TALLINN UNIVERSITY OF TECHNOLOGY
DOCTORAL THESIS
38/2022

Ventilation Performance in Deep Renovation of Multifamily Apartment Buildings

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TAL TECH PRESS

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This dissertation was accepted for the defence of the degree 25/05/2022

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Alo Mikola

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ISSN 2585-6898 (publication)
ISBN 978-9949-83-860-8 (publication)
ISSN 2585-6901 (PDF)
ISBN ISBN 978-9949-83-861-5 (PDF)
Printed by Koopia Niini & Rauam

TALLINNA TEHNIKAÜLIKOOL
DOKTORITÖÖ
38/2022

Terviklikult renoveeritud korterelamute ventilatsioonisüsteemide toimivus

ALO MIKOLA

TALTECH KIRJASTUS

Abstract

Ventilation Performance in Deep Renovation of Multifamily Apartment Buildings

In many European countries, there is increasing awareness of the need for renovation of old apartment buildings. Renovation of ventilation systems in the apartment buildings is one of the biggest bottlenecks. The topic of the thesis was chosen to provide answers to the questions raised during the renovation of the Estonian housing stock. The results of the thesis can be used for renovation of the similar apartment buildings in other European countries.

The performance of ventilation and air change in Estonian apartment buildings with different ventilation systems is analysed by field measurements. The average air change rate in old buildings was 0.24 h^{-1} and the technical inspection of studied ventilation systems pointed out that natural ventilation systems are in poor condition. Laboratory and on-site studies of the CO_2 based tracer gas method proved that the daily variation of CO_2 level can be used to estimate the air change rate in apartments and CO_2 based tracer gas can be used to measure air change efficiency.

As the air change rate in old apartment buildings was too low, technical requirements on the ventilation system were introduced when renovating apartment buildings using the state financial support. There were three renovation financial support levels for construction work for the first grant scheme and two basic levels for the second grant scheme. The financial support levels were based on the designed energy performance level. There were no specific requirements for ventilation in the first support grant. As the results of the air change rates in renovated apartments did not meet the expectations in the first grant scheme, specific technical requirements were added to the second grant requirements.

Single room ventilation units with heat recovery was one of the ventilation renovation solutions during the first support grant in Estonia. The initial analysis of air change rates of these units showed that the solution did not work as designed. Therefore, the performance of two types of single room ventilation units were measured and their suitability as ventilation renovation solutions was assessed with simulations. The pressure difference values were determined and proposed for correct design of single room ventilation units. Also, the measurements to analyse the air change efficiency of different room-based ventilation renovation measures for old apartment buildings were made. Nearly ideal mixed ventilation was achieved both for ventilation radiators and two types of single room ventilation units.

During the first renovation grant period, the average air change rate in the studied apartments was as low as 0.17 h^{-1}, and in the second grant period air change rate had improved to 0.57 h^{-1}, complying with requirements. Room-based ventilation requirements as well as heat recovery and preheating of intake air, mandatory airflow rate and sound pressure level measurement protocols, and third party inspection of design documentation assured adequate ventilation and indoor air quality in the second grant period. Centralized mechanical supply and exhaust ventilation with heat recovery resulted in the best performance, but an alternative system with exhaust heat pump and ventilation radiators can also be recommended.

Lühikokkuvõte

Terviklikult renoveeritud korterelamute ventilatsioonisüsteemide toimivus

Paljudes Euroopa riikides on hakatud üha enam teadvustama vanade kortermajade renoveerimise vajadust. Kortermajade puhul on üheks suurimaks kitsaskohaks just ventilatsioonisüsteemide renoveerimine. Doktoritöö eesmärk on anda vastuseid Eesti kortermajade ventilatsioonisüsteemide renoveerimise käigus tekkinud küsimustele. Doktoritöö tulemusi saab kasutada sarnaste Euroopa kortermajade renoveerimisel.

Eesti erinevate kortermajade ventilatsioonisüsteemide toimivust ja õhuvahetust analüüsiti mõõtmiste baasil. Vanade kortermajade keskmine õhuvahetuse kordarv oli 0,24 h^{-1} ning uuritud ventilatsioonisüsteemide ülevaatus näitas, et vanade kortermajade loomulikud ventilatsioonisüsteemid on halvas seisukorras. Laboris ja objektidel teostatud CO_2-põhise märkegaasi meetodi uuringud tõestasid, et CO_2 taseme igapäevast varieerumist saab kasutada korterite õhuvahetuse kordarvu leidmiseks ja CO_2-põhist märkegaasi meetodit saab kasutada ka õhuvahetuse efektiivsuse mõõtmiseks.

Kuna õhuvahetuse kordarv uuritud vanades kortermajades oli liiga madal, kehtestati riigipoolse rahalise toetuse kaasabil korterelamute ventilatsiooni renoveerimisele tehnilised nõuded. Esimesel toetusskeemi puhul oli kolm renoveerimistoetuse taset ning teisel toetusskeemil kaks baastaset. Need tasemed põhinesid arvutatud hoonete energiatõhususe klassidel. Esimese toetusskeemi puhul ventilatsioonisüsteemidele konkreetseid nõudeid ei olnud. Kuna renoveeritud korterite õhuvahetuse tulemused ei vastanud ootustele, lisati teise toetuse nõuetele spetsiifilised tehnilised tingimused.

Üks ventilatsioonilahendustest, mida esimese toetusskeemi puhul ventilatsiooni renoveerimislahendusena kasutati, oli ruumipõhised soojustagastusega ventilatsiooniseadmed. Nende seadmete kasutamisel näitas õhuvahetuse kordarvude esialgne analüüs, et see lahendus ei täitnud oma eesmärki. Seetõttu mõõdeti kahte tüüpi ruumipõhiste ventilatsiooniseadmete toimimist ning simulatsioonitulemuste abil hinnati nende sobivust ventilatsioonisüsteemide renoveerimislahendusteks. Uuringu tulemusena pakuti välja sobivad rõhuerinevuse väärtused ruumipõhiste ventilatsiooniseadmete korrektseks projekteerimiseks. Lisaks viidi läbi mõõtmised vanades kortermajades erinevate ruumipõhiste ventilatsioonisüsteemide õhuvahetuse efektiivsuse analüüsimiseks. Nii ventilatsiooniradiaatorite kui ka kahte erinevat tüüpi ruumipõhiste seadmete puhul saavutati ideaalselt segunev õhuvahetus.

Esimesel renoveerimistoetuse perioodil oli keskmine õhuvahetuse kordarv uuritud korterite puhul vaid 0,17 h^{-1} ja teisel toetusperioodil paranes õhuvahetuse kordarv 0,57 h^{-1}-ni, mis vastas kehtestatud nõuetele. Teisel toetusperioodil tagasid piisava õhuvahetuse ja siseõhu kvaliteedi kehtestatud detailsed ruumipõhised ventilatsiooninõuded, sissepuhkeõhu soojustagastuse ja eelsoojenduse nõue, kohustuslike õhuvooluhulga ja helirõhutaseme mõõtmisprotokollide esitamise nõue ning kolmanda osapoole poolt projekteerimisdokumentatsiooni kontrolli teostamise kohustus. Parima ventilatsioonisüsteemi toimimise tagas tsentraalne mehaaniline sissepuhke- ja väljatõmbeventilatsioon koos soojustagastusega, kuid soovitada võib ka alternatiivset väljatõmbeõhu soojuspumba ja ventilatsiooniradiaatoritega süsteemi.

Contents

List of publications

The thesis is prepared on the following peer-reviewed journal and conference publications:

I A. Mikola, T. Kalamees, and T. A. Kõiv, “Performance of ventilation in Estonian apartment buildings,” in Energy Procedia, 2017, vol. 132, pp. 963–968. https://doi.org/10.1016/j.egypro.2017.09.681.

II A. Mikola, T. A. Kõiv, J. Rehand, and H. Voll, “The usage of CO_2 tracer gas methods for ventilation performance evaluation in apartment buildings,” in 10th International Conference on Environmental Engineering, ICEE 2017, 2017. https://doi.org/10.3846/enviro.2017.267.

III A. Mikola, J. Rehand, and J. Kurnitski, “Air change efficiency of room ventilation units,” in E3S Web of Conferences, 2019, vol. 111. https://doi.org/10.1051/e3sconf/201911101017.

IV A. Mikola, R. Simson, and J. Kurnitski, “The Impact of Air Pressure Conditions on the Performance of Single Room Ventilation Units in Multi-Story Buildings,” Energies, vol. 12, no. 13, 2019. https://doi.org/10.3390/en12132633.

V A. Mikola, A. Hamburg, K. Kuusk, T. Kalamees, H. Voll, and J. Kurnitski, “The impact of the technical requirements of the renovation grant on the ventilation and indoor air quality in apartment buildings,” Build. Environ., vol. 210, p. 108698, Feb. 2022. https://doi.org/10.1016/j.buildenv.2021.108698.

These publications are referred to in the text by their Roman numbers.

Author's contribution to the publications

Contribution to the papers in this thesis are:

I Performance of ventilation in Estonian apartment buildings
The field measurements were performed mainly by A.M. Analyses of the measured data was carried out by A.M. The research principles and methods of the study were developed by A.M., T.K. and T.-A. K.

II The usage of CO_2 tracer gas methods for ventilation performance evaluation in apartment buildings
The laboratory and field measurements were performed by A.M. and J.R. Analyses of the measured data was carried out by A.M. The research principles and methods of the study were developed by A.M. T.-A. K. and H.V.

III Air change efficiency of room ventilation units
The laboratory and field measurements were performed by A.M. and J.R. Analyses of the measured data was carried out by A.M. The research principles and methods of the study were developed by A.M. and J.K.

IV The impact of air pressure conditions on the performance of single room ventilation units in multi-storey buildings
The laboratory and field measurements were performed by A.M. and R.S. Analyses of the measured data was carried out by A.M. and R.S. The simulation model was calibrated by R.S. The research principles and methods of the study were developed by A.M., R.S. and J.K.

V The impact of the technical requirements of the renovation grant on the ventilation and indoor air quality in apartment buildings
The field measurements were performed mainly by A.M and A.H. Analyses of the measured data was carried out by A.M. The research principles and methods of the study were developed by A.M., T.K., H.V., K.K. and J.K.

Introduction

Background

In many European countries, there is increasing awareness of the need for building renovation. As buildings account for 40% of the total energy consumption in the European Union (EU), it is the leading source of carbon dioxide (CO_2) emissions [1]. According to the Energy Performance of Buildings Directive (EPBD) [1] countries in the EU need to reduce energy consumption and produce energy from renewable sources in the building sector. Moreover, the new recast of the EPBD suggests that the renovation of existing buildings into nearly zero-energy buildings needs to take place [2]. Current renovation practices show that deep renovation is at a 0.2–0.3% renovation rate in the EU, and a similar situation has been reported in Estonian commercial buildings [3], [4]. To change this situation, EU member states have prepared long term renovation strategies (LTRS) to renovate about 75% of existing building stock into nearly zero energy buildings (NZEB) by year 2050. The EPBD directive [1], [2] also emphasises that during renovation, the quality of indoor air in buildings must be maintained. Indoor air quality (IAQ) in apartment buildings often depends strongly on heating and ventilation systems [5].

In Estonia, multi-story apartment buildings constitute about 60% of the whole dwelling stock, and the majority (75%) of the buildings were built primarily in 1961–1990 [6]. Thus, in Estonia two thirds of the population is living in old apartment buildings [7]. Due to the increase in the price of energy, the energy policies of the European Union [2], the age, construction quality, and poor thermal insulation of the buildings, as well as both morally and technically outdated, obsolete heating and ventilation systems, there is an increased need for retrofitting [8]–[12]. Part of the building stock built before the 1990s has already been renovated but for many apartment buildings this process is yet to start [11], [13]. Typical multi-story apartment buildings have been built with natural ventilation where fresh outdoor air enters through leaks or openings of the windows and doors, mixes with the warm room air, and leaves the building through shafts in the bathroom and kitchen. With retrofitting the building envelope, in order to achieve necessary thermal insulation for reducing the energy consumption for space heating, the air tightness of the building increases and the air flow through cracks and leaks is reduced, which makes the air change with natural ventilation very poor and does not provide the required air change rate [14].

Based on the review of scientific papers, a multidisciplinary group of European scientists have agreed that ventilation is strongly associated with comfort, productivity and health [15]–[17]. Considering the importance of ventilation rate as an influencing factor for the quality of indoor air and health outcomes that may be influenced by indoor environmental quality, more studies would be valuable [18]. Previous cross-sectional national studies have shown that a significant proportion of dwellings mainly have low ventilation rates [19]–[22]. Measurements of ventilation in dwellings exhibit random variations because of the differences in the building technologies, air tightness, occupancy, human behaviour, maintenance, weather, artistry, and material ageing. With the renovation of old apartment buildings, the improvement of ventilation is unavoidable in order to provide healthy indoor environment for the occupants [23].

In order to carry out deep renovation of apartment buildings, Estonia is implementing one of the very few and validated deep renovation support schemes – the KredEx renovation grant scheme for apartment buildings. This practice proves that large-scale deep renovation with good energy and indoor climate performance is possible and that subsidies can be budget neutral [11]. The ventilation systems of old apartment buildings in neighbouring countries of Estonia are quite similar to the technical solutions that are used in Estonia. All in all, the experiences and practices that are studied in this thesis, can be valuable in other EU countries to reduce CO_2 emissions.

Some case studies have also shown that renovation of old apartment buildings may even reduce the air change rates in apartments [24]. It is possible to conclude, that renovation of ventilation systems in the apartment buildings is one of the biggest bottlenecks. As the renovation need of old apartment building is high, the best practice in apartment building ventilation renovation is needed. Many solutions work well only on paper therefore there is a demand for analysing the actual performance of different ventilation renovation measures by field measurements.

In this thesis, the actual performance of ventilation systems of old and renovated Estonian apartment buildings is studied. According to the air change rate and IAQ measurements in old buildings, the need for renovation is identified. The air change efficiency of commonly used residential room ventilation units is analysed. The air pressure conditions in typical renovated multi-story apartment buildings are predicted to analyse the performance of room-based ventilation units. Also, the impact of the technical conditions for the ventilation renovation measures in renovation support grant are analysed. As the study is based on long-term measurements in buildings renovated with grants provided by two different renovation grant schemes, it gives the answer which ventilation renovation measures are best suited for renovation of old apartment buildings. The results and outcomes of this thesis can be used to develop the model ventilation renovation solutions and design guidance for renovation of apartment buildings in Estonia and its neighbouring countries. A new scientific contribution is made in the research of air change efficiency and pressure differential design conditions of single room based ventilation units (SRVUs).

Objective and content of the thesis

I defended my master's thesis entitled "Indoor air quality in apartment buildings and improvement possibilities" in 2010. That study showed that not enough attention is paid to ensure the IAQ in apartment buildings [25]. In addition, the master thesis and other studies have shown that there are not enough well established technical solutions for the successful renovation of ventilation systems in apartment buildings [25]. On this basis, the topic of the thesis was chosen to provide answers to the questions raised during the renovation of the Estonian housing stock. The ventilation renovation need is evident but documentation was needed for instance for renovation grant development and feasible ventilation renovation measures leading simultaneously to high energy and IAQ performance was the main issue.

The main objectives of the thesis are:

- Quantify and document the actual performance of ventilation and the need for renovation in different type of Estonian apartment buildings.
    - To measure and assess the sufficiency or deficiency of the indoor air CO_2 concentration and air change rate in apartments in old panel apartment buildings and brick apartment buildings.
- Develop and apply reliable air change rate and air change efficiency measurement methods that are based on CO_2 tracer gas.

