). Secondly, the selected independent variables in the models were included. Retrofit status was based on case/control and before/after retrofits variables, so that the reference group was case buildings during the first measurements (before retrofit), and the other groups included case buildings during second (after retrofit) measurements as well as control buildings during first and second measurements. In addition, the fixed effects included country (Finland/Lithuania), as well as in case of the model for CO_2, number of occupants and pressure difference against outdoors. The models were also run separately for each country.

3. Results and discussion

3.1.Pressure differences across building envelope

Measured air pressure differences against the staircase and outdoor are presented on Table 2. Minus (-) indicates that the air pressure in the staircase or outdoors is higher than indoors. The results from Finland are divided into three groups: CASE (retrofitted) buildings with mechanical exhaust, CASE buildings with natural ventilation, and

CONTROL buildings (no retrofits) with mechanical exhaust (there were no control buildings with natural ventilation). The results from Lithuania are divided into four groups: CASE (retrofitted) buildings with natural ventilation, CASE buildings with mixed ventilation, CONTROL buildings (no retrofits) with natural ventilation and CONTROL buildings with mixed ventilation.

In Finland, the average pressure differences were usually slightly higher after the retrofits or based on the second measurement in all case groups (both mechanical and natural ventilated), but the difference was not statistically significant. The pressure differences against the staircase were within the guidelines (0…-5 Pa, see Table 1) before the retrofits in 42% and after the retrofits in 34% of the case apartments with mechanical exhaust ventilation. The pressure difference against outdoor was within the guidelines (-5…-20 Pa) before the retrofits in 52% and after the retrofits in 42% of the case apartments with mechanical exhaust. The pressure difference against the staircase was within the guidelines in 73% of the apartments in the control buildings during the first measurement and in 30% of the apartments in the control buildings during the second measurement. The pressure difference against outdoor was within the guidelines during the first measurement in 91% and during the second measurement in 80% of the control apartments, correspondingly. None of the case buildings with natural ventilation met the guideline values (0 Pa) for the pressure difference against staircase, while the pressure difference against outdoor was within the guidelines (0….-5 Pa) in 33% and 20% of the apartments, correspondingly.

In Lithuania, the average pressure differences were in most cases lower after the retrofits or based on the second measurement. There were no clear differences in the average pressures between buildings with natural or mixed ventilation. If the Finnish guideline values (as in Table 1) were used, the pressure difference against outdoor was within the guidelines (0…-5 Pa) in 77% (before retrofits) and 52% (after retrofits) of the case apartments with natural ventilation. In the control buildings with natural ventilation, the pressure difference against outdoor was within the guidelines in 80% of the apartments during the first measurement and in 67% during the second measurement.

It should be noted that the pressure difference measurements were one time measurements and the prevailing weather conditions affect the values. Also the measurements were performed during the heating season, when there is a larger buoyancy effect due to the temperature differences between indoor and outdoor air.

3.2.Air ventilation rates

Calculated air ehange rates (ACR) based on measured airflows from ventilation outlets and information on the apartment volumes are shown on Figure 1. In addition to air change through ventilation outlets, there is always some air infiltration through air leakages of the building envelope.

In Finland, the average ACR was slightly higher after the retrofits in buildings with mechanical exhaust ventilation. In buildings with natural ventilation, the average ACR was lower than in buildings with mechanical exhaust ventilation, and it was the same before and after the retrofits. In the control buildings, the average ACR was lower during the second measurement than during the first measurement.

In all Lithuanian buildings (both case and control) with natural ventilation, the average ACR through ventilation outlets was about the same in all measurements. In the buildings with mixed ventilation, the average ACR was lower after the retrofits (CASES) or during the second measurement (CONTROLS). However, the results from the control buildings (esp. with mixed ventilation) are inconclusive due to small samples size.

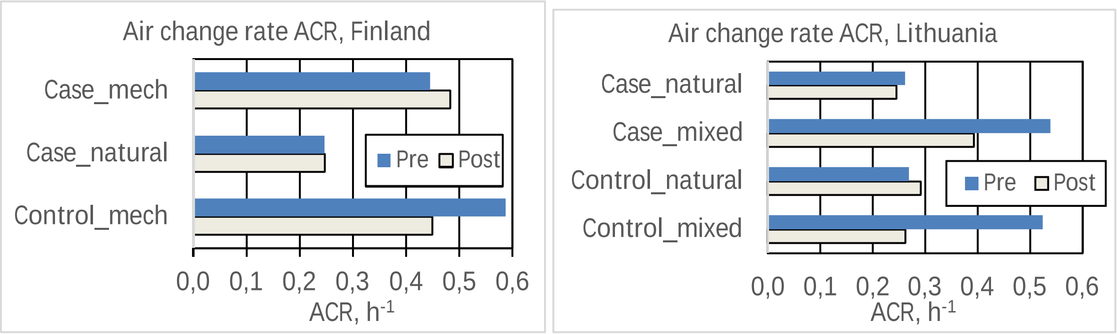

Figure 1. Air change rates (ACR) in Finnish and Lithuanian buildings.

