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Impacts of energy retrofits on ventilation rates, CO_2-levels and occupants' satisfaction with indoor air quality

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Abstract

INSULAtE-project assessed impacts of energy retrofits on indoor environmental quality and occupants' satisfaction. Most common retrofit actions included changing new windows and installing heat recovery into exhaust ventilation system. This paper presents results related to ventilation in Finnish apartment buildings before and after the retrofits. Average ventilation rates (from exhaust vents) in buildings with mechanical ventilation were 0.43 ACH before and 0.48 ACH after the retrofits. Average CO_2 concentrations were 750 ppm before and 715 ppm after the retrofits, correspondingly. Percentage of occupants satisfied with IAQ was 22% before and 41% after the retrofits. In conclusion, ventilation rates, CO_2-levels, and occupants' satisfaction with IAQ were improved in most retrofitted buildings.

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Keywords: Energy retrofit; indoor environmental quality; ventilation rate; CO2; occupant satisfaction

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1. Introduction

European Commission has implemented Energy Performance of Buildings Directive (EPBD) recast (2010) to reduce the building energy consumption and strengthen the energy performance requirements, requiring that by the end of 2020 all new buildings are so-called nearly zero-energy buildings (nZEBs), and also existing buildings subjected to major retrofits have to meet minimum energy performance requirements adapted to the local climate [1]. The total residential floor area in the EU-27 member states is approximately 17.6 billion m^2, of which 15.1 billion m^2 is estimated to be heated [2]. Most of the residential buildings (about 70% of the building area) in the EU-27 countries have been constructed before 1980.

The objective of INSULAtE-project was to assess impact of energy retrofits on indoor environmental quality (IEQ) and occupants' satisfaction, health and wellbeing, and to develop a common assessment protocol. The assessment protocol includes measurements of building related parameters (e.g. ventilation rate, pressure difference across envelope, thermal conditions), IEQ parameters (including carbon dioxide (CO_2) and carbon monoxide (CO) concentrations, and various indoor air pollutants), and questionnaires to the occupants [3].

2. Case study buildings and measurement methods

This paper presents results from totally 46 buildings. Data were collected on the average from five apartments per building (1-11 apartments depending on the size of the building and number of occupants willing to participate) before energy retrofit and after retrofit. Multi-family buildings that were planned to be retrofitted were eligible for the study. Also some control buildings, which were not retrofitted during the project, were included. The study area included several regions in Southern and Eastern Finland (Tampere, Hämeenlinna, Imatra, Helsinki, Porvoo, Kuopio). The buildings were chosen from among volunteers: primary criteria were planned retrofits, which had to be related to energy efficiency and finished before the fall of 2015.

Age distribution and performed retrofit actions are presented on Fig. 1. Most of the buildings were built between 1960 and 1980, and the most common retrofit action was changing new windows and/or installing heat recovery system into exhaust ventilation system. Majority of the buildings had mechanical exhaust ventilation system, where more efficient exhaust is typically turned on for two hours once or twice a day: in the morning (10 am to 2 pm) and in the afternoon (4 pm to 6 pm).

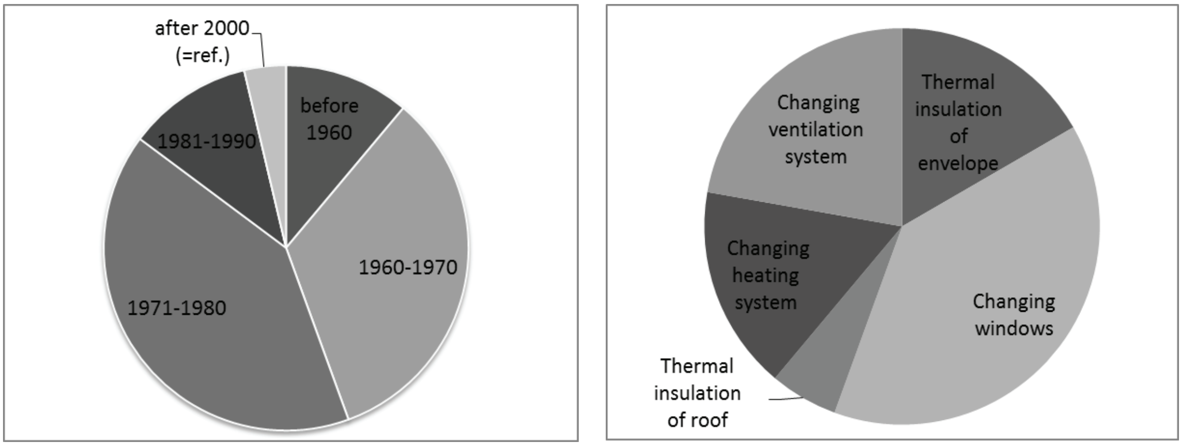

Fig. 1. (a)Year of construction of the case buildings; (b) performed retrofit actions.