    - Find out if air change efficiency and air change rate can be measured using the CO_2-based tracer gas methods.
    - Find out if air change efficiency influences the air change rate calculation.
    - Find out if the position of the inner doors of apartments influence the tracer gas-based air change rate and air change efficiency calculation.
- Identify the best ventilation renovation measures for old apartment buildings in Estonia based on actual performance in field measurements among available system options in terms of sufficient IAQ and air change rate for:
    - renovation of natural ventilation;
    - single room ventilation units;
    - mechanical exhaust ventilation;
    - mechanical exhaust ventilation with exhaust heat pump heat recovery and ventilation radiators;
    - mechanical supply and exhaust ventilation with heat recovery.
- Develop the basis for ventilation design and sizing of single room ventilation units:
    - to develop realistic pressure design conditions for single room wall-mounted apartment ventilation units;
    - to determine whether the air distribution of studied ventilation renovation measures are capable of providing a fully mixed ventilation.
- To assess the role and impact of technical requirements of renovation grants on the ventilation performance in renovated buildings.
- To propose improvements to the technical conditions of the ventilation renovation support grant schemes according to air change rate and CO_2 measurement results in renovated apartment buildings.
- Further develop the technical solutions of the ventilation renovation measures according to air change rate and CO_2 measurement results.

Structure of the thesis

The thesis is based on peer-reviewed journal and conference articles.

- **Paper** I gives the overview of the performance of ventilation in Estonian apartment buildings with different ventilation principles by field measurements. A total of 167 apartments from 107 buildings with natural and mechanical ventilation were studied. Airflow and CO_2 levels were measured in the heating period and summer period.
- **Paper II** specify the possibility to use the metabolic CO_2-based tracer gas methods for ventilation performance evaluation in renovated apartments with room-based units. To test and elaborate the methods, the ventilation air change rate and air change efficiency measurements were performed. The methods were tested in laboratory conditions and apartments with natural ventilation. Concentration decay method was applied with both artificially and metabolically increasing the concentration of tracer gas. The air change rate was also calculated using metabolic constant dosing method with the effective volume.
- **Paper III** presents a new scientific knowledge of air change efficiency of room ventilation units and ventilation radiator. The main purpose of this study was to investigate the air change efficiency of commonly used residential room ventilation units with CO_2-based tracer gas concentration decay method. Tested systems included pair-wise units, a monoblock unit and a ventilation

radiator, which was combined with mechanical extract ventilation. The measurements were carried out both during the heating period and outside the heating period. The performance of room ventilation units was compared to the conventional mixing ventilation.

- **Paper IV** brings out the new realistic pressure design conditions for room-based wall-mounted ventilation units in case of apartment buildings which can be considered a new approach. The aim of this study was to predict the air pressure conditions in typical renovated multi-story apartment buildings and to analyse the performance of room-based ventilation units. The field measurements of air pressure differences in a renovated 5-story apartment building during the winter season were conducted and the results were used to simulate whole-year pressure conditions with IDA ICE software. Performance of two types of single room based ventilation units were measured in the laboratory and their suitability as ventilation renovation solutions was assessed with simulations.
- **Paper V** describes how the requirements for the ventilation renovation influence the quality of the final results, and how to improve the quality of requirements and achieve the required air change rates. The study looked at the effects of renovation measures applied in two grant periods on air change rate and IAQ of apartments. CO_2 levels and airflow rates were measured in 21 buildings in the first renovation grant period and in 15 buildings in the second grant period.

The results and outcomes of this study have been used to work out the technical conditions of ventilation renovation support grant schemes and technical renovation schemes (Paper III, Paper IV and Paper V).

Methodology

To achieve the objectives, the following methods were used:

- Long-term on-site indoor climate parameters and air change rate measurements in apartments in the panel, brick, wooden and new apartment buildings.
- On-site pressure difference measurements between the indoor and outdoor air in apartments that were renovated using room-based ventilation renovation measures.
- Laboratory measurements to analyse the influence of pressure difference between the indoor and outdoor air to the room-based ventilation units.
- On-site and laboratory measurements to analyse the air change rate and air change efficiency measurements using CO_2-based tracer gas methods.
- Laboratory measurements to analyse the air change efficiency of different ventilation renovation measures for old apartment buildings.
- Dynamic computer simulations to develop realistic pressure design conditions for room-based wall-mounted apartment ventilation units.
- Long-term on-site indoor climate parameters and air change rate measurements in apartments of renovated apartment buildings.
- On-site supply air temperature measurements to analyse the frost formation inside the plate heat exchanger of the renovation measure of centralized balanced ventilation with ventilation heat recovery.

New knowledge, scientific contribution and practical outcomes

The thesis presents the following new knowledge:

- The thesis gives the overview of the performance of ventilation in Estonian apartment buildings with different ventilation principles by field measurements, including air change rates in old panel, brick, and wooden buildings, and new buildings built in 2000–2010.
- A new application of the metabolic CO_2 tracer gas method was developed and tested for ventilation performance evaluation in old apartment buildings with natural ventilation systems, and renovated apartments with room-based units.
- A new scientific contribution was made in the research of air change efficiency of room ventilation units and ventilation radiator as a ventilation renovation measure in apartment buildings; to my knowledge the evidence for these systems is scientifically reported for the first time.
- New and realistic design principles in terms of pressure differential design conditions for single room wall-mounted ventilation units were developed. Design pressure differential is a new approach for design and practical performance assessment of SRVUs and the study was among the first ones reporting unsatisfactory performance of SRVUs.
- The thesis shows the impact of the technical ventilation, thermal comfort and heat recovery requirements of deep renovation grants on the actual air change and some other aspects of IAQ, and thermal comfort in renovated buildings. It is shown how the ventilation shall be dealt with in the renovation grants to achieve adequate air change rates.

The thesis presents the following practical outcomes:

- The results and outcomes of this thesis have been used to develop the model ventilation renovation solutions and design guidance for apartment building renovation.
- The results and outcomes of this thesis have been used to improve the technical conditions of ventilation renovation support grant schemes in Estonia.

Limitations of the work

The main limitations of the thesis are:

- The work is based only on climate and building types of Estonia.
- The energy consumption of studied buildings and ventilation systems is not studied in this thesis.
- The study of IAQ does not consider the measurements of other indoor climate parameters and pollutants rates expect indoor air CO_2 concentration and air change rates in apartments.
- During the field measurements of CO_2 levels and air change rates in old and renovated apartment buildings 1–4 apartments from every building were studied.
- The measurement uncertainty of ventilation airflow, indoor air CO_2 concentration, and other indoor climate parameters is not analysed.
- The renovation need of old apartment ventilation systems is analysed only from the technical point of view. Other aspects such as social, economic, demographic etc. are not studied.

- Only the most used and promising ventilation renovation measures were studied. The studied ventilation renovation measures are centralized balanced ventilation with ventilation heat recovery, mechanical exhaust ventilation with heat pump heat recovery, mechanical exhaust ventilation without heat recovery, renovating the old natural ventilation systems (without heat recovery), and SRVUs with ventilation heat recovery. All the other renovation measures are not studied in this thesis.
- The study does not focus on the other utility systems beside ventilation system.
- The study does not include the analyses of renovation of constructive part, moisture safety, electricity system, fire safety, sewage system etc.
- Air change rate in apartments might also be influenced by infiltration rate, wind speed, and window opening which have not been taken into account.
- Human presence and activities, indoor hygrothermal loads were not analysed.
- Noise level of studied ventilation renovation measures was not analysed.
- Cost of studied ventilation renovation measures was not analysed.
- Paper I points out the IAQ and air change rate also in case of new Estonian apartment buildings and in old wooden apartment buildings. In the thesis, no specific ventilation renovation solutions will be developed for these types of buildings.

Notations

Abbreviations

ACE	Air change efficiency
ACR	Air change rate
AHU	Air handling unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CO_2	Carbon dioxide
CRE	Contaminant removal efficiency
EAHP	Exhaust air heat pump heat recovery
EN	European standard
EPBD	Energy Performance of Buildings Directive
EU	European Union
EVS	Estonian standard
HEX	Plate heat exchanger
HR	Heat recovery
HRV	Centralised balanced ventilation with ventilation heat recovery
HVAC	Heating, ventilation and air conditioning
IAQ	Indoor air quality
ICC	Indoor climate category
IDA ICE	Ida Indoor climate and energy
LBL method	Simplified method for combining weather information with air tightness to calculate residential air infiltration
LTRS	Long term renovation strategy
ME	Mechanical exhaust ventilation without heat recovery
NV	Natural ventilation
NZEB	Nearly zero energy building
PE	Primary energy
REHVA	Federation of European Heating, Ventilation and Air Conditioning Associations
SCOP	Seasonal coefficient of performance
SRVU	Single room ventilation unit with heat recovery
TRY	Test reference year
VR	Ventilation radiator

Symbols

$\overline{t_{sup}}$	Time-averaged value of the supply air temperature, °C
ε_p^a	Local air change index in point P, %
‹τ›	Mean age of the room air, h
A	Area, m^2
C	Concentration of tracer gas, g/m^3
C	Flow coefficient (related to the opening), -
$C_{(0)}$	Tracer gas concentration at start of decay, g/m^3
$C_{(t)}$	Tracer gas concentration at time "t" after start of decay, g/m^3
C_{ex}	Outdoor concentration of tracer gas, g/m^3
C_p	Pressure coefficient, -
E	Tracer gas generation, g/h
H	Height, m
h	Height from the surface of the ground, m
h_m	Height of the measurement equipment , m
k, a	Terrain coefficients, -
L	Ventilation air flow rate, m^3/h
n	Flow exponent which is characterizing the flow regime, -
p_{wind}	The static wind pressure outside the building facades, Pa
Q	Internal/external airflow, m^3/h
q_{50}	Air leakage rate of building envelope at 50 Pa pressure difference, $m^3/(h \cdot m^2)$
R	Tracer gas removal rate by means other than ventilation, g/h
R^2	Coefficient of determination, -
t	Time, s, min or h
t_{exh}	Extract air temperature, °C
t_{out}	Outdoor air temperature, °C
U	Local wind velocity, m/s
U(h)	Local wind velocity, m/s
U_m	Measured wind speed at the weather station (at a height of 10 m), m/s
V	Volume of room, m^3
ΔP	Pressure difference over the opening, Pa
ε^a	Air change efficiency, %
η_{temp}	Temperature ratio (efficiency) of ventilation heat exchanger, -
λ	Average air change rate and depression angle of the function, 1/h
ρ_a	Air density, kg/m^3
τ	Mean age of air, h
τ_n	Nominal time constant, h
τ_p	Local mean age of air in point P, h
τ_r	Actual air change time in the room, h

1 IAQ and ventilation systems in apartment buildings

1.1 Old apartment buildings and ventilation systems in Estonia

1.1.1 Old apartment buildings in Estonia

Dwellings in Estonia can be divided into two bigger groups: apartment buildings and detached houses. The majority of apartment buildings are built after the Second World War in 1950–1990. Old brick and panel apartment buildings (Figure 1) were built between 1955–1990 [26]. Apartments consisted of one, two, or three rooms, with a separate kitchen, entry, and sanitary rooms. Buildings were heated with district heating and one-pipe radiator heating systems. Typically, radiators were not equipped with special thermostats, therefore individual control of the room temperature was not possible. Room temperature for the whole building was controlled in heat substations depending on outdoor temperature. Studied dwellings had natural ventilation (NV). In all of the old dwellings, windows could be opened for airing purposes.

Figure 1. Example of studied brick apartment buildings (left) and panel apartment buildings (right).

1.1.2 Ventilation systems of old apartment buildings in Estonia

In the Estonian apartment buildings that were built before 1991 have NV system. NV functions due to the indoor and outdoor air pressure differences. The pressure difference between indoor and outdoor air is caused by the difference of air tightness, wind speed and the high of the channels. Air intake of NV systems was designed to take place from air leakages of leaky windows and walls. The windows were tightened into the wall using tow which means that this connection was also not very airtight. Fresh air inlets were also sometimes used in case of apartment buildings. The used outdoor air design temperature in case of designing NV systems in old Estonian apartment buildings was +5 °C. If the outdoor air temperature is higher than +5 °C and wind speed is low, then the extract airflow from apartments is lower than designed. As the temperature difference of in- and outdoor air and wind speed is not constant, NV systems cannot ensure stable airflow in apartments during the whole year.

There are two most common design solutions for the connecting the NV channels to the extract grilles in toilets and bathrooms (Figure 2). Apartment buildings up to 6 stories have separate ventilation channels for every apartment, and apartment buildings which have 7 floors or more usually have separate ventilation channels for the 2 upper floors and lower apartments are connected to the main NV channel (Figure 3). The exhaust fans were also designed for the 2 upper floors, but in practice, these fans were never installed, or even if the fans were installed, the sound level was too high and therefore the fans were not used.

The ventilation design solution provides that the extract grilles are installed in kitchens, bathrooms, or toilets. In some buildings, the extract element is also designed into living room or bedrooms. A common solution for toilets and bathrooms is a common extract grille for both rooms and a transfer air grille in the wall connecting the rooms (Figure 2). If the ventilation shaft is close to toilet, the extract grille is installed on the wall of the toilet, and there is a transfer air grille on the wall of the bathroom. However, if the bathroom is close to the ventilation shaft, there are separate extract grilles both in the toilet and in the bathroom. Depending on the type of building and the size of the apartment, there are altogether 1–3 NV extract channels for the apartment. The most typical size of the ventilation channels is 140 x 140 mm. The size of main channels for higher buildings is 270 x 270 mm or 270 x 140 mm. If the extract air grille is not on the wall of the extract channel, the square metal duct with the size of 160 x 160 mm is used.

Previous studies of old Estonian apartment buildings have brought out that air change rate (ACR) in Estonian apartment buildings is often insufficient because the old NV systems are in poor condition and need renovating [10], [27], [28]. The existing old NV systems and exhaust channels are in bad technical condition (Figure 4 and Figure 5). Improvement of ventilation together with improving thermal insulation of the building envelope, renovation and rebalancing of heating systems with thermostats equipped to the radiators, are necessary to provide a healthy indoor environment for the occupants [9].

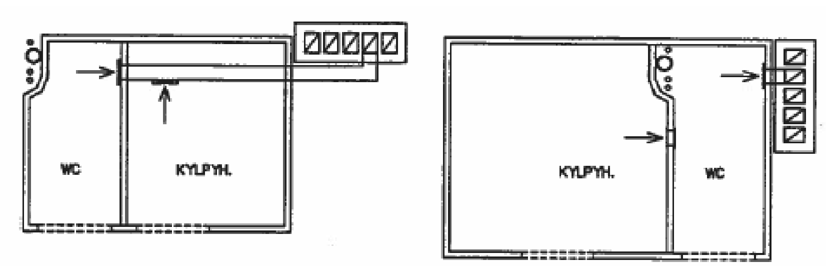

Figure 2. The main connection schemes for NV channels to the extract grilles [29].

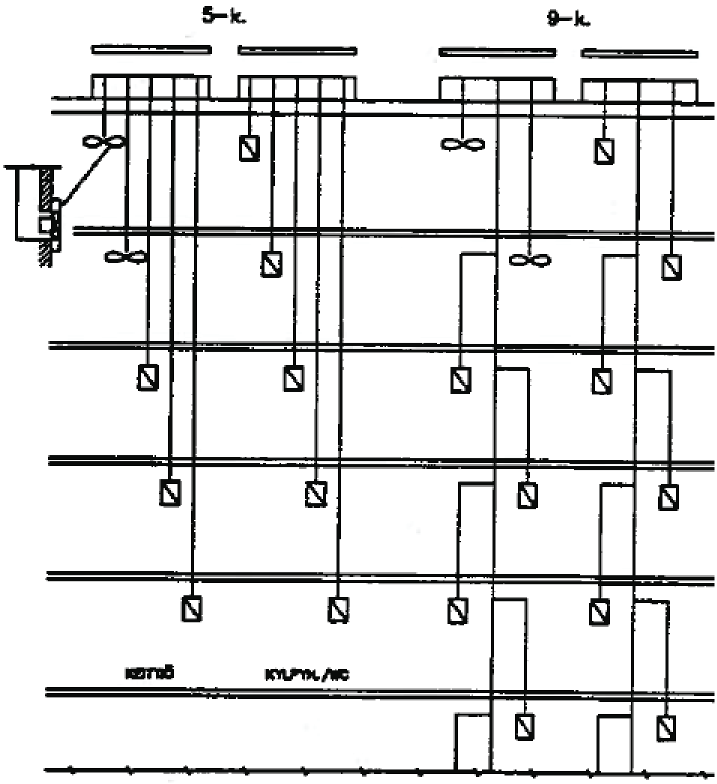

Figure 3. The principal schemes of NV system for 5-storey brick apartment building (left) and 9-storey building (right) [29].