Estimation of air volumes based on blue prints and other information is a potential source of error. For example, if the actual ventilated air volume of the apartments was 5% less than assumed (due to furniture etc.), this error would result in about 0.03 h^{-1} error in the average air change in Finnish buildings with mechanical ventilation (true ACR would be 0.46 h^{-1} instead of 0.43 h^{-1} based on data from 119 apartments). However, we used same volumes both before and after the retrofits in ACR calculations. Therefore trend of changes (decrease/increase) in ACR before and after should be reliable.

3.3.Indoor CO_2 concentrations

Measured 24-hour CO_2 concentrations have been presented in Figure 2. In Finland, the average CO_2 concentrations were lower after the retrofits in the case buildings with both mechanical exhaust and natural ventilation. In the control buildings, CO_2 concentrations were about the same during both measurements. In Lithuania, the average CO_2 concentrations were higher after the retrofits in the case buildings with both natural and mixed ventilation. In the control buildings with natural ventilation, the average CO_2

concentration was the same in both measurements, but in the control buildings with mixed ventilation, the CO_2 concentration was lower during the second measurement.

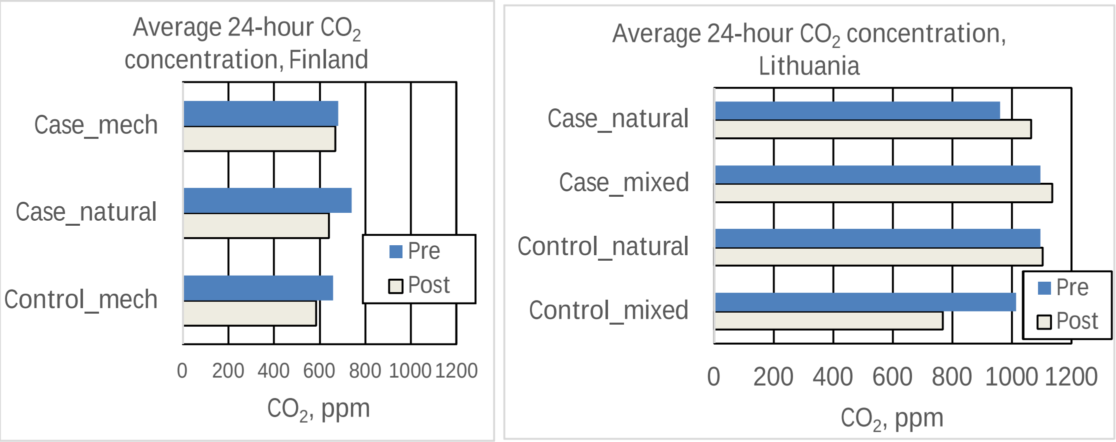

Figure 2. Average 24-hour CO_2 concentrations in Finland and Lithuania.

Measured CO_2 concentrations during the measurements are presented in Table 3. (In Lithuania, data are available only after the retrofits / 2nd measurements.)

Table 3. CO_2 concentrations (ppm) during measurements.

Finland (CO_2 during ACR measurements)						
CO_2	CASE_Mechanical		CASE_Natural		CONTROL_Mechanical	
ppm	1st	2nd	1st	2nd	1st	2nd
N	115	84	15	10	11	9
Average	901	834	924	693	854	747
SD	226	179	179	121	145	153
Median	854	802	901	711	826	767
5th	607	569	645	500	697	506
95th	1263	1184	1162	819	1108	940

Lithuania (CO_2 during pressure difference measurements)								
CO_2	CASE_Natural		CASE_mixed		CONTROL_Natural		CONTROL_Mixed	
ppm	1st	2nd	1st	2nd	1st	2nd	1st	2nd
N	-	28	2	24	-	4	-	4
Average	-	1243	1376	1366	-	1250	-	1135
SD	-	370	2	656	-	383	-	202
Median	-	1171	1376	1149	-	1100	-	1179
5th	-	740	1374	777	-	930	-	867
95th	-	1801	1378	2644	-	1780	-	1342

3.4.Paired samples and LMM analyses

As shown in Table 4, paired samples analyses indicated that all pre-post measurements were significantly correlated, except the pressure difference against staircase in Lithuanian buildings. Based on these results, there exists a moderate level of correlation with respect to pressure differences and ventilation rates between the measurements before and after the retrofits, which is interesting given that there was a minimum of one year between the measurements.