Air flows were measured from the exhaust vents using rotating vane anemometer (Testo 417 with measurement range from +0.3 to +20 m/s, and accuracy ±0.1 m/s +1.5% of mv) with built-in 100mm vane and temperature probe. Ventilation rates were calculated based on the air flows and volume of the apartments. Each ventilation outlet was measured. The measured values were considered not reliable if the outlet was irregular or the air flow was too small.

Carbon dioxide (CO_2) and carbon monoxide (CO) concentrations were measured every minute during a 24-hour period, usually from the living room, using portable meter (HD21AB/HD21AB17, Delta OHM, Italy, with measurement range of 0 - 5000 ppm, and accuracy ±50 ppm or ± 3%). If needed, the sensors were sent to manufacturer's calibration between measurement rounds. Also air pressure differences between indoor and outdoor and staircases were measured. The results of the measurements have been reported elsewhere in detail [4].

Occupant surveys were used to collect information concerning occupants' health and satisfaction with their housing conditions. One adult per apartment was asked to fill in a questionnaire, which have been developed, tested, and used in previous housing and health studies [5]. The final questionnaire comprised 49 questions related to the building and living environment; physical, biological and chemical conditions; hygiene; occupant behaviour, health and well-being; and background information (e.g. respondent's age and gender). In addition to the questionnaire, all adults living in the apartment were asked to fill in a diary once a day during a two-week period. The diary consisted of two-sided one-page form, including questions concerning symptoms, time consumption, and activities. Detailed results from the occupant surveys will be reported elsewhere, this paper includes results from occupants' satisfaction with indoor air quality (IAQ).

3. Results and discussion

Measurement results are presented by dividing case buildings into three groups:

- Case buildings (CASE_Mechanical), where some energy retrofit actions have been performed and the buildings have mechanical exhaust ventilation,
- Case buildings (CASE_Natural), where some energy retrofit actions have been performed and the buildings have natural ventilation
- Control buildings (CONTROL_Mechanical), where no energy retrofit actions have been performed and the buildings have mechanical exhaust ventilation.
- There were no control buildings with natural ventilation.

3.1 *Air change rates*

Table 1 presents results from the air flow measurements in air change rates (ACR). The average ventilation rates in apartments in case buildings with mechanical exhaust ventilation (CASE_Mechanical) were 0.43 ACH before and 0.48 ACH after the retrofits. The ventilation rates varied between 0.02 … 1.04 ACH before retrofits and between 0.03 … 1.57 ACH after the retrofits. The lowest values were measured when exhaust was off. In the case buildings with natural ventilation (CASE_Natural), ACR was 0.25 ACH both before and after the retrofits. ACR was lower based on the second measurement in the control buildings (CONTROL_Mechanical). It should be taken into account that the number of measurements in the control buildings is low.

ACR improved in 52% of the apartments in CASE_Mechanical buildings, and the average increase was about 0.22 1/h. In the CASE_Natural buildings, ACR improved in 38% of apartments, and the average increase was only 0.03 1/h. However, air flow measurements do not take into account air infiltration, so it is not necessarily correct to interpret the results so that the ventilation rates are lower in buildings with natural ventilation than in buildings with mechanical exhaust. In addition to air change through ventilation outlets, there is always some air infiltration through the building envelope. Also it should be taken into account that the number of the buildings with natural ventilation is low. Many other studies have not found significant differences in total ventilation (ventilation + infiltration) rates between different ventilation systems. [6, 7]

Table 1. Air change rate (ACR, 1/h)

	CASE_Mechanical		CASE_Natural		CONTROL_Mechanical	
	Pre	Post	Pre	Post	1st	2nd
N	119	71	11	8	10	8
Average	0.43	0.48	0.25	0.25	0.59	0.45
SD	0.23	0.24	0.12	0.10	0.27	0.16
Median	0.42	0.43	0.24	0.21	0.56	0.41
5th	0.09	0.18	0.08	0.15	0.25	0.26
95th	0.87	0.85	0.45	0.39	0.97	0.63

3.2 Carbon dioxide concentrations

Carbon dioxide measurements may give additional information about the ventilation adequacy in occupied spaces. Measured 24-hour average CO_2 concentrations in the apartments in "CASE_Mechanical" buildings were 750 ppm before and 715 ppm after the retrofits, whereas in "CASE_Natural" buildings they were 740 ppm and 640 ppm, respectively (Table 2). In the control buildings, average CO_2 concentrations were about the same in both measurements. In all buildings, the levels were relatively low and below existing limit values. According to new Finnish decree on housing and health [8], indoor CO_2 concentration should not be over 1150 ppm above the outdoor CO_2 concentration. Guideline value of CO_2 concentration for "adequate IAQ" is 1200 ppm [9].