Figure 4. The installation quality of old ventilation shafts is poor (left and right).

Figure 5. The connection between the old ventilation channels and ductworks of the kitchen hood are not airtight (left) and the dust have accumulated inside the old NV systems (right).

1.1.3 Requirements for the ventilation design in Estonian apartment buildings

The ventilation systems of Estonian apartment buildings that were built before 1990 were designed with NV and were designed by the Construction codes and regulations of the Soviet Union (СниП II-Л.1-71 and СниП 2.08.01-85) [9]. At first, the designed air change level in living rooms was 1 h^{-1}, later it changed to 0.8 $l/(s*m^2)$ [9]. Extract air was removed from toilets, bathrooms and kitchens. The normative extract airflow from the kitchen was 20 l/s, from the bathroom 7 l/s, and from toilet 7 l/s. Intake air was designed to enter through the cracks of leaky windows and external walls. At the beginning of the 1990s Finland design norms part D2 [9] were used to design residential ventilation systems. The first Estonian standard for residential buildings, EVS 845-2:2004 [30] in year 2004, was also composed according to Finnish standards. Indoor environmental input parameters standard EVS-EN 15251:2007 was taken into use in 2007 [31].

In accordance with the requirements of regulation no. 38 of the Government of the Republic of Estonia [7], the living area must have natural or technical ventilation, which guarantees the air change necessary for human activity. According to the requirements of the EVS-EN 15251:2007 [31] and EVS-EN 16798-1:2019 [32] air velocity in living spaces, the volume of the room per person, and the content of harmful substances in the indoor air must not exceed the values permitted. Indoor air CO_2 concentration is considered to the standard of the indoor environmental input parameters and designing criteria CR 1752 [33] and the standard of energy performance of buildings EVS-EN 16798-1:2019 [32] (Table 1). The performance of ventilation can be assessed based on the target values from the standard EVS-EN 15251:2007 (2007–2018) and EVS-EN 16798-1:2019 (since 2019). The II indoor climate category (ICC), representing normal level of expectation for new buildings and major renovations, was selected for comparison. The general ventilation airflow in new apartments (ICC II) should be at least 0.42 $l/(s*m^2)$ or 0.6 h^{-1}, and airflows in living rooms and bedrooms should be at least 1.0 $l/(s*m^2)$ or 7 l/(s*person). According to the II ICC, the extract airflow from the kitchen should be 20 l/s (25 l/s), from the bathroom 15 l/s, and from the toilet 10 l/s.

Table 1: Class of the indoor climate for rooms with human activity by EVS-EN 16798-1:2019 [32].

Category	Expected percentage dissatisfied, %	Indoor air CO_2 concentration, ppm
II (B)	20	1200
III (C)	30	1750

1.1.4 Ventilation systems in old apartment buildings in Northern and Eastern Europe

The ventilation systems of old apartment buildings in neighbouring countries of Estonia are quite similar to the technical solutions that are used in Estonia. The greatest similarity is especially between the old apartment buildings built before 1990 in Post-Soviet countries like Latvia, Lithuania, Poland, Slovakia, and other eastern European countries [34]–[38]. In all countries in the region, the NV is used in old apartment buildings [24], [38], [39]. Similar input data was used in the design process of the NV in these countries. For example in case of typical old Russian multifamily apartment buildings (from series 114–85), same outdoor air temperature (+5 °C) for the NV design and also similar technical solution for the NV system construction has been used as in old Estonian apartment buildings [40]. In Poland, the initial distribution of ventilation shafts in apartments of multifamily buildings is similar to Estonian solutions (extract grilles in bathroom, kitchen and in separate toilets) [41]. It is possible to conclude that the old NV systems in old apartment buildings in Eastern Europe have similar technical characteristics.

At the same time, in Finland, Norway, Denmark, and Sweden, the majority of old apartment buildings are equipped with mechanical exhaust ventilation systems [42]–[44]. It means that the renovation solutions used in these countries are not directly transferable to Estonian conditions. It is also found that, for example, in Denmark, there are also some old multifamily apartment buildings that are equipped with NV system [45], [46].

1.1.5 The need to renovate the ventilation systems in old apartment buildings

According to the Energy Performance of Buildings Directive (EPBD) [1] countries in the EU need to reduce energy consumption and produce energy from renewable sources in the building sector. Moreover, the new recast of the EPBD suggests that the renovation of existing buildings into nearly zero-energy buildings needs to take place [2]. Current renovation practices show that deep renovation is at a 0.2–0.3% renovation rate in the EU, and a similar situation has been reported in Estonian commercial buildings [3], [4]. To change this situation, EU member states have prepared long term renovation strategies (LTRS) to renovate about 75% of the existing building stock to nearly zero energy buildings (NZEB) by year 2050. The Estonian LTRS states that all buildings built before 2000 must undergo major renovation [47].

Estonia is implementing one of the very few and validated deep renovation support schemes – the KredEx renovation grant scheme for apartment buildings. This practice proves that large-scale deep renovation with good energy and indoor climate performance is possible and that subsidies can be budget neutral [11]. These experiences and practices can be valuable in other EU countries to reduce CO2 emissions. The EPBD directive [1], [2] also emphasises that during renovation, the quality of healthy indoor air in buildings must be ensured. IAQ in apartment buildings often depends strongly on heating and ventilation systems [5]. Heating, ventilation and air conditioning (as shortened to HVAC) systems in old buildings are often technologically obsolete; thus, using integrated renovation packages, including measures to improve IAQ, is inevitable [48].

Measurements during large-scale field campaigns on the performance of ventilation in old apartment buildings revealed that the ACR in Estonian apartment buildings is often insufficient because old NV systems are in poor condition and need to be renovated [10], [27], [28]. Additionally, the renovation of ventilation systems in apartment buildings is one of the biggest obstacles to achieving the objectives [49]. If the existing NV system is not renovated during the renovation of the building envelope, the ACR may be reduced [24], [34].

1.2 Ventilation renovation solutions in old apartment buildings

The renovation of old ventilation systems is a natural part of the renovation process and using exhaust air heat recovery (HR) in cold climate regions is the only solution to reach the energy saving targets of the EU [50]. Leech et al. [51] showed that in energy-efficient houses with mechanical supply and exhaust ventilation with HR, the health of occupants improved over one year period. Additionally, the energy consumption of ensuring sufficient ACR is between 30 and 60% of the total energy demand of an apartment building [11], [13], [52], [53]. If a high-efficiency exhaust HR system is used, the consumption of supply air heating falls below 10% of the total heating energy consumption [54]. The behaviour of occupants can also influence the practical performance of apartment ventilation systems [12], [55], [56]. Park et al. [55] conducted a questionnaire survey of the residents of 139 apartments with mechanical ventilation; they found that 68% of the residents did not turn on the ventilation units and 58% of residents who did not use mechanical ventilation said that the primary reason was the cost of heating energy. Based on the referenced studies [54], [55], the mechanical ventilation without HR can cause the ventilation systems to be turned off, which means very low ACRs and extra energy costs because of the opening of the windows. Moreover, the renovation of old NV systems can increase electricity consumption [57], which is inevitable because the initial ACR does not fulfil these requirements.

Olsson et al. [58] interviewed six Swedish property owner organisations and concluded that increasing the sustainability of the built environment would require government subsidies. Pikas et al. [59] calculated that 17 jobs per EUR 1 million of investment were generated in the renovation of old Estonian apartment buildings and that the tax revenue from renovation construction projects was over 32%. The same study also pointed out that it is most beneficial to invest in integrated renovation, which includes both measures to improve IAQ and increase energy efficiency [59]. Kurnitski et al. [11] developed the Estonian energy roadmap and pointed out that support schemes for apartment buildings are necessary if the renovation cost is higher than 200 €/m^2. Additionally, because the integrated renovation process generates 32% of tax revenue, the invested money is partially or totally returned to the state budget. Thus, it can be concluded that renovating schemes can revive the economy, increase the energy efficiency of apartment buildings, and improve IAQ.

The most common ventilation renovation measures used in cold climates are centralised balanced ventilation with ventilation HR (HRV), mechanical exhaust ventilation with exhaust air heat pump HR (EAHP), and mechanical exhaust ventilation without HR (ME) [60]–[62]. Some alternative ventilation renovation measures, such as SRVUs with HR [63]–[65] or renovation of the old NV system, have also been used [66]. Even if ventilation systems are renovated using viable ventilation renovation measures, the correct design, construction, operation, and maintenance of all parts of the system must be implemented [9]. Discomfort to the occupants may be caused if mistakes have been made in a renovation phase [8], [24], [34], [67], for example, the wrong position of the supply air valves [8] or an incorrect solution to frost protection of the plate heat exchanger (HEX) [68], [69]. Studies of Estonia [12], [49] have shown that some ventilation renovation measures and technical solutions are not suitable for renovating apartment ventilation systems, for example SRVUs.

Many studies have investigated buildings in which the IAQ has worsened after building renovation [8], [24], [34]. Földváry et al. [24] measured indoor air CO_2 concentration before and after apartment building renovation and found that the median night-time level of CO_2 was higher than before the renovation. In addition to the CO_2 measurement results, concentrations of other pollutants should also be investigated, for example, the concentration of fine particles in indoor and outdoor air in Estonian old apartment buildings [70]. The main conclusion of this study was that, in Nordic countries, the indoor/outdoor ratios of fine particles are approximately 1, which means that a higher ACR does not affect the IAQ level [70], [71] because there is no significant outdoor air filtration in old buildings. Studies have shown that the IAQ and the human health are strongly related [72], [73] and that low air changes can cause health problems [74], [75] and loss of productivity [76], [77]. Because insufficient ventilation of buildings is related to adverse health effects, ensuring an adequate ACR should be prioritised over other renovation measures [48], [78].

1.3 Apartment ventilation renovation measures using SRVUs

The impact of ventilation on the energy use of buildings can be between 30–60% for new and retrofitted buildings [13], [79], [80] thus HR from the exhaust air is inevitable. Depending on the type of the heat exchanger (HEX) used in the air handling unit (AHU), it is possible to recover either sensible and latent heat or only sensible heat from the exhaust [81], [82]. Few solutions used in new buildings are suited for retrofitting purposes, mainly for construction-technological reasons. Other factors that affect the choice of suitable system are the cost of the system, the volume of the construction work, aesthetics, adjustability and the costs of maintenance and operation. SRVUs could be a possible ventilation renovation solution which would disturb the residents of the apartments as little as possible and still achieve the sufficient air change rate and ventilation HR.

The need for electricity to move the air increases at higher ventilation rates, becoming in some cases the main factor of increase in the final energy demand [23], [83]–[85]. Ductless systems with SRVUs tend to have the lowest construction and operation costs, and to be simplest in design and most aesthetic [86]. The lack of ducts is a clear advantage since the most common problems are caused by the poor installation quality of ducts and inadequate project design [9]. It is also essential for the ventilation unit to have a low electric power consumption, suitable acoustic properties [87] and sufficient energy saving performance, which is strongly related to outdoor climatic conditions, the enthalpy efficiency, fan power consumption and necessary fresh air change rate [88].

During the period of 2010 to 2014 a total of 663 apartment buildings in Estonia were renovated using the renovation grant scheme [12]. The main principle of this grant scheme was to improve indoor climate and energy efficiency of Estonian apartment buildings. There were 3 different grant levels, but in order to qualify for the highest financial support of 35% of the renovation costs provided by the state, the designed ventilation system was required to include HR. The two most commonly used types SRVUs used to renovate ventilation systems of apartment buildings during the retrofits between 2010–2014 were: unit with recuperative plate HEX and centrifugal fans (Figure 6 top) and unit with regenerative ceramic HEX and an axial fan (Figure 6 bottom). The SRVUs works in cycles, switching between the supply and exhaust mode every

60–70 seconds. During the exhaust cycle, the heat from the warm exhaust air is accumulated in the ceramic comb-like HEX and is then used to heat up the cold outdoor air during the supply cycle.

Since the ventilation units are mounted inside the exterior wall of the building, the performance of the units is directly affected by the pressure differences between indoor and outdoor air across the building envelope. During the ventilation renovation between 2010–2014, the NV system was often not replaced. It means that the SRVUs had to operate together with the pressure difference in buildings with NV caused mainly by the wind and the stack effect. There are numerous studies on both the stack effect [89]–[93] and the wind-induced pressure [94]–[96] in different building types with variable height, geometry and location. Wind conditions depend on the location and surroundings of the building. The stack effect depends on the height of the building and the temperature difference between indoor and outdoor air. The temperature differences of the air cause density differences that induce buoyancy force; the warm indoor air rises and is replaced by the colder outdoor air through the building envelope during the heating season. Studies indicate larger air pressure difference over the building envelope in more airtight buildings [80], [97]. Shafts, staircases and other vertical openings, but also leaks through the cracks in floors, walls and ceilings can contribute considerably to the stack effect [98]. IAQ measurements in Estonian renovated apartment buildings have shown that SRVUs are not ensuring the necessary air change rate [8], [12]. To secure the success of the renovation work, it is necessary to find out the reasons why the ACR is below the designed values.

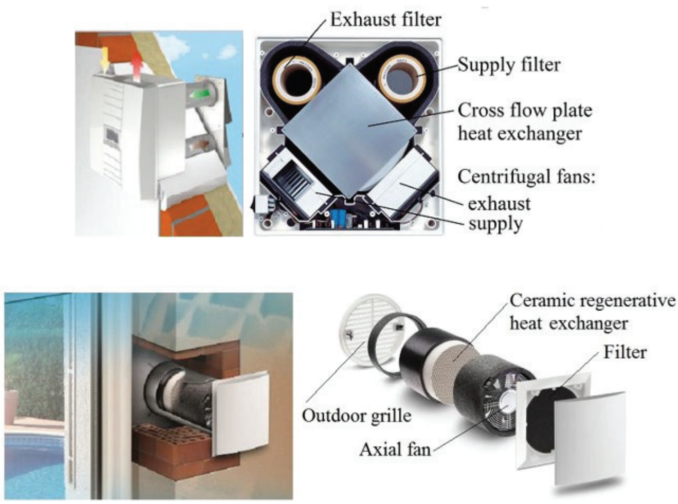

Figure 6. Types of SRVUs used in the renovation of old apartment buildings: with recuperative cross-flow plate HEX (top) and with regenerative ceramic heat exchanger (bottom) [99], [100].

1.4 Tracer gas techniques for ACR and ACE measurements

1.4.1 Measurement of ACR using tracer gas method

In many studies, the key indicator for the assessment of IAQ and ventilation performance in buildings is CO_2 [101]. CO_2 is often used as a passive tracer gas to determine human occupancy in the space and ACR in rooms is controlled by the level of CO_2 in rooms.

However, CO_2 produced by people can also be used as a natural tracer gas for ACR measurements [102]. Tracer gas methods are widely used practice for assessing the performance of ventilation systems in many countries as these do not request the air speed or pressure measurements from ducts [103]. ACR is determined by adding a certain amount of tracer gas to the indoor air of tested zone. According to the change of tracer gas concentration in the air, it is possible to calculate the airflow. The process of ACR measurements is described in detail in the standard EN ISO 12569:2012 [104]. Various tracer gas techniques have been used to measure the ACR in buildings. SF6 is the most often used tracer gas [105]. However, in some studies other gases, for example CO_2, are used [106]. Traces gas techniques are also used to measure the airtightness in buildings [107].

The transient tracer gas techniques for measuring the ACR in a single zone are simple decay, two-point decay, integral decay and charge up method. The steady-state methods to measure airflow are a pulse, constant injection, long-term integral and constant concentration [108]. In the same study [108], it is also pointed out that the most common mistake made in tracer gas analyses, is the fact that, the measurements are made under poorly mixed conditions. The best possible method depends on the specific characteristics of the measurement object. For example, the ACR measurements in five-room test-building have shown that only the constant concentration method is suitable for separate airflow calculations in rooms [109]. Other techniques are appropriate for whole house ACR calculations. Chao et al. [105] compared the concentration decay and constant concentration methods in an office building with mechanical ventilation system with VAV-dampers and apartment buildings with the NV. They found that the difference in airflows was 16%. This means that there is a correlation between these methods. The study also points out that one of the advantages of the constant concentration method is a possibility to measure the airflows in the VAV type ventilation system [105].