In paired samples test, only significant difference in the Finnish buildings was seen in CO_2 concentrations during measurements, possibly due to instantaneous nature of the measurement. On the other hand, there appeared to be significant differences in the pressure differences in Lithuanian buildings, especially against the staircase, but also (to a lesser extent), against outdoor. Our previous study indicated that both ventilation rates and maximum night time CO_2 concentrations may be affected by energy retrofits (Leivo et al. submitted manuscript); in addition, this study found a possible association with pressure differences in Lithuanian buildings, but the sample size and the short term measurements limit the possibilities to draw more definite conclusions.

Table 4. Paired samples statistics among case study buildings.

		Finland						Lithuania					
		N	Mean	SD	p*	Correl.	p**	N	Mean	SD	p*	Correl.	p**
Pair													
1	P_staircase [Pa]	108	-8.24	9.77	0.739	0.32	0.001	55	-2.22	1.90	0.000	-0.03	0.820
	P_staircase [Pa]	108	-7.90	7.09				55	-0.17	3.11			
2	P_outdoor [Pa]	108	-18.11	17.05	0.500	0.50	0.000	46	-4.39	5.09	0.078	0.51	0.000
	P_outdoor [Pa]	108	-19.21	15.12				46	-2.78	6.93			
3	ACR [h^{-1}]	87	0.42	0.22	0.151	0.39	0.000	55	0.39	0.29	0.084	0.43	0.001
	ACR [h^{-1}]	87	0.46	0.24				55	0.32	0.25			
4	CO_2 average [ppm]	108	684.25	161.45	0.268	0.54	0.000	52	994.61	340.20	0.172	0.45	0.001
	CO_2 average [ppm]	108	664.94	186.39				52	1077.53	461.55			
5	CO_2 during measurements [ppm]	101	913.41	223.74	0.000	0.25	0.019	§	1823.00	.			

CO_2 during measurements [ppm]	101	814.53	178.79			§	1145.00	.

§ The correlation and t cannot be computed because the sum of caseweights is less than or equal to 1.
* for paired samples test
** for paired samples correlation

Results from the LMM models are presented in Tables 5-7. Based on the models for pressure differences in the Finnish buildings, mechanical ventilation was associated with about 4.4 Pa negative pressure difference against the staircase and 13.6 Pa against outdoors, but the retrofit status did not associate with the pressure difference against the staircase. Lithuanian buildings did not have mechanical ventilation systems, but concurring with the paired samples analyses, a statistically significant positive association was observed in pressure difference against the staircase between pre- and post-retrofit measurements.

We previously reported results related to LMM models for ventilation rates and maximum night time CO_2 concentrations (Leivo et al. submitted manuscript). The models predicted average ventilation rate of about 2.6 l/s per person higher in Finnish buildings as compared to Lithuanian buildings, whereas maximum CO_2 level was significantly ($p<0.05$) lower in Finland than in Lithuania, correspondingly. There was also a significant association between CO_2 concentration and number of occupants; the association was stronger in Lithuania. Additional model was fitted for CO_2 concentration at the time of the measurements with pressure difference against outdoor added. However, the pressure difference was not significantly associated with CO_2 concentration during the measurement (Table 7).

3.5 ACR in relation to CO_2 concentrations

Pearson correlations between pressure difference, ACR, and CO_2 are presented on Table 8. Correlations between pressure difference against outdoor and CO_2 concentration during the first and second measurements were 0.28 and 0.34, which are weak but statistically significant. The correlations between ACR and CO_2 were also significant, 0.24 and 0.18.