We also checked short term CO_2-levels during the air flow measurements. Apparently the research personnel cause some disturbance to the recordings during the measurement visit, conducted at the same time as the air flow measurements. However, the observed trend based on the short term measurements is mainly to the same direction than based on the 24-hour measurement, which is also limited in a sense that daily variations (e.g. due to possible differences in occupancy levels and climate) cannot be detected. There is a weak correlation between ACR calculated based on air flow measurements and ACR calculated based CO_2 measurements in the largest group (CASE_Mechanical): Pearson correlation is -0.28 before and -0.19 after the retrofits.

Table 2. CO_2 concentrations (ppm)

CO_2	CASE_Mechanical		CASE_Natural		CONTROL_Mechanical	
ppm	Pre	Post	Pre	Post	1st	2nd
24-h measurement						
N	171	131	15	10	32	30
Average	750	715	740	640	628	625
SD	256	243	145	120	107	121
Median	689	654	679	647	629	609
5th	492	455	599	483	481	467
95th	1300	1174	996	815	819	838
Short term measurement (during the air flow measurement)						
N	100	83	13	10	10	8
Average	913	834	948	693	854	758
SD	233	181	147	127	161	171
Median	869	797	901	711	826	767
5th	614	567	782	500	697	494
95th	1279	1186	1162	819	1114	944

3.1 Occupant satisfaction with IAQ

Results from occupant questionnaires are reported elsewhere in more detail [10]. A total of 235 and 170 people (response rates 94% and 75%) answered to the first and second questionnaires, respectively. Out of these samples, 31 responses came from the control buildings at the baseline (1st questionnaire) and only 11 came from the control buildings at the follow-up (2nd questionnaire), while the rest of the responses came from the case buildings.

As shown in Table 3, 45% of the respondents from the control buildings were satisfied with IAQ at the baseline, while the percentage was 22% in the case buildings. At the follow-up, the percentage was 36% in the control buildings, whereas the satisfaction with IAQ increased to 41% in the case buildings. The improvement seen after the retrofits in the study buildings was statistically significant ($p<0.05$).

We also checked is there was any difference in the satisfaction with IAQ between the case buildings with natural and mechanical ventilation. Before the retrofits, the percentage of respondents satisfied with IAQ was 20% in the buildings with natural ventilation and 22% in the buildings with mechanical ventilation. After the retrofits, the percentages were 50% and 41%, respectively. It should be noted that there were no statistically significant differences, and the results are inconclusive due to small number of building with natural ventilation.

A literature survey [11], comparing how different factors influence on human comfort in different studies, found that occupants living in buildings with natural ventilation accepted higher indoor temperatures in summer and lower indoor temperatures in winter, and they also accepted wider temperature range. Based on our data at the baseline, 73% of the respondents from the case buildings with natural ventilation reported suitable temperature in summer and 27% in winter, respectively. In the case buildings with mechanical ventilation the corresponding percentages were 57% in summer and 67% in winter. At the follow-up, 50% of the respondents from the case buildings with natural ventilation reported suitable temperature both in summer and in winter. In the study buildings with mechanical ventilation the corresponding percentages were 57% in summer and 66% in winter. Therefore, thermal comfort in the mechanically ventilated buildings did not change, whereas in the naturally ventilated buildings the variation could be related to small sample size. Further analyses are needed to study the effects of ventilation on IEQ and occupant health and comfort.

Table 3. Occupants' satisfaction with indoor air quality and temperature.

	CASE		CONTROL	
	Pre N=204	Post N=159	1st N=31	2nd N=11
Satisfied with IAQ, %	22	41	45	36

	CASE_Mechanical		CASE_Natural		CONTROL (Mechanical)	
	Pre N=189	Post N=151	Pre N=15	Post N=8	1st	2nd
Satisfied with IAQ, %	22	41	20	50	45	36
Suitable temperature in summer, %	57	57	73	50	48	73
Suitable temperature in winter, %	67	66	27	50	55	55

4. Conclusions

Ventilation rates and CO_2 concentrations were improved after the retrofits in most cases. In majority of cases, CO_2 levels were below the national limit values both before and after energy retrofits, indicating adequate ventilation in these buildings. 24-hour monitoring of CO_2 appeared to give more reliable results as compared to short term measurements during the measurement visit, where the research personnel may cause some disturbance to the recordings. The percentage of occupants satisfied with indoor air quality was significantly increased after the retrofits.

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