The tracer gas techniques have also been used to assess the ACR in the case of natural [107] and different types of mechanical ventilation [106]. Labat et al. [107] used CO_2 as a tracer gas to obtain ACR measurements in a naturally ventilated building. The measurements were done using the concentration decay method, from October to January during different wind and thermal conditions. The ACR of the building measured from 3 to 18 h^{-1} [107]. In across Catalonia the ACR in 16 single-family dwellings were measured using the tracer gas technique [110]. CO_2 were released until the concentration in rooms were 1500 ppm, and the ACR were calculated using concentration decay method. The ACR of studied dwellings varied from 0.074 to 0.541 h^{-1} [110]. You et al. [111] calculated the ACR based on the measured CO_2 data. They used the decay model using non-linear regression analysis to minimise squared residuals for selected periods when a smooth decay curve in CO_2 levels was observed [111]. Another possibility to evaluate the performance of ventilation system is to use the continuous monitoring strategy. It means that the level of CO_2 is measured during a longer period and afterwards the ACR in rooms is calculated according to the measurement results [111]. Baránková et al. [102] developed a method for ACR measurements in naturally ventilated dwellings. The method includes one-parameter and two-parameter emission decay technique. The two-parameter emission technique was used to calculate ACRs based on concentration build up measured in bedroom and guest room during the night when occupants were sleeping. Decay technique was used during the period after the occupants had left the building [102].

The Estonian standard of the airflow measurements [112] states that the preferred way to calculate the ventilation airflows is measuring the air speed in ducts. However, in case of apartment buildings with NV, the air speed is not always possible to measure. The same problem is also with retrofitted apartment buildings were SRVUs had been used. As these wall-mounted ventilation units are sensitive to in- and outside pressure differences, the measurement of ventilation airflow in the traditional way can be inaccurate. In some cases, it is possible to use the anemometer together with the flow hood, but this measurement method can give inaccurate results. There are also studies which show that the pressure loss in flow hood influence the measurement result [113].

The passive CO_2 method gives the correct values only in case of perfect mixed ventilation. The analyses show that the measurement results are not accurate in the case of poorly mixed conditions [108]. That is the reason why it is important to consider the ACE in ACR measurements.

1.4.2 Continuity equation of tracer gas techniques

Lawrence and Braun [114] have shown that a quasi-static model for CO_2 levels in buildings is sufficiently accurate for evaluating the performance of ventilation in small commercial buildings. A general equation of CO_2 concentration in a well-mixed room is based on mass balance equation for the tracer gas, as in

$$V\frac{dC}{dt} = QC_{ex} - QC + E - R\,, \tag{1}$$

where: V – effective volume of enclosure (m^3); C – concentration of tracer gas (g/m^3); C_{ex} – outdoor concentration of tracer gas (g/m^3); Q – internal/external airflow (m^3/h); t – time (s); E – tracer gas generation (g/h); R – tracer gas removal rate by means other than ventilation [114].

If the tracer gas removal rate by other processes than ventilation is zero then R = 0. In the concentration decay method, the injection of the tracer gas is stopped, and the rate E also becomes zero. Integration of Equation 1 yields the equation

$$C_{(t)} = C_{ex} + (C_{(0)} - C_{(ex)})e^{-\frac{Q}{V}t}\,, \tag{2}$$

where: $C_{(0)}$ – tracer gas concentration at start of decay (g/m^3); $C_{(t)}$ – tracer gas concentration at time "t" after start of decay (g/m^3) [101]. If tracer gas is released at a constant rate, Equation 1 becomes [101]

$$C_{(t)} = C_{ex} + \frac{E}{Q} + (C_{(0)} - C_{(ex)} - \frac{E}{Q})e^{-\frac{Q}{V}t}\,. \tag{3}$$

1.4.3 Measurement of ACE using tracer gas method

ACE is based on the mean age of air, which was first introduced by Sandberg in 1981 [115]. The mean age of air is a statistical figure which is based on the age distribution of air components in a certain point and it is expressed in time units. The counting of the age starts at the moment when air enters the room. Air in certain point consists of components which have covered different distance in the room and also spent different period of time there. Local mean age of air (τ_P) is the statistical average value of those components. The mean age of air ($\langle\tau\rangle$) in the whole room is the average local mean age of air of all the points in the room. In case of fully mixed ventilation, τ_P is equal in all room points. On the contrary, in case of short-circuit flow, the local mean age of air is low in the short-circuit zone and high in the stagnant zone. According to the definition, τ_P in the extract air is always equal to the nominal time constant (τ_n) of the room, which is the minimal possible time for the exchange of all room air [116]

$$\tau_n = \frac{V}{L} \text{ ,} \tag{4}$$

where: τ_n – nominal time constant, h; V – volume of the room, m^3; L – ventilation air flow rate, m^3/h.

The mean age of air can be calculated according to the international standard ISO-16000-8 [117]. Although the standard provides methodology for the calculation of local mean age of air, it can be expanded to the whole room based on the definition shown above. To calculate the mean age of air in the room, the average concentration of all measured room points on each minute can be plotted in logarithmic scale in relation with time. If the relation between the two values is exponential, the curve will be a straight line. The absolute value of the depression angle of the curve shows the average ACR and the reciprocal of which is the mean age of air in the room [117]

$$\tau = \frac{1}{\lambda} \text{ ,} \tag{5}$$

where: τ – mean age of air, h; λ – average ACR and depression angle of the function, 1/h.

ACE is defined as a ratio between the shortest possible air change time and the actual air change time τ_r. It can also be described as the ratio between the shortest possible mean age of air and the actual mean age of air. The shortest possible mean age of air in the room is $\tau_n/2$ which occurs in case of the ideal piston flow [116]

$$\varepsilon^a = \frac{\tau_n}{\tau_r} \cdot 100 = \frac{\tau_n}{2 \cdot \langle \tau \rangle} \cdot 100 \text{,} \tag{6}$$

where: ε^a – ACE, %; τ_n – nominal time constant, h; τ_r – actual air change time in the room, h; ‹τ› – mean age of the room air, h. ACE is expressed as a percentage with the maximum value 100% which occurs during piston flow. The ACE of ideally mixed flow is 50%, displacement flow between 50% and 100% and short-circuit flow under 50% [116]. The ACE value 50% is normal for an occupied room [118].

A concept of local air change index ε_p^a is defined to measure the ACE in a certain room point. It is defined as a ratio between nominal time constant and local mean age of air [116]

$$\varepsilon_p^a = \frac{\tau_n}{\tau_p} \cdot 100 \text{ ,} \tag{7}$$

where: ε_p^a – local air change index in point P, %; τ_n – nominal time constant, h; τ_p – local mean age of air in point P, h. The local air change index in point P indicates ideally mixed type of airflow in case the value of index is 100%.

The ACE can be calculated using tracer gas methods. A certain amount of tracer gas is added to the room air and the concentration alteration is examined. The calculation methods for the mean age of air using tracer gas methods are described in detail in international standard ISO16000-8 [117]. A thorough instruction for the calculation methods has been compiled by REHVA [116].

Chung and Hsu [119] measured ventilation efficiency with different supply diffuser positions and concluded that the position of the diffuser had a remarkable effect on the contaminant removal efficiency (CRE). The maximum difference of the CRE was 39% [119]. On the other hand, Mainz et al. [87] studied the efficiency, including ACE of room ventilation air-handling units with regenerative and recuperative HR and came to an opposite result. ACE was not affected by the position of the air-handling unit and was uniformly high – the mean value was around 60%. [87] ACE value for fully mixed ventilation is 50%. Rojas et al. [120] studied ACE in a apartment with cascade ventilation. The supply air was provided to the bedrooms, which were connected to the living room through a corridor. The ACE of the living-room was low, between 30% and 40% with that solution [120].

2 Methods

The main focus of the thesis is to identify the need to renovate the ventilation systems in different types of apartment buildings and to find out the best ventilation renovation measures for old apartment buildings. The detailed flowchart of the methods of the thesis is shown in Figure 7. The flowchart points out the contribution of the articles to the thesis and opens the main structure of the used methods.

The ACR in existing Estonian apartment buildings before the start of the renovation grants is a starting point of ventilation renovation measures and this topic is reflected in Paper I. Different types of apartment buildings were tested to study the IAQ, ACR and the actual performance of apartment ventilation systems. The problem how to measure ACRs in case of NV systems using CO_2 based tracer gas methods is analysed in Paper II. During this study on-site and laboratory measurements to analyse the possibility of using CO_2 based tracer gas methods for ACR and ACE measurements were performed. The metabolic CO_2 based tracer gas method that was tested in Paper II, was used to assess the ACR in apartments equipped with NV systems in Paper I. The results of Paper I give an answer to the question about the renovation need of old ventilation systems in apartment buildings. As the test buildings also contain buildings in which the ventilation systems have been renovated without state support grants, the paper also answer the question if the ventilation renovation can be solved on a market basis.

As the IAQ and ACR in studied old apartment buildings that were renovated without the financial support from the state did not meet the requirements (according to Paper I), new technical requirements for indoor climate and ventilation were introduced when renovating apartment buildings using the state financial support. In Paper V, the test objects of the first renovation grant were chosen and the IAQ and ACR measurements were done. The initial analysis of ACRs and indoor air CO_2 levels during the first grant scheme showed that SRVUs did not work as expected. This is the reason why the detailed study of the performance of SRVUs was done in Paper IV. In this study, the on-site pressure difference measurements between the indoor and outdoor air in apartments that were renovated using room-based ventilation renovation measures, were done. At the same time, laboratory measurements to analyse the influence of pressure difference between the indoor and outdoor air on the performance of SRVUs was also performed. To find out the realistic pressure design conditions for SRVUs dynamic computer simulations were performed. In parallel the laboratory and on-site measurements to analyse the ACE of different room-based ventilation renovation measures were demonstrated in Paper III. The methods for the analyse of the ACR using CO_2 based tracer gas methods were introduced together with the tracer gas based ACR measurement methods in paper II.

According to the performed studies and the results of the measurements of renovation grant scheme 1, the input to change the technical requirements of renovation grant 2 were suggested. The next step in Paper V was to choose the test buildings from the period of support grant 2. The IAQ and ACR in apartments was also analysed in buildings that were renovated according the technical requirements of support grant 2. Paper V analyses how the technical requirements of renovation grant 1 and 2 improved the IAQ and ACR, and which ventilation renovation measures can be used to ensure the acceptable IAQ in renovated apartment buildings. The paper also brings out the main technical solutions for the renovation of ventilation systems in old apartment buildings.

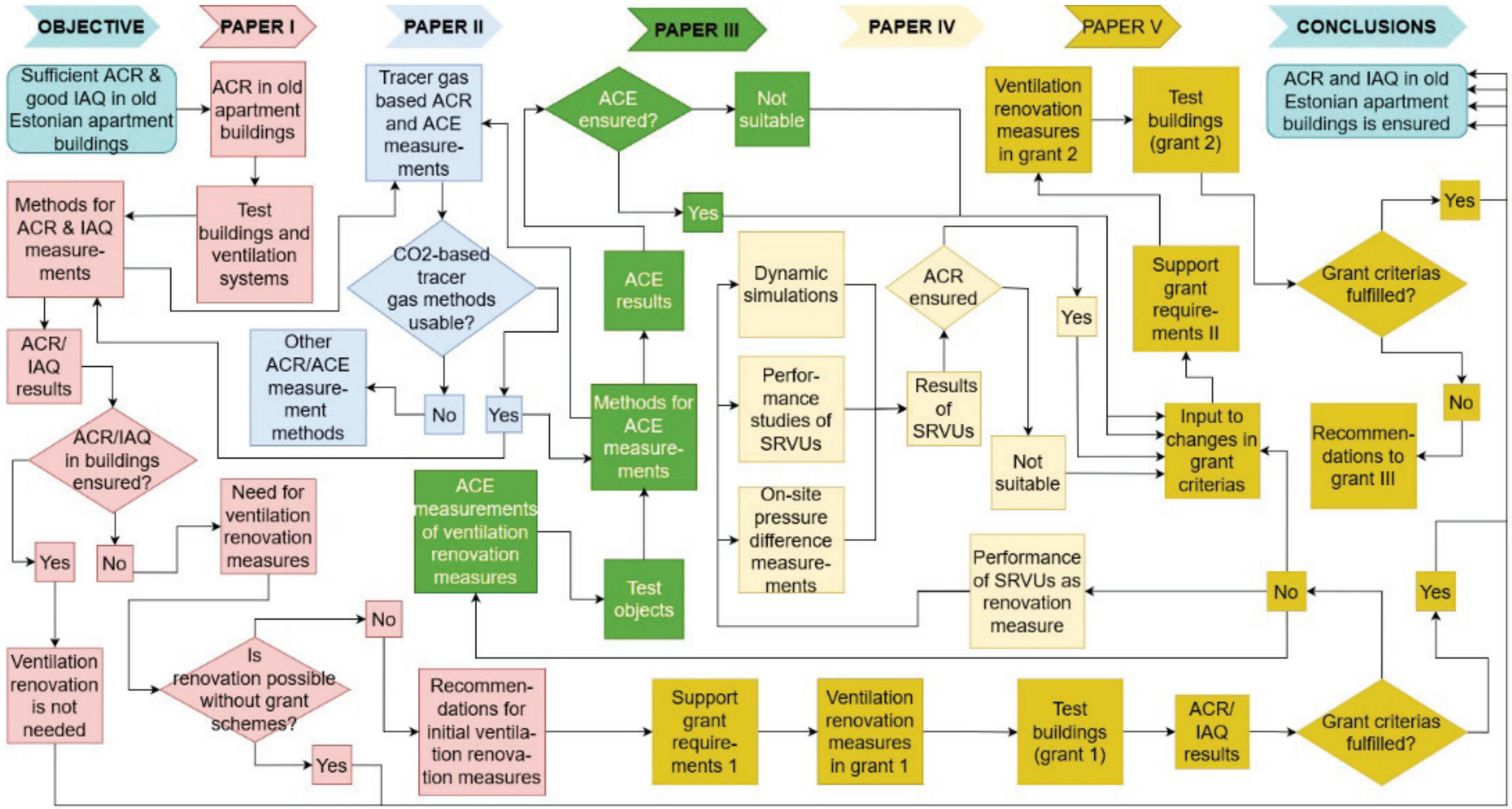

Figure 7. General flowchart of the methods of the thesis.

2.1 CO_2-based tracer gas methods for ACR and ACE measurements

To evaluate the performance of different ventilation systems using the CO_2-based tracer gas method, laboratory and field measurements were conducted. Concentration decay method was applied with both artificially and metabolically increasing the concentration of tracer gas. Tracer gas measurements were carried out in naturally ventilated apartments to study the influence of the position of the inner doors to the ACE. The flowchart of used measuring and the analysing process is indicated in Figure 8.

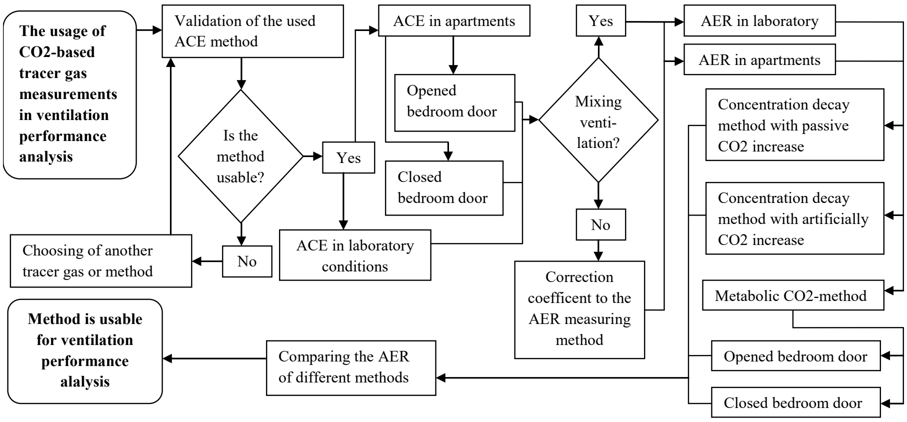

Figure 8. The flow chart of the performed studies of tracer gas methods.