In Finland, mechanical ventilation systems are designed to create a small under pressure within the building. That means that the airflows through inlets are designed to be smaller than airflows through outlets. It can be assumed that the majority of the airflows from inside are flowing through the outlets. However, mechanical exhaust is not continuously on (or on the more efficient mode) and therefore the buildings do not have negative pressure all the time, which could result in some air infiltration. The pressure differences and airflows are more depending on prevailing outdoor conditions (temperature and wind) in buildings with natural ventilation. Under some conditions there could be over pressure at the upper part of the building and under pressure at the lower part. In such conditions, there are some airflows (filtration) out through air leakages of upper part of the building envelope and the total air change rate is a combination of airflows through outlets and air filtration.

It should be also noticed that the correlations between 24-hour average CO_2 concentration and momentary CO_2 value were statistically significant (0.67 and 0.68, Table 8), indicating that even momentary measurements could be useful when assessing IEQ and the impacts of retrofits on CO_2 concentrations.

Table 8. Pearson correlations between pressure difference, ACR and CO_2.

	Pressure difference			CO_2	
	Staircase	Outdoor	ACR	Average	During measurement
1st measurement					
P_staircase	1	.678**	-.237**	.265**	.213*
P_outdoor		1	-.278**	.285**	.208*
ACR			1	-0.091	-.235**
CO_2 average				1	.673**
CO_2 during measurement					1
2nd measurement					

P_staircase	1	.563**	-.232**	.219**	.248**
P_outdoor		1	-.336**	.345**	.258**
ACR			1	-.201*	-.182*
CO_2 average				1	.681**
CO_2 during measurement					1

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Measured pressure differences against outdoor were usually higher in Finnish apartments. However, the air change rates in the apartments with natural ventilation were about the same in both countries. These results indicate that there could be some differences in the average airtightness of the buildings between countries. Previous studies found higher average airtightness in Finnish multi-family buildings than in Lithuanian buildings [9] [10].

There is a nonlinear dependency between the air flow rate and pressure difference [5]. In the standard for determining air permeability of buildings using fan pressurization method [18], measured data are fitted into power law equation (1) in order to determine the air flow (or leakage) coefficient, C_{env}, and air flow exponent, n, using the least squares technique:

$$q_{env} = C_{env} (\Delta p)^n \qquad (1)$$

where n is the air flow exponent (-); Δp is the induced pressure difference (Pa) and q_{env} is the air flow rate through the building envelope ($m^3 h^{-1}$). The air flow coefficient is the building leakage rate when there is an indoor/outdoor pressure difference of 1 Pa across the building envelope. If the coefficient values are known, it is possible to estimate the air infiltration rate at a certain (measured) pressure difference. Commonly it is assumed that in naturally ventilated buildings, the pressure difference is about 4 Pa [19]. Based on a total of 1758 measurements performed in five countries (UK, Netherlands, Canada, USA, and New Zealand) the average n-value was 0.66 [20].

The average n-value was 0.72 based on measurements of 170 detached houses in Finland [21] and it was 0.64 based on 28 detached or semi-detaches houses in Ireland [22].

The power law equation (1) can be expressed by Equation 2 for calculation of air infiltration rate in certain (measured) pressure difference when airtightness (n_{50}) is known.

$$n_{infilt} = n_{50} \left(\Delta P_{meas}/50\right)^{n} \qquad (2)$$

where n_{infilt} is air infiltration rate (1/h); ΔP_{meas} measured pressure difference (Pa); n_{50} airtightness value (1/h); and n is the air flow exponent (-).

Figure 3 explains how pressure difference and airtightness effect on air infiltration. Three schematic airtightness curves for airtightness values n_{50} =1, 2 or 4, are calculated using Eq. 2 and assuming the air flow exponent, n=0.7. If the building envelope is leaky (n_{50} =4), low pressure difference (2.5 Pa) creates air infiltration (0.5 h^{-1}), which is considered an adequate ventilation rate. If the airtightness is better (n_{50} = 2) the same pressure difference creates less than 0.3 h^{-1} air filtration. Therefore, higher airtightness of Finnish buildings could explain why air change rates are about the same in buildings with natural ventilation in both countries, although the pressure differences are higher in Finland. If the airtightness is improved (e.g. from n_{50} =4 to n_{50} =2) much higher pressure difference (6.5 Pa) is required to create the same air filtration or ventilation. Therefore, it is important to check that there is a sufficient amount of compensatory air inlets after the retrofits for ensuring adequate natural ventilation.