2.1.1 Validation of the CO_2-based tracer gas method for ACE measurements

Concentration decay method was applied and CO_2 was used as a tracer gas. The atmospheric concentration of CO_2 was subtracted from the test values to minimize the impact on the results. Frozen carbon dioxide, also known as “dry ice” was used as a source. It was vaporized in hot water. Room air was mixed with fan to ensure uniform concentration in the room at the beginning of the experiment. People were not present in the test room during the measurement period. The concentration of CO_2 in the room was raised to 5000 ppm. The lower limit of the decay calculation was set to 1500 ppm.

Firstly, ACE was measured in Mektory ventilation laboratory using perforated overhead air diffuser with horizontal supply jet. Two different supply air temperatures were tested. To achieve the ideal mixing ventilation the mixing fan which was placed in the middle of the test room and was used to verify the used methods. The floor area of the test room was 33 m^2 and the effective volume was 90 m^3. A total of ten CO_2 sensors were placed in different positions in the test room, including one on the extract grille. The positions of the sensors are shown in Figure 9. The objective was to cover the room evenly to measure ACE in all areas of the room. Evikon E2228L CO_2 sensors (CO_2 level 0–5,000 ppm and accuracy ±50 ppm or 5% of reading) were used. The recording interval of CO_2 logger was 1 second. The ventilation airflow and pressure difference measured with Testo 435-4 measuring unit (air speed 0–20 m/s and accuracy ±0.03 + 5%; differential pressure 0–250 Pa and accuracy ±1 Pa) and Testo 410 flow hood. Supply air temperature measured with HOBO UX100-014M Type K thermocouple (temperature –20 to 70 °C and accuracy ±0.21 °C). All the measurements were conducted on the fixed airflow.

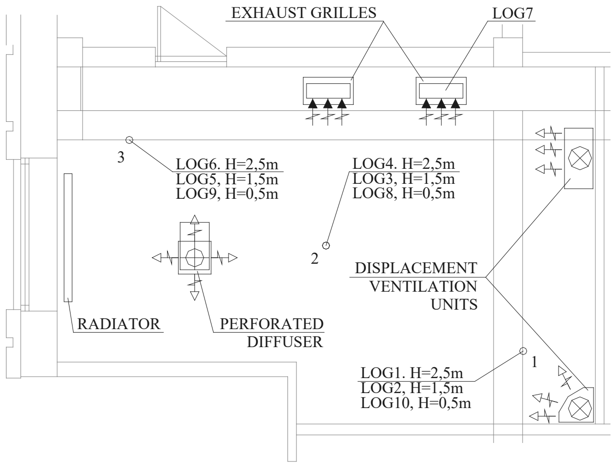

Figure 9. The position of measuring devices and air diffusers in Mektory laboratory.

2.1.2 ACE measurements in laboratory conditions and in apartment buildings

After the ACE measuring method was validated the next step of the study was to analyse the functioning of the method in apartment buildings and in laboratory equipped with the various ventilation systems. In the laboratory, the value of ACE was measured in the case of room-based pair-wise and monoblock VUs and fresh air radiator. The ventilation radiator was combined with mechanical extract ventilation. The same measurement devices were used as in the previous step. The CO_2 sensors were located at a different heights of test-room as shown in Figure 10. According to the results of the laboratory measurements, the values of ACE were calculated in case of 3 different ventilation solution. These results make it possible to compare the ventilation efficiency of these systems and also give the answer on how to use the tracer gas method to calculate the ACR values.

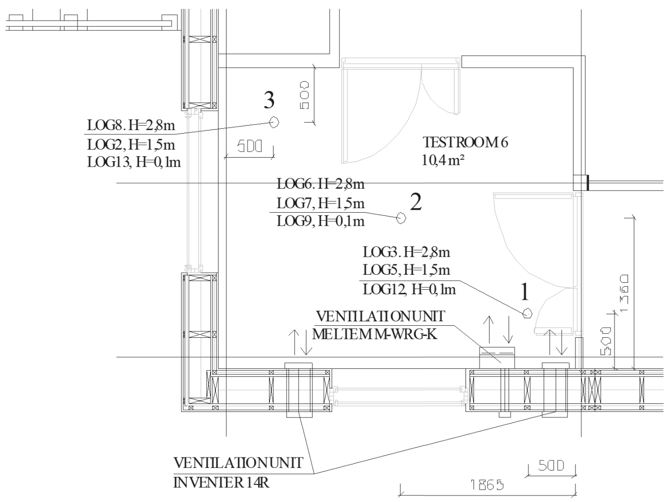

Figure 10. The position of measuring devices and ventilation units in NZEB test building.

The ACE was also determined in two apartments. The tested apartments were equipped with NV with extract grilles in bathroom, toilet and kitchen. Such buildings represent an old not renovated building stock in Estonia. The floor areas of the apartments were 43.3 m^2 and 29.1 m^2. The apartments were occupied by two and one persons, respectively. The floor plans of the apartments are shown in Figure 11.

Providing sufficient ventilation is especially important in the bedroom of the apartment because occupants spend most time in there. In the apartments where intake and extract openings are positioned in different rooms, the ACE can be significantly affected by the position of the inner doors, because pressure differences of NV are small. Therefore, tests were conducted in two different situations – with open and closed bedroom door. The doors of bathroom and toilet were closed to imitate the most common situation. CO_2 sensors were placed in each room and also on each extract grille. Nominal time constant was calculated based on the average concentration decay of the extract grilles. The logging interval of the concentration was one minute. The whole apartment was considered as one air zone. Therefore, local air change index, which describes the ventilation efficiency can be calculated for each room separately.

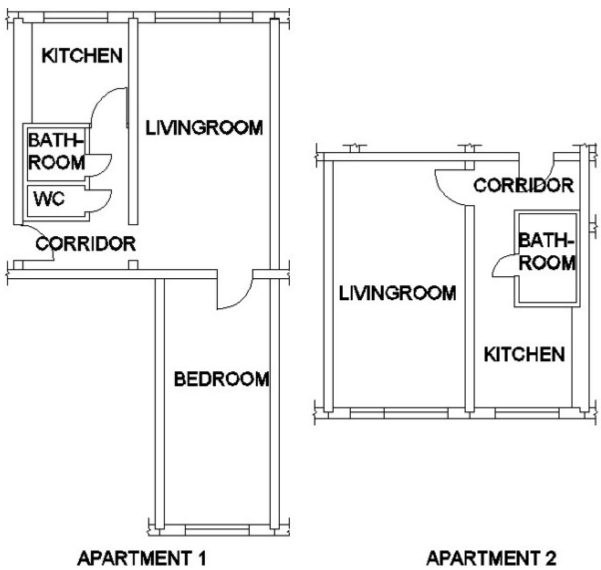

Figure 11. The layout of the studied apartments.

2.1.3 Experimental measurement of ACR in old apartment buildings

The ACRs in the studied apartments were measured with three different subdivision of tracer gas method. These methods are the concentration decay method with the occupant created CO_2, the concentration decay method with the artificially added CO_2 and metabolic CO_2 method. In the case of artificially added CO_2 method dry ice was dosed in the same way as in laboratory tests.

The CO_2 sensors were installed in bedrooms, and the measurements were done with opened and closed bedroom door. The concentration decay method with occupant generated CO_2 as the tracer gas was also used to calculate the ACR. As in case of the NV the level of CO_2 increases in sleeping period and after people have left the apartment in the morning, the airflow can be calculated according to the decay period. As the increase of the tracer gas concentration is usually lower in occupant generated case, then this method can be more inaccurate. Also, if people are present all the time then this method cannot be used as there is no decay period.

The ACR of the studied apartments was also calculated with the metabolic CO_2 method. The measurements of the CO_2 level were performed at night time when people were sleeping. The CO_2 sensors were installed in bedrooms, and the measurements were done with opened and closed bedroom door. The ACR were calculated using the least squares method. The ACR values of all three tracer gas methods were compared with each other. If the results of the measurements are different, then the methodology is corrected. To study the performance of the calculation methods in wider scale four additional apartments where the indoor air CO_2 level was previously already measured were analysed. The size of the apartments were 38–62 m^2 and there lived 1–2 occupants. The ACR in these apartments were calculated according to the concentration decay method using the occupant created CO_2 and metabolic CO_2 method. The door between bedroom and other apartment was opened all the time.

2.1.4 Measurements of ACE of room based renovation solutions in laboratory conditions

As SRVUs have been widely used to renovate the ventilation systems of old apartment buildings, the objective was to determine whether these ventilation solutions are capable of providing fresh air to all areas of the room and therefore create a mixed air flow which is recommended solution for a common apartment. All three devices were tested on two different fan speeds to verify, if the air distribution in the room was affected by the airflow rate. Fan power levels were chosen the way that the sound pressure levels in the room would be under 25 dB(A) and 30dB(A), which are maximum recommended and allowed values respectively according to Estonian regulations [121], [122]. The technical parameters of both tested SRVUs are pointed out in Table 2 and main parameters of VR are described in Table 3. To avoid the effects of the sun and other heat loads, the tests were made during stable outdoor climate conditions and cloudy periods and the curtains were in front of the windows. The area of the test rooms was 10.4 m^2 and volume 31.2 m^3 which is a similar size to the bedroom of a common apartment in Estonia.

The first examined room solution was pair-wise unit, which is a device with regenerative heat exchanger (Figure 12 top left). The unit is equipped with only one fan, which operates cyclically both as supply and exhaust, and is located on the wall of the test room. Two units, which operated in the opposite direction, were installed in the test room. The air flow was directed upward along the wall. The second unit was a monoblock VU equipped with recuperative heat exchanger and supply and exhaust air fans (Figure 12 top right). The device was placed on the wall of the test room. Supply and exhaust terminals are both located on the top of the device quite close to each other. Finally, a ventilation radiator combined with mechanical extract ventilation was tested (Figure 12 bottom). The radiator was located under the window and the extract valve in the ceiling in the middle of the room. The same ten CO_2 sensors with a similar setup were used for concentration decay measurements. The layout of the test rooms is shown in Figure 13.

Table 2. Main technical data of tested SRVUs.

Parameter/type of ventilation unit	Monoblock	Pair-wise (2 units)
Range of airflow, l/s	4.2…27.8	4.2…10.6
Type of fan	centrifugal	axial
Nominal power consumption, W	3.8…34	<6
Nominal airflow (at pressure drop 0 Pa), l/s	1. speed – 4.2 2. speed – 8.3 3. speed – 17.2	1. speed (25%) – 7.5 2. speed (50%) – 11.1 3. speed – 16.1
Type of heat exchanger	plate	regenerative ceramic comb
Heating coil	no	no
Temperature efficiency, -	1. speed – 0.76 2. speed – 0.73 3. speed – 0.71	7.5…11.1 l/s – 0.89 11.1…16.1 l/s – 0.79
SFP value, W/(m^3/h)	1. speed – 0.25 2. speed – 0.17 3. speed – 0.20	7.5…16.1 l/s – 0.11
Sound pressure level L_{PA} (A_{eq} = 10 m^2), dB(A)	19…44	14…38
Filter class (supply and extract)	2xG4	2xG3

Table 3. Main technical data of tested ventilation radiators.

Technical parameter of VR	Value
Diameter of ventilation duct inside the wall, mm	100
Filter class	G1 (possibility to install F7 and F9)
Installation high from floor, mm	20…75
Installation distance from outdoor wall, mm	20
Shut off damper	included
Total pressure drop in VR (outdoor grille+duct+filter (G1)+radiator) in different airflows, Pa	5 l/s – 3 Pa 10 l/s – 8 Pa 15 l/s – 18 Pa
Air speed in occupied zone of room, m/s	<0.15
Sound attenuation (R_w), dB	38

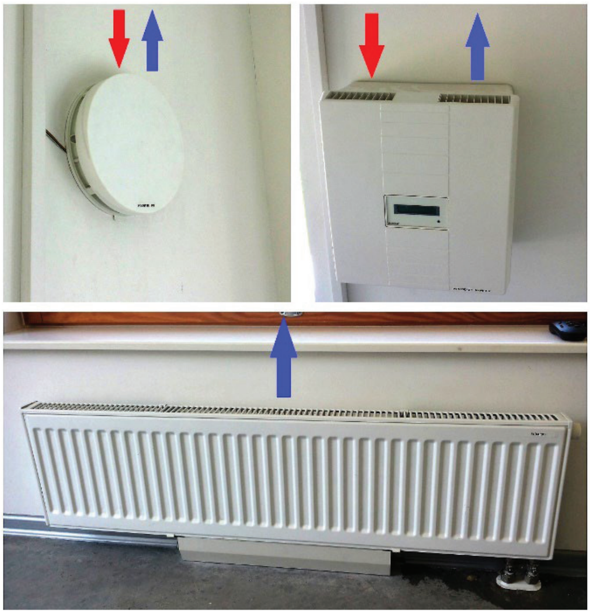

Figure 12. Tested pair-wise (top left), monoblock (top right) and ventilation radiator (bottom) units in nearly zero energy test building.

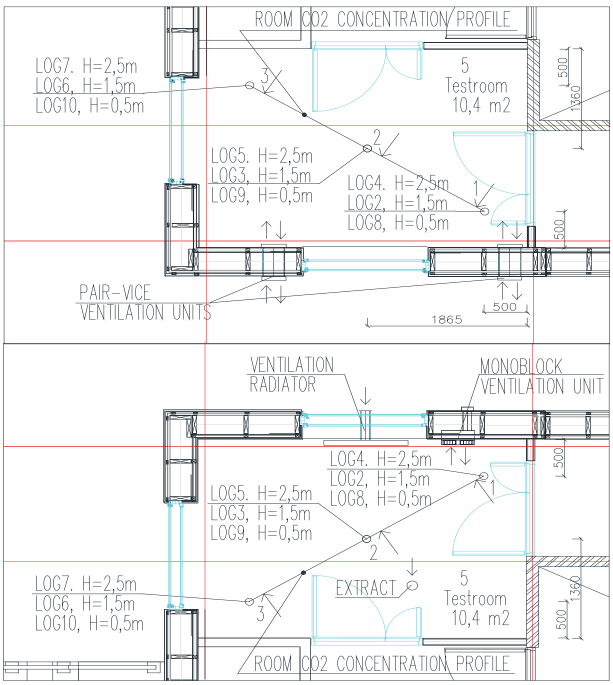

Figure 13. The setup of CO_2 sensors and air diffusers in nearly zero energy test building.

2.1.5 Calculation of ACR and ACE using CO_2-based tracer gas method

In the case of the concentration decay method, the ACR is calculated according to Equation 2. If tracer gas is released at a constant rate, the ACR is calculated according to Equation 3. In some studies, the CO_2 emissions from people are observed as the average value of 24 h period and the CO_2 emission is calculated based on the normal metabolism of the same period. In the other studies, the CO_2 emissions of sleeping period are used. As the CO_2 emission varies in wide scale in daytime, the night period when people are sleeping should be used in ACR calculations [101].

In earlier studies of the IAQ in Estonian apartment buildings, the night time emissions were used for ACR calculations with metabolic CO_2 method [8]. The CO_2 emission of adults is 13 l/h and the emission of children up to 12 years 6.5 l/h. At the same time, various studies have pointed out that the emission of CO_2 can vary in large scales. In this study, the least squares method as an alternative possibility is used. The main idea of the least squares method is to find the values of airflow, CO_2 emission to the room and effective volume of the zone in a way that the cure of real CO_2 measurements would be as close as possible to the theoretical curve of the CO_2 variation. The curve fitting process is done by using "Solver" function in Microsoft Excel. In the case of the real CO_2 measurements in apartments, optimising the value of the effective volume of the zone should also be considered.

The nominal time constant of the room and in the extract air is calculated using Equation 4. The mean age of air is calculated according to the method of international standard ISO-16000-8 [117] using Equation 5. ACE is calculated using Equation 6. A local air change index is used to measure the ACE in a certain room point and calculated according Equation 7.

2.2 IAQ and ACR measurements in Estonian apartment buildings

The cross-sectional study about the performance of ventilation was carried out in 167 apartments in 107 different types of apartment buildings. Wooden apartment buildings (45 apartments in 29 buildings) built before 1940 and concrete apartment and brick buildings built between 1955 and 1990 (83 apartments in 54 buildings), had NV. Different structure apartment buildings built after 2000 (39 apartments in 24 buildings) had mechanical ventilation. From each building, one to three apartments were selected for the indoor climate study. Typically an apartment was selected from one of the upper floors and the ground floor. Apartments consisted of one, two or three rooms, with a separate kitchen, entry, and sanitary rooms.

Extract airflows were measured with an anemometer. Indoor air CO_2 concentrations were measured with HOBO U12-013 together with TelAire 7001 CO_2 loggers. ACR in bedrooms was determined based on the measurement of the dynamics and level of CO_2 produced by the occupants at 10 min intervals during 2–3 week periods during winter and summer. Based on measurements of indoor CO_2 levels in bedrooms, the ACR in bedrooms was estimated according to metabolic CO_2-based tracer gas method. In order to establish the boundary conditions of the metabolic CO_2-based tracer gas method the laboratory validation of the method was performed. CO_2-based tracer gas method for air change calculations in apartments is described in detail in chapter 2.1. As the CO_2 emission varies on a wide scale in daytime, the night period when people are sleeping should be used in ACR calculations. CO_2 emission of adults is taken 13 l/h and the emission of children up to 12 years 6.5 l/h.

For assessment criteria we used EN-15251 [31] indoor climate category (ICC) III (acceptable, moderate level of expectation, for old buildings) for old (<1990) buildings (1750 ppm) and ICC II (normal level of expectation, for new buildings and major renovations) for new (>2000) buildings (1200 ppm). The measurement results of CO_2 level are brought out for occupancy time only. The average human presence in apartments during the heating period was 68% and 55% in summer period. Because the occupancy time was not measured directly, a special algorithm was developed to select only the period when residents were at home and windows were not opened. The algorithm included ACR and apartment volume information, and it identified the moments when the CO_2 level decreased faster than would be normal if there was one sleeping person in an apartment. For calculating the normal decrease of the CO_2 level, the instantaneous CO_2 value was compared with the average CO_2 value of the last 50 min. In addition, CO_2 measurements close to ambient air levels were excluded from the occupancy period.

2.3 Studies of ventilation renovation solutions in old apartment buildings

The performance of ventilation was studied using field measurements. A detailed flowchart of the methods of the study is presented in Figure 14. The ACR in existing Estonian apartment buildings before renovation grants is the starting point for ventilation renovation measures. The activities in steps 1 and 2 outlined in the flowchart have been performed in Paper I. Because the ACR during the old renovation measures did not fulfil the requirements, new technical requirements for indoor climate and ventilation were introduced for renovating apartment buildings using state financial support. In Figure 14, the first renovation grant scheme is outlined in Step 3, and the second scheme is outlined in Step 4. The main focus of this study is to determine how the technical requirements of the first and second renovation grants improved IAQ and the ACR.

In response to the first and second support grants, 21 buildings and 15 buildings were analysed, respectively. All renovated buildings had NV systems before renovation. The studied buildings were built between 1953 and 1986. The net heated area for buildings varied between 550 m^2 and 5030 m^2, and the number of apartments varied between 12 and 72. The average number of apartments in one building was 27, and the average heated area was 1757 m^2. In four buildings, the performance of NV was improved by cleaning the old NV shafts, and in six buildings, the performance of NV was increased by adding fresh air intakes. In 10 buildings, HRV systems were installed; in eight buildings, EAHP systems were installed; in three buildings, ME without HR was installed; and in five buildings, SRVUs were installed.

Ventilation renovation measures in the first grant scheme did not perform effectively, and the requirements of the grant scheme were not fulfilled. This failure initiated the development of new requirements to improve the situation. Because some ventilation renovation measures in the first grant scheme did not ensure adequate indoor climate parameters, these solutions were excluded from the second grant scheme. New recommendations to improve the technical conditions of the ventilation renovation measures were made according to the airflow and supply air temperature measurement results of the second grant scheme. The new inputs to the grant scheme developed in this study are shown in flowchart Step 5. In the conclusion, suitable ventilation renovation measures and the main technical principles of these measures are discussed.

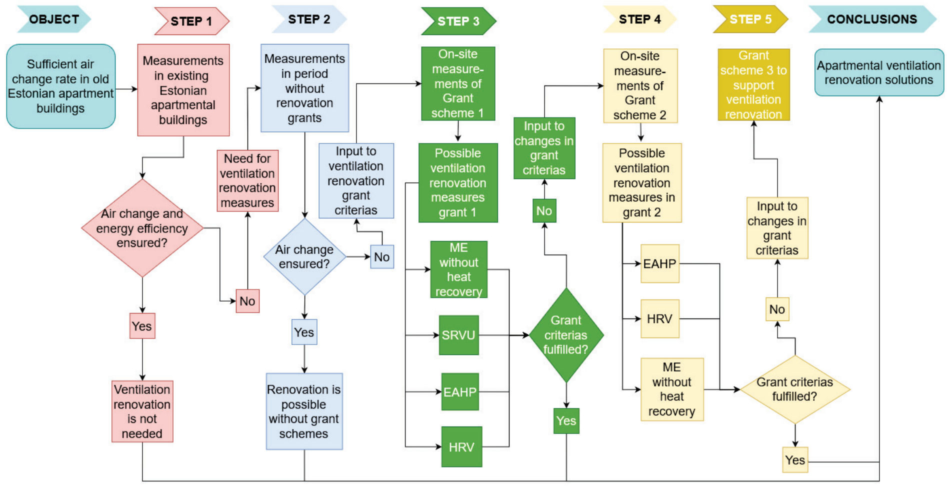

Figure 14. General flowchart of the methods of the ventilation renovation measures.

2.3.1 The requirements for the renovation in apartment buildings according to the Estonian grant schemes

There were three renovation grant support levels for construction work (15%, 25%, and 35%) for the first grant scheme and two basic levels (25% and 40%) for the second grant scheme (Table 4).These levels are based on the designed energy performance level achieved after renovation work has been completed. In Estonia, energy performance levels in buildings are expressed using primary energy (PE). The PE requirement accounts for the energy used for space heating, ventilation, domestic hot water, appliances, and lighting, with the national primary energy factors of energy carriers.

There were no specific requirements for ventilation and indoor climate in the first support grant. After the renovation, the indoor climate had to fulfil the EN-15251 ICC II requirements (this standard has been updated with minor changes to EN 16798-1:2019). The heating system has two requirements: the system must be hydraulically balanced, and radiators must be equipped with thermostats to allow room-based indoor temperature control. Typical ventilation renovation measures were fresh air intakes for NV, SRVU, ME without HR, EAHP, and HRV.

According to the ACR measurement results in the buildings renovated during the first grant scheme, specific requirements were added to the requirements of second support grant. These requirements included room-based airflow rates, mandatory airflow measurement report, third party inspection for design documentation, preheating the intake air and specific airflow calculation rules. Typical ventilation renovation measures were ventilation radiators (VR) with EAHP, HRV with ductwork installation on the façade, and ME without HR (only for the 25% grant level).

Table 4. Overview of the financial support and requirements on energy performance of renovating Estonian apartment buildings using the state support.

Period	Financial support	Requirements for energy performance
2010 – 2014 first grant	Support at 15%, 25% or 35% depending on the renovation solution	15% support: heating energy reduction ≥20% (<2000 m²) and ≥30% (>2000 m²), PE ≤ 250 (kWh/m²)/year; 25% support: heating energy reduction ≥40%, PE ≤200 (kWh/m²)/year; 35% support: heating energy reduction ≥50%, PE ≤150 (kWh/m²)/year.
2014 – 2018 second grant	Support at 25% or 40% depending on the renovation solution	25% support: PE ≤180 (kWh/m²)/year; 40% support: PE[1] ≤150 (kWh/m²)/year.

[1]Estonian PE values include appliances and lighting which contribution is 59 kWh/m²/year, therefore PE requirement for EPBD uses is 91 kWh/m²/year.

2.3.2 IAQ and ACR measurements methods for renovated apartment ventilation systems

In the case of the first grant scheme, the indoor air CO_2 levels and airflow were measured in 21 renovated apartment buildings. Three to four apartments were studied in each building (a total of 83 apartments), and the measurement period was one year. During the second grant scheme, 15 renovated apartment buildings were selected. In each building 2 to 4 apartments were studied, and the measurement period was four months (a total of 42 apartments). The same measurement methodology was used in both grant schemes. The indoor air temperature, relative humidity of indoor air, and the level of CO_2 were measured using an Evikon E6226 measurement unit (temperature –10 – +50 °C; relative humidity 0–100%; CO_2 level 0–10,000 ppm and accuracy ±50 ppm or 5% of reading). All measurement units were located in the bedrooms. To measure the airflow, we used a multifunction IAQ metre Testo 435-4 with a hood Testo 410 (air speed 0–20 m/s and accuracy ±0.03 + 5%; differential pressure 0–250 Pa and accuracy ±1 Pa). Airflow in the supply and extract valves was calculated according to the differential pressure measurements in the valves. Airflow was measured twice during the installation and removal of the sensors. In the case of SRVU and NV, the ventilation airflows were measured using the measuring hood Testo 410. All airflow measurements in apartments were collected in the mode of operation of the ventilation system that was used daily in the building.

For assessment of CO_2 levels, the ICC II (1200 ppm) of the standard EVS-EN 16798-1:2019 [32] was used. The measurement results of the CO_2 level are reported for occupancy time only. The allowed exceeding time of the CO_2 level according to the standard in CEN/TR 16798-2:2019 [123] is 6% of the measuring time. Because the occupancy time was not measured directly, a special algorithm was developed which is described in chapter 2.2.

ACR in apartments was assessed using the requirements of the second support grant. Thus, the continuous ACR in apartments must be at least 0.5 h^{-1}, and the supply and extract airflows must be calculated according to the requirements listed in Table 14. One of the requirements for applying the support grant during the second grant scheme was the mandatory airflow measurement report according to the methodology of the standard in EVS-EN 12599:2012 [112]. The airflow measurement report was available for all the studied buildings, and during the study, the reports were examined. According to the measurement reports, airflow in the measured valves conformed to the designed values. During the apartment visits, the positions of the valves were recorded and compared with the values in the airflow measurement reports.

To study the influence of frost formation inside the plate HEX of air handling units (AHUs), the supply air temperature, extract air temperature, outdoor temperature, and temperature after the HEX on the supply side were measured. For measuring the temperatures, Onset Hobo UX100-014M, U12-006, and U12-013 data loggers together with K-type thermocouple probes (air temperature 0–1250 °C, accuracy ±0.75%) were used. The supply air temperature was measured only during the second grant scheme.

2.4 Description of ventilation renovation solutions used in studied buildings

Five types of ventilation systems have been installed during the renovation of Estonian apartment buildings:

- centralized balanced ventilation with ventilation HR (HRV);
- mechanical exhaust ventilation with heat pump HR (EAHP);
- mechanical exhaust ventilation without HR (ME);
- renovating the old natural ventilation systems (without HR) (NV);
- single room ventilation units with ventilation HR (SRVU); used in 2010–2014.

2.4.1 HRV ventilation renovation measure

The most widely used ventilation renovation solution for old apartment buildings is HRV with ductwork installation on the façade (60% in the second grant period). The ventilation unit of this system is installed on the roof or in the attic. Flat-or round-shaped supply ducts are installed inside the additional insulation of the external walls and roof (Figure 15 and Figure 16). Old ventilation shafts are used to extract air from apartments. Because the air tightness of old ventilation shafts is often low, new ventilation ducts should always be installed inside old shafts. Occasionally, an air ductwork is installed on the façade in a similar fashion to that of the supply air ductwork. The supply air is ducted to the living rooms, and the bedrooms and extracts are in toilets, bathrooms, and kitchens. Installing ventilation ducts inside the additional insulation layer helps avoid visible ducts inside the apartments. The supply air diffusers were installed on the external wall of the living room and bedroom, and the extract air valves were placed on the wall near ventilation shafts. The volume of ventilation work inside the apartment is minimal and does not disturb individuals much. Ventilation ducts on the roof should be installed inside the insulation layer of the roof or covered with a separate insulation layer. In ensuring high HR efficiency and avoid the spread of odours, the counter-flow plate HEX is commonly used. According to the EVS-EN 16798-3:2019 [32], the supply side of the unit should be equipped with the ePM1 60% (F7) and exhaust side with ePM10 60% (M5) filters. According to requirements of the support grant, a water-based heating coil should be used to reheat the supply air. The detailed working principle of the HRV with ductwork installation on the façade is shown in Figure 15, Figure 16 and Figure 17.

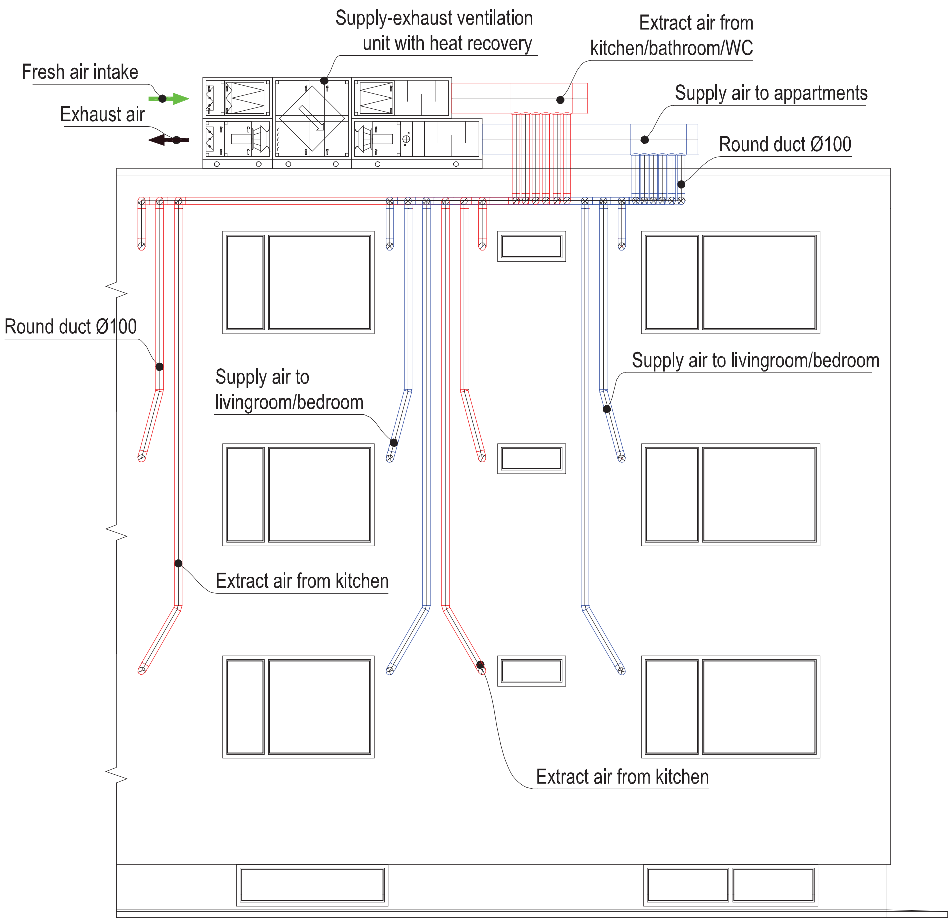

Figure 15 . Section of ventilation ducts inside the building facade.