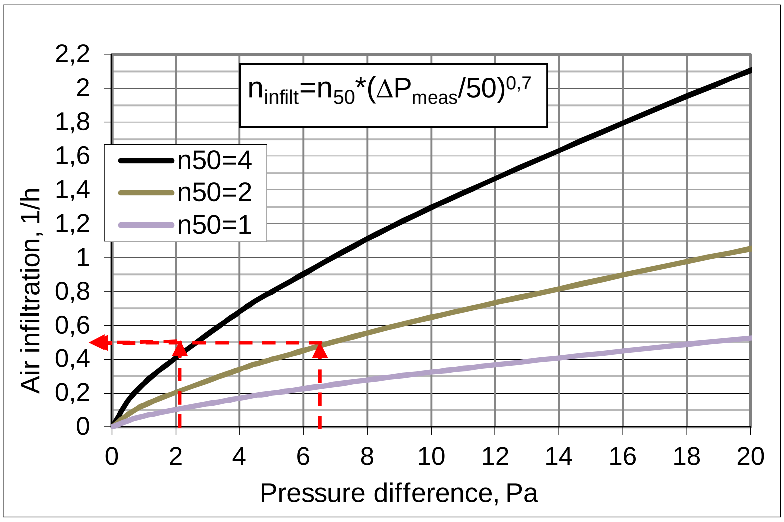

Figure 3. Airtightness curves.

3.6. *Study limitations*

Instantaneous nature of the pressure difference and air flow measurements results in error where prevailing weather conditions strongly affect the values. Utilizing simultaneous measurements of pressure differences, ACR and CO_2 concentrations may give a more comprehensive picture of the building dynamics before and after energy retrofits. In addition, the sample size (esp. small number of control buildings) limits the conclusions with respect to differences between measurements.

4. Conclusions

Higher air pressure differences and air change rates were observed after the retrofits in Finnish buildings with mechanical exhaust ventilation, corresponding to lower CO_2 concentrations. On the contrary, the air pressure differences and ACR were lower after the retrofits in Lithuanian buildings with natural ventilation, along with higher CO_2 concentrations. In the Finnish buildings, mechanical ventilation was associated with higher negative pressure differences, but the retrofit status did not associate with the pressure differences. In the Lithuanian buildings, the pressure difference against the staircase was significantly associated with the retrofit status.

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Table 2. Measured pressure differences against staircase and outdoor in Finland and Lithuania.

FI	CASE_Mechanical				CASE_Natural				CONTROL_Mechanical			
Pressure,	1st	1st	2nd	2nd	1st	1st	2nd	2nd	1st	1st	2nd	2nd
Pa	Staircase	Outdoor	Staircase	Outdoor	Staircase	Outdoor	Staircase	Outdoor	Staircase	Outdoor	Staircase	Outdoor
N	134	128	89	89	15	15	10	10	11	11	10	10
Average	-7.7	-18.8	-8.4	-20.5	-4.5	-7.0	-3.8	-7.9	-4.2	-13.8	-4.9	-14.0
SD	9.1	17.2	7.3	15.3	3.9	4.2	1.6	2.7	2.7	5.5	5.0	9.0
Median	-5.7	-14.2	-6.6	-19.4	-3.1	-5.7	-4.0	-8.0	-4.1	-13.0	-5.2	-11.6
5th	-21.2	-52.9	-21.3	-44.8	-12.2	-13.8	-6.2	-12.1	-8.7	-22.8	-11.0	-29.5
95th	-0.3	-1.0	0.5	-0.3	-1.1	-2.1	-1.7	-4.4	-1.2	-8.3	2.9	-3.9

LT	CASE_Natural				CASE_Mixed				CONTROL_Natural				CONTROL_Mixed			
Pressure	1st	1st	2nd	2nd	1st	1st	2nd	2nd	1st	1st	2nd	2nd	1st	1st	2nd	2nd
Pa	Staircase	Outdoor	Staircase	Outdoor	Staircase	Outdoor	Staircase	Outdoor	Staircase	Outdoor	Staircase	Outdoor	Staircase	Outdoor	Staircase	Outdoor
N	43	31	31	30	29	25	25	25	11	10	4	3	12	12	4	2
Average	-2.0	-3.9	0.3	-3.3	-2.3	-4.5	-0.4	-1.8	-3.3	-3.7	-2.0	-0.5	-2.8	-8.5	-2.8	-1.3
SD	1.8	3.8	2.7	6.1	2.0	5.6	3.5	7.6	4.6	3.1	1.4	5.1	3.8	8.6	2.9	5.5
Median	-1.7	-2.5	-0.3	-2.4	-2.2	-2.5	-0.5	-2.0	-1.9	-3.1	-2.0	-1.6	-1.4	-7.2	-1.7	-1.3
5th	-5.0	-13.1	-2.5	-14.2	-5.9	-16.4	-4.8	-15.0	-9.8	-8.6	-3.5	-3.4	-10.0	-22.7	-6.4	-4.8
95th	-0.2	-0.5	6.0	3.7	-0.2	-0.3	3.4	8.4	0.4	-0.4	-0.3	3.1	0.7	-0.9	-0.8	2.2

Table 5. Linear mixed model for pressure difference against staircase.