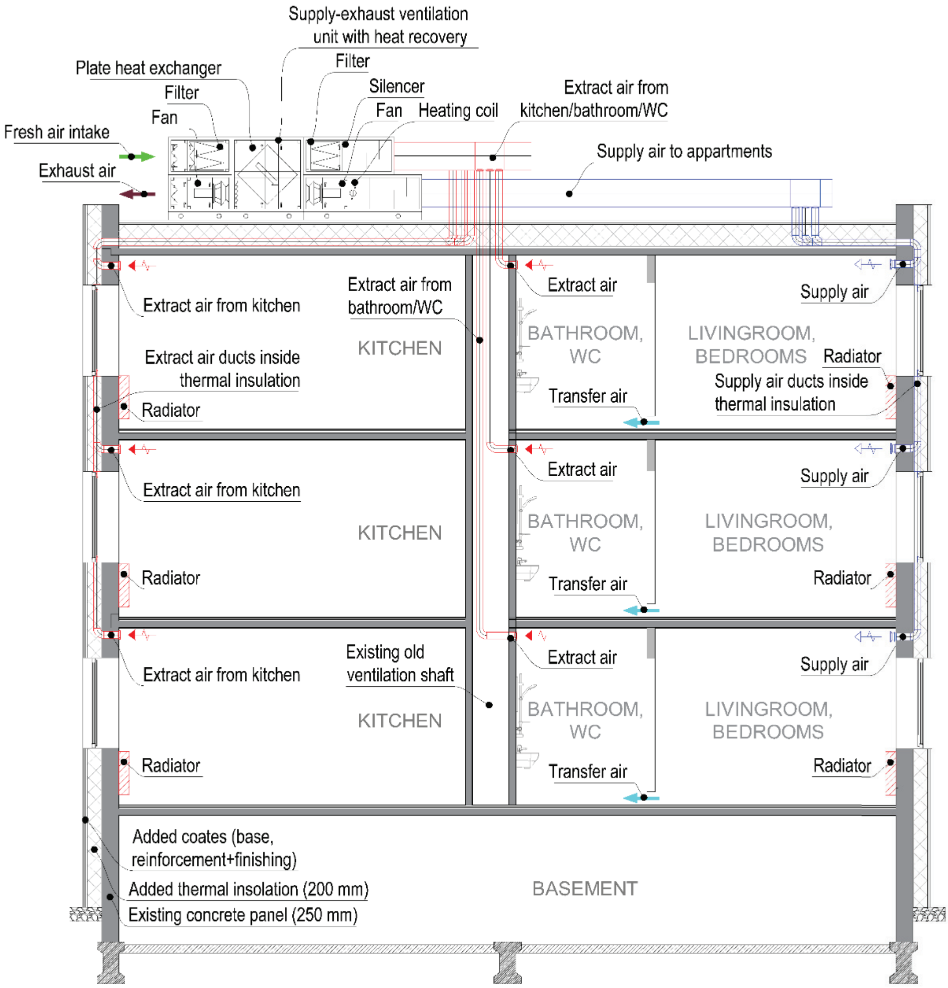

Figure 16. Working principle of HRV renovation measure.

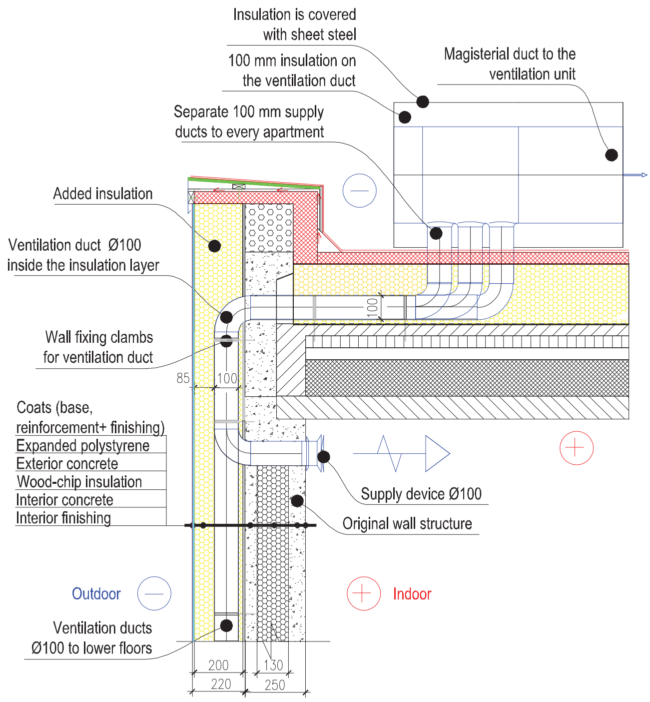

Figure 17. Ventilation ducts inside the wall and on the roof.

2.4.2 EAHP ventilation renovation

The EAHP system with VRs has also been actively used (35% in second grant period) in apartment building renovation. During the first grant period, fresh air inlets were used to supply air, but due to many negative reports on cold draughts, the requirement to preheat the supply air was added under the conditions of the second grant. VRs are used to preheat air. Outdoor air enters through the VRs, where it is filtered (typically ePM1 60% (F7) filters) and heated. Exhaust air moves through ventilation shafts to the air to water HEX of the VU, where the heat is transferred through a brine loop to a water-water heat pump. The heat pump provides heat to the domestic hot water and space heating system. The seasonal coefficient of performance is 3.0–3.5 [54], [67], [124]. The main problem of this renovation solution is using old NV shafts without inserting new ducts inside old shafts. The airtightness of old shafts is too low; therefore, ventilation systems are often unbalanced and noisy. This implies that airflow rates are reduced. The main principle of the EAHP system is illustrated in Figure 18.

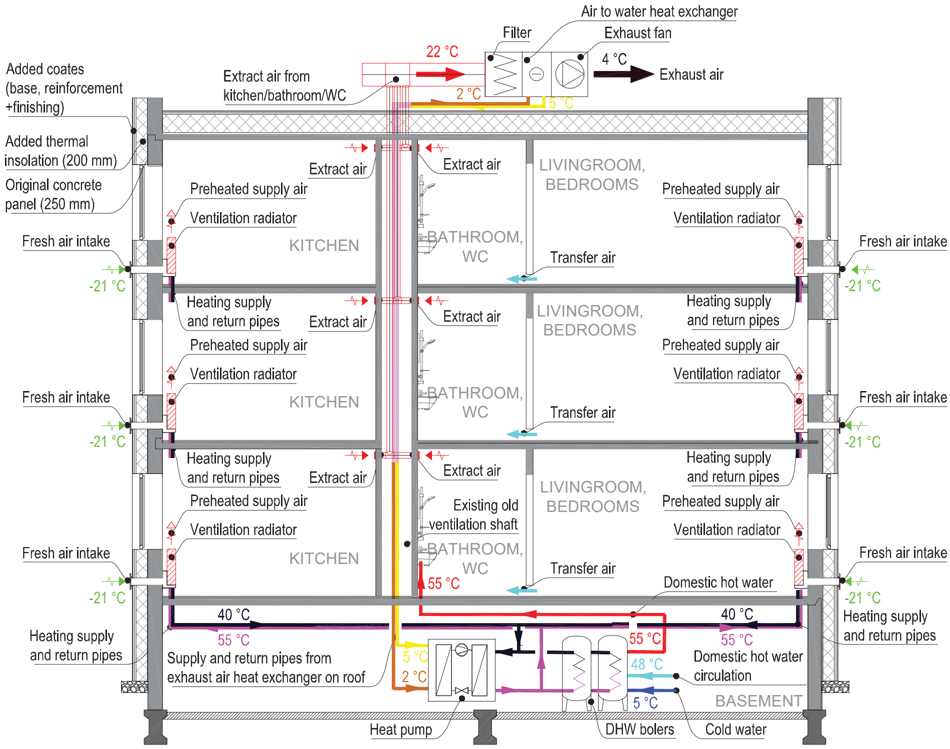

Figure 18. Ventilation radiators with exhaust heat pump HR.

2.4.3 SRVU ventilation renovation measure

SRVUs with HR (Figure 19) has also been used for ventilation renovation during the first grant period (40% in the first grant period), mainly SRVUs with regenerative ceramic HEXs. Single-fan-based units work in cycles, switching between the supply and exhaust modes every 60–70 seconds. During the exhaust cycle, the heat from the warm exhaust air accumulates in the ceramic comb-like HEX and is then used to heat the cold outdoor air during the supply cycle. These units were equipped typically with G3 type of coarse filters. Field measurements have shown that this system does not ensure sufficient ACR and efficient HR [83], [122], [125], [126]. The main problem is related to the large negative pressure due to the stack effect in the lower-floor apartments. Fans used in SRVUs are not capable of working under typical pressure conditions in multi-story buildings in cold periods [8], [122]. Because the results of using SRVUs as a ventilation renovation measure were unsatisfactory, this solution was not accepted for use in implementing the second grant scheme which detailed technical conditions made it impossible to use this system.

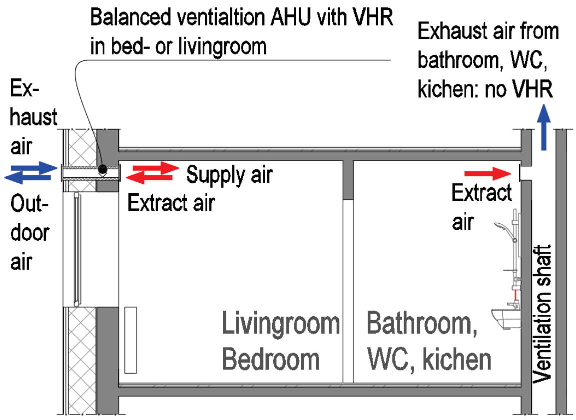

Figure 19. SRVU with HR (2010–2014) banned since 2015.

2.4.4 Other ventilation renovation measures

Apartment-based HRV has also been used. The ventilation unit of this system is installed in staircases, corridors, or sanitary rooms, under the ceiling or on the wall. A plate or rotary HEX was used for HR. These units have adequate filters, ePM1 60% (F7) on the supply side and ePM10 60% (M5) filters in extract air following the requirements of the EVS-EN 16798-3:2019 [32]. Air is extracted from kitchen hoods, toilets and bathrooms. Supply air devices are installed in living rooms and bedrooms. Since installing this system to an apartment requires space and construction work in the apartment, it was used very rarely (~1%).

2.5 Laboratory and field measurements to analyse the performance of SRVUs

The performance of the exterior wall mounted SRVUs with regenerative and recuperative HEX were studied. Firstly, the on-site measurements were made in a renovated five-story apartment building. In the next step, the measurements of units with regenerative HEX and recuperative HEX were performed in laboratory conditions. The results of field and laboratory measurements were used to compile a simulation model of the studied renovated apartment building with regenerative ventilation units. The next step was to calibrate the simulation model according to the measured indoor- and outdoor pressure differences, indoor temperatures, airflows, and outdoor climate data. Then the simulations of indoor and outdoor pressure differences, fan performance curves and HR were performed. Lastly, the simulation and measurement results of room-based AHUs were analysed and the conclusions on the performance of SRVUs in apartment buildings were outlined. The flow chart of the main methods of the study is described in Figure 20.

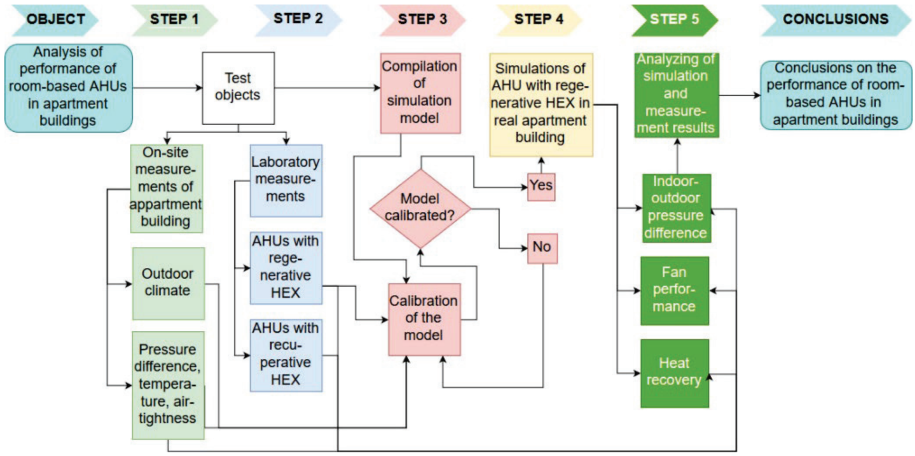

Figure 20. The flow chart of the performed studies of SRVUs.

2.5.1 Studied buildings

The pressure differences between the indoor and outdoor air across the exterior wall were measured during a 3-month period of the heating season in renovated 5-story apartment building. The fan performance and the temperature efficiency of room-based VU with regenerative and recuperative HEX were studied in technological facility of Tallinn University of Technology.

The studied building was a typical precast large concrete panel 5-story apartment building located in an urban area built in 1975 with 30 apartments, 2 staircases and a full cellar. The building is connected on both sides with two buildings of the same type. The height of stories is 2.7 m and the height of rooms is 2.5 m. The building is heated with water radiators by district heating. The cross-section of the studied building is shown in Figure 21.

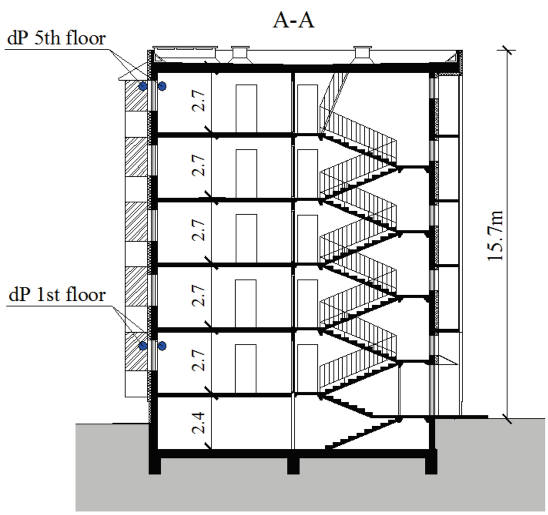

Figure 21. Cross-section with pressure difference measurement point locations of the studied building.

The building was renovated in the years 2003 and 2012: the exterior walls, roof, and balconies were insulated, the windows were replaced; and the heating system was reconstructed. The thermal transmittances of the envelope before and after the retrofitting are presented in the Table 5. For ventilation, wall mounted regenerative HEX ventilation units were installed in the bedrooms and living rooms, in the bathrooms and kitchens natural exhaust ventilation was used (Figure 22). The diameter of the ventilation shafts with round cross-sections is 140 mm and height varies between 0.7 m and 12.6 m, depending on the story. All the units with regenerative HEX were controlled from the control centre. It means that all the units worked in the same speed and in the same working cycle.

Table 5. Thermal transmittances of the envelope before and after retrofitting.

Part of the Thermal Envelope	Thermal Transmittance, W/(m^2·K)	
	Before	After
External walls	1.05	0.22
Roof	0.45	0.15
Doors	2.0	1.2
Windows	2.9	1.4

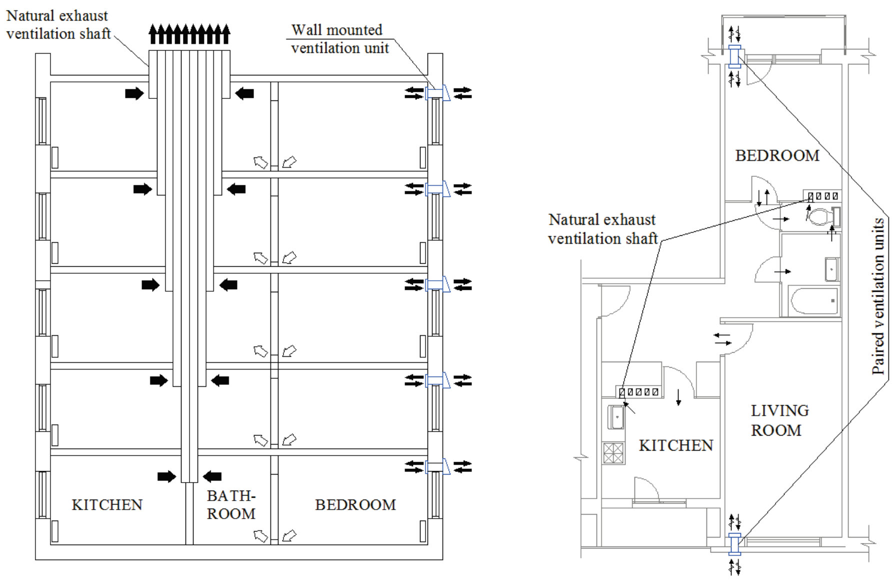

Figure 22. Principle solution of the ventilation system with room-based units: cross-section (left) and floor plan of a typical apartment (right).

2.5.2 Field measurements

Pressure differences between the indoor and outdoor air across the exterior wall were measured during a 3-month period of the heating season (December 2013–February 2014) in 4 apartments located on different floors. Measurements were taken at the height of 2 m from the floor level. For the outdoor pressure component, a plastic tube of 4 mm in diameter was planted through the window seal with one end connected to the pressure transducer. Diaphragm-type pressure transducers were used: Dwyer Magnesense

MS-221 and Onset T-VER-PXU-L both with the measuring range of –50 to +50 Pa (output 0–10 VDC) and accuracy of 1% full scale output. Readings were taken in every 1 min and an average of the readings was saved with a 10 min interval using Onset Hobo U12 and Squirrel Q2010 data loggers. For environment measurements and data logging Hobo U12 devices were used with the temperature measuring range of –20 to +70 °C with accuracy ±0.35 °C and relative humidity 5% to 95% with accuracy ±2.5% of full-scale output.

2.5.3 Laboratory measurements

In the laboratory-controlled environment, performance and efficiency of two types of SRVUs were studied. The core elements of the first unit are cross-flow plate HEX, centrifugal fan, supply and exhaust filters, transfer ducts and outdoor hoods (Figure 23 left). The second unit has a ceramic HEX, axial fan, mounting tube, outdoor hood, inner cover and air filter (Figure 23 right). The first device is a constant flow ventilation unit compared to the latter, which works in cycles, switching with 70-s intervals between the supply and exhaust mode. During the exhaust cycle, heat from the warm exhaust air is accumulated in the ceramic comb and is then used to heat up the cold outdoor air during the supply cycle. Both devices are installed without the heating coil.

The setup of the experiment of recuperative units is shown in Figure 23 left and the setup of the regenerative HEX is shown in Figure 23 right. In the case of the unit with regenerative HEX, the temperature sensor was placed in the center of the airflow behind the air distributor. To measure the room and exhaust air temperature, another temperature sensor was placed to the top of the room 0.3 m away from the ventilation unit. The outdoor air temperature was measured close to the fresh air grille. The measuring cone was placed over the inner cap of the unit and the air speed was measured inside the cone. To measure the outside pressure, the pressure sensor was installed outside through the window. The inside and outside pressure were both measured at a height of two meters. In case of unit with recuperative HEX, the temperature sensors were installed on the top of the unit inside the supply and exhaust airflow. The airflow, fresh air temperature, and pressure difference were measured in the same way as described in case of unit with regenerative HEX.

During the experiments, the pressure difference between the indoor and outdoor air, outdoor temperature, supply/exhaust air temperature and air speed inside the measuring cone were measured and logged in every second. The same temperature and pressure sensors and loggers were used as in field measurements. The measured air speed was used to calculate the volumetric air flow through the unit. Airflow measurements were carried out using Testo 435-4 measuring instrument/data logger with hot-wire anemometry probe (measuring range from 0 to 20 m/s, with accuracy 0.01 m/s and +4% of reading). The pressure conditions in the test room were achieved using a central air handling unit and by adjusting the supply/exhaust valves of the ventilation system.

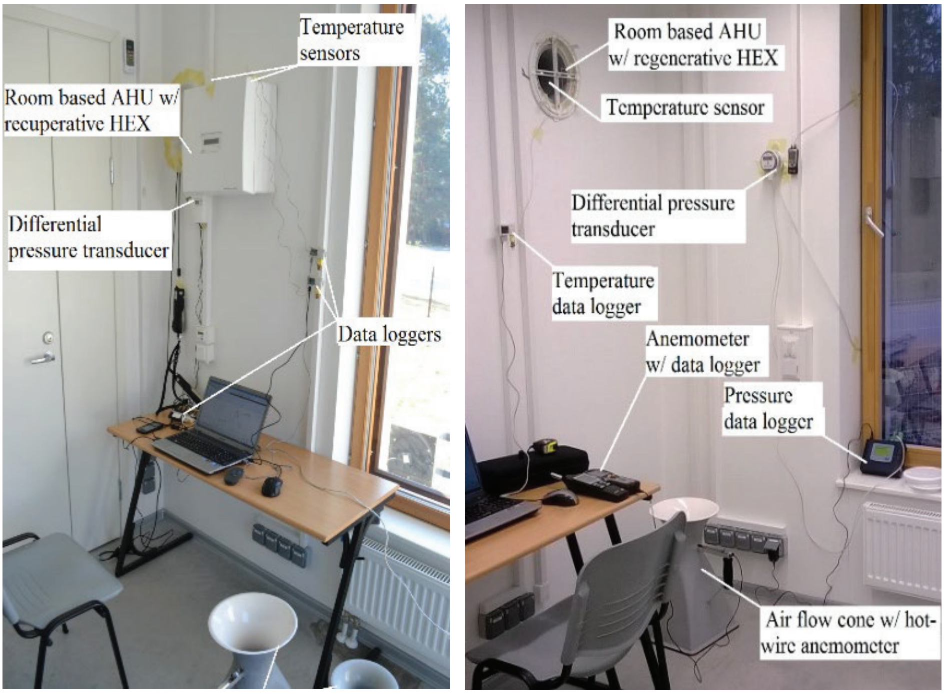

Figure 23. Experimental setup with the studied room-based ventilation units: with recuperative HEX (left) and regenerative HEX (right).

2.5.4 Temperature efficiency of SRVUs

The temperature efficiency was used to quantify the effect of HR of the studied ventilation system. As the main purpose of the study was to evaluate the performance of the room-based ventilation units, then the temperature ratio (efficiency) η_{temp} is defined as

$$\eta_{temp} = \frac{\overline{t_{sup}} - t_{out}}{t_{exh} - t_{out}}, \tag{8}$$

where t_{out} is the outdoor air temperature and t_{exh} is the extract air temperature [87], [88]. The time-averaged value of the supply air temperature of ventilation units with the regenerative HEX, has to be used and it is given by

$$\overline{t_{sup}} = \frac{1}{\tau} \int_{t=0}^{t=\tau} t_{sup}(t) \cdot dt, \tag{9}$$

where t is the time and τ is the semi-period, which means the duration of the supply or extract process [87]. In the case of the recuperative HEX, the process is in a steady state [87], [88]

$$t_{sup}(t) = \text{const.} \tag{10}$$

2.5.5 Description of simulation model of SRVUs

A model of the building was created and simulated using IDA Indoor Climate and Energy (IDA ICE) software version 4.6 developed by Equa Simulation AB. Each room of the composed building model is the separate zone. As there is a common NV exhaust channel for the bathroom and toilet, these rooms were composed as one zone. The building model was calibrated using the measured data from field studies. A custom climate file with hourly wind data, outdoor temperature and relative humidity of the measurement period from the local weather station located ~1 km from the site was used for the validation process.

For a whole-year simulation, weather data from Estonian Test Reference Year (TRY) were used. The TRY is constructed using selected months from a number of calendar years, and may be used for many applications, such as indoor climate and energy simulations, HVAC system performance, or simulation of active or passive solar energy systems [127]. The air tightness of the building was defined with air leakage rate per envelope area at 50 Pa of pressure difference (q_{50}). A value of 3.0 $m^3/(h \cdot m^2)$ was used in the calibration process, as also achievable with the renovation of building envelope for pre-fabricated large-panel buildings [49].

The VUs were inserted according to the standard renovation solution that means 1 pair-wise ventilation system, which consist of 2 separate units, was added in every living room and bedroom. The NV system was not renovated and it continued to work as before. To modulate the NV system, the "chimney" component was used. Chimney takes into account the height and length of ventilation channels but also friction and minor pressure losses. Chimney elements were added to the kitchens and toilets or bathrooms. Two chimney components were added per each apartment. The airflows of natural exhaust systems were measured using hot wire anemometer with a cone. During the airflow measurements, the specific indoor and outdoor parameters were also measured and for the model calibration average values of airflow measurements were used.

The studied VU with regenerative HEX was modelled using IDA ICE advanced modelling interface. The exterior wall leak module was used to calculate the differential pressure across the building exterior wall, which was used as an input for supply and exhaust airflow control accordingly to the laboratory measurements results. The main principles of the model are described in Figure 24. The pressure-airflow dependencies were inserted to the linear segment controller and connected to the respective air terminal. To model SRVUs, some simplifications were made. Firstly, the standard ventilation unit macro was used and the control signal to the HEX was removed. The working cycle of the unit is 60 seconds in supply mode and after that the unit is turned off and the pairing device is switched on for 60 seconds in exhaust mode. Switching the units between supply and exhaust mode is achieved using the "gain" component. Regulating the supply and exhaust airflow was performed according to the differential pressure variable (DPA_S) of the exterior wall in "leak" component.

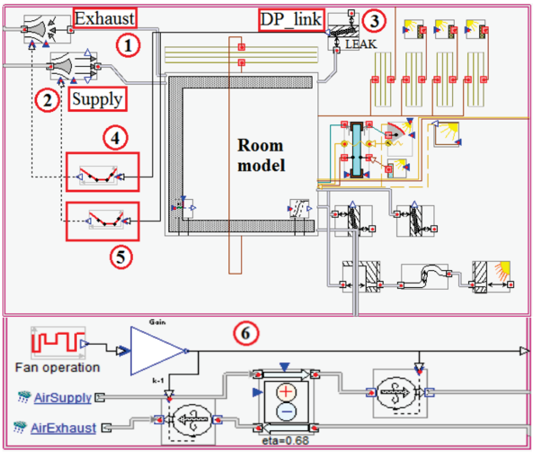

Figure 24. Schematics of the studied ventilation units modelling in IDA Indoor Climate and Energy (IDA ICE): (1) exhaust air terminal; (2) supply air terminal; (3) exterior wall leak module; (6) ventilation unit module; (4) and (5) linear segment controllers.

2.5.6 Air Pressure Calculations

The simulation model was calibrated according to the outdoor climate, indoor temperature, ACR and air tightness measurements. During the calibration, the values of measured pressure difference were compared to the simulated data. The wind pressure distribution around the house is composed in a way the wind flow is horizontal and an atmospheric boundary layer is neutral without vertical airflow [80]. The static wind pressure p_{wind} (Pa) outside the building facades is given by equation

$$p_{wind} = C_p \cdot \rho_a \cdot U^2/2, \quad (11)$$

where C_p (dimensionless) is the pressure coefficient, ρ_a is the air density (kg/m^3) and U (m/s) is the local wind velocity [80], [128].

Pressure coefficients are empirically derived parameters determined either experimentally in a wind tunnel [129], [130] or numerically using computational fluid dynamics [131], [132]. In the studied building model the wind-induced pressure conditions were simulated using constant wind-pressure coefficients defined at 45° intervals of a wind direction. Approximate values of wind pressure coefficients were used on external boundaries based on the exposure of the building. The pre-coded values of the “semi-exposed” option founded to be accurate enough (Table 6).

Table 6. Facade average wind pressure coefficients used in the building simulation.

Facade	Orientation	Wind Angle (°)							
		0	45	90	135	180	225	270	315
Exterior wall	NE	0.4	0.2	−0.6	−0.5	−0.3	−0.5	−0.6	0.2
Exterior wall	SE	0.25	0.06	−0.35	−0.6	−0.5	−0.6	−0.35	0.06
Exterior wall	SW	0.4	0.2	−0.6	−0.5	−0.3	−0.5	−0.6	0.2
Exterior wall	NW	0.4	0.2	−0.6	−0.5	−0.3	−0.5	−0.6	0.2
Roof		−0.8	−0.8	−0.8	−0.8	−0.8	−0.8	−0.8	−0.8

The local wind velocity is calculated according to the simplified method for combining weather information with air tightness to calculate residential air infiltration (LBL method) recommended by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [128]. The local wind velocity U(h) (m/s) is calculated by the equation

$$U(h) = U_m \cdot k \cdot (h/h_m)^a, \quad (12)$$

where U_m (m/s) is the measured wind speed at the weather station (at a height of 10 m), h (m) the height from the surface of the ground, h_m (m) the height of the measurement equipment and constants k and a are the terrain coefficients. For the terrain coefficients k and a ASHRAE [128] recommended values for suburban terrain of 0.67 and 0.25 respectively were used. The LBL method, that is used in simulation model, has been proposed by Sherman and Grimsrud [133] and Modera et al. [134]. Modera et al. [134] have pointed out the typical values of terrain parameters for the standard terrain classes. The IV class is described as urban, industrial or forest areas and fitted best with the conditions of tested the apartment building. Sherman and Grimsrud [133] have pointed out that this method can also be used when the wind speed was not measured on-site.

The airflow Q (kg/s) through the bi-directional leakage opening is simulated in the building model with the empirical power law equation

$$Q = C \cdot \Delta P^n, \quad (13)$$

where C (dimensionless) is a flow coefficient (related to the opening), ΔP (Pa) is the pressure difference over the opening and n is a flow exponent which is characterizing the flow regime [80]. The infiltration air flow is calculated for the facade of every zone [80]. The leakage openings in model are distributed over the building model according to the total infiltration airflow.

3 Results

3.1 Measurements of ACR using tracer gas method

3.1.1 Laboratory test results to verify the concentration decay method

The CO_2 concentration decay method was used in Mektory ventilation laboratory to verify the presumed ACE of mixed ventilation. Firstly, the conditions of ideal mixing ventilation laboratory was tested, using the mixing fans. The results of ACE were close to ideal mixing. To analyse the influence of supply air temperature, two different supply air temperatures were tested and two separate measurements were carried out on each setting (Table 7). The nominal time constant during all the tests was 0.25 h, which was calculated based on the fixed airflow rate of the ventilation unit. Figure 25 shows that the actual CO_2 concentration decay during all the tests correlated very well with the theoretical exponential decay curve that proved the accuracy of the method. The correlation was at least 0.99 in all four experiments. The steeper depression angle on Figure 25 expresses bigger ACR and lower mean age of air in the room air. According to the definition, the mean age of air in the extract air is equal to the nominal time constant. The maximum difference in the test results was 15%.

If the supply air temperature was 16 °C, the ACE values were 51.3% and 50.9% and if the supply temperature was 21 °C, the ACE values were 43.1% and 46.1%. This shows that the ventilation in the test room with 16 °C supply air temperature can be considered fully mixed. The mixing was less efficient during tests K3 and K4, when the supply air temperature was 21°. ACE values were 43.1% and 46.1%, respectively. As both supply diffuser and extract grille were on the ceiling, the most important factor in terms of high ACE was the supply air jet throw length to reach to the floor. A visual test with smoke was also conducted. The observation verified that the supply air with lower temperature reached the floor with higher velocity. The local air change index values were constantly higher with the lower supply air temperature as well. The correlation with theoretical decay was at least 0.98 for all the loggers. The local air change indexes were between 93% and 109% in tests K1 and K2 and between 82% and 92% in tests K3 and K4. No stagnant zone was detected based on the local measurements.

The ACE analyses in laboratory conditions showed that ACE of all tested ventilation systems was close to 50%. The ventilation distribution is mixing type, and the tracer gas method can be used without any correction factors.

Table 7. Results of laboratory validation test.

Test no.	K1	K2	K3	K4
Room and supply air temperature difference (°C)	-6.0	-6.9	-1.1	-2.2
Mean age of air (h)	0.24	0.25	0.29	0.27
Nominal time constant (h)	0.25	0.25	0.25	0.25
Mean age of air in extract air (h)	0.25	0.25	0.29	0.28
Air change efficiency (%)	51.3	50.9	43.1	46.1

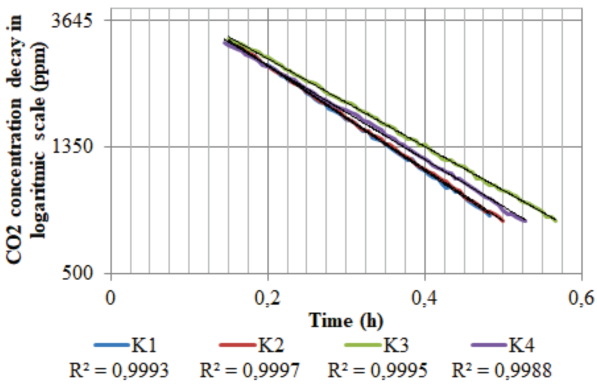

Figure 25. Concentration decay in laboratory validation tests.

3.1.2 Laboratory test for ACR measurements

The next step of the study was to measure the airflow using CO_2 as the tracer gas. The method is firstly tested in laboratory conditions, and the values of ACR are compared to the anemometer measured values. The level of CO_2 is increased artificially and two measurements were done for each airflow. The values of ACR are compared in Table 8. The average variety of ACR