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	-2.01	-3.05	-0.96	***	-3.38	-5.92	-0.85	**	-2.10	-2.74	-1.46	***
Country												
Finland	-1.75	-4.03	-0.53									
Lithuania	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Retrofit status												
Control; 2nd measurement	1.24	-1.18	3.65		3.14	-0.73	7.01		-0.27	-2.29	1.74	
Case; 2nd measurement	0.44	-0.48	1.36		-0.53	-1.91	0.84		1.96	1.00	2.93	***
Control; 1st measurement	0.95	-0.83	2.73		3.99	-0.77	7.22	*	-0.97	-2.25	0.30	
Case; 1st measurement	0[b]	.	.		0[b]	.	.		0[b]	.	.	
Type of ventilation				***								
Mechanical	-3.99	-6.22	1.77		-4.38	-7.07	-1.69	**				
Natural	0[b]	.	.		0[b]	.	.		0[b]	.	.	

b This parameter is set to zero because it is redundant. *p<0.05 **p<0.01 ***p<0.001 †p<0.1

Table 6. Linear mixed model for pressure difference against outdoor.

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	-3.91	-6.40	-1.42	0.002	-5.37	-11.20	0.45	0.070	-4.00	-5.51	-2.50	0.000
Country												
Finland	-1.93	-7.26	3.39	0.475	0[b]	.	.	.	0[b]	.	.	.
Lithuania	0[b]	.	.	.								
Retrofit status												
Control; 2nd measurement	3.60	-1.98	9.17	0.205	5.55	-2.83	13.93	0.193	3.26	-1.73	8.25	0.199
Case; 2nd measurement	-0.66	-2.50	1.18	0.480	-1.87	-4.56	0.82	0.170	1.39	-0.29	3.07	0.103
Control; 1st measurement	1.13	-2.94	5.20	0.586	6.12	-1.04	13.28	0.093	-2.33	-5.25	0.59	0.117
Case; 1st measurement	0[b]	.	.	.	0[b]	.	.	.	0[b]	.	.	.
Type of ventilation												
Mechanical	-13.04	-18.19	-7.90	0.000	-13.62	-19.82	-7.43	0.000	0[b]	.	.	.
Natural	0[b]	.	.	.	0_b	.	.	.				

b This parameter is set to zero because it is redundant. *p<0.05 **p<0.01 ***p<0.001 †p<0.1

Table 7. Linear mixed model for CO_2 concentration during measurements.

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	1113.63	972.05	1255.20	0.000	846.91	739.46	954.36	0.000	969.83	339.88	1599.78	0.003
Country												
Finland	-363.76	-519.44	-208.08	0.000	0^b	.	.	.	0^b	.	.	.
Lithuania	0^b	.	.	.								
Retrofit status												
Control; 2nd measurement	-201.15	-355.99	-46.31	0.011	-178.41	-323.81	-33.02	0.016	-220.72	-909.81	468.37	0.523
Case; 2nd measurement	-96.56	-152.45	-40.67	0.001	-95.10	-146.80	-43.39	0.000	-109.82	-704.07	484.42	0.712
Control; 1st measurement	-90.00	-258.67	78.67	0.294	-79.00	-210.63	52.63	0.238				
Case; 1st measurement	0^b	.	.	.	0^b	.	.	.	0^b	.	.	.
Type of ventilation												
Mechanical	18.36	-120.58	157.29	0.794	43.85	-52.99	140.70	0.372	0^b	.	.	.
Natural	0^b	.	.	.	0^b	.	.	.				
Number of occupants	101.68	57.04	146.31	0.000	35.30	-8.97	79.56	0.117	156.43	60.63	252.24	0.002
Pout	-0.14	-2.82	2.54	0.918	1.38	-0.77	3.53	0.206	-8.16	-24.75	8.44	0.328

b This parameter is set to zero because it is redundant. *$p<0.05$ **$p<0.01$ ***$p<0.001$ †$p<0.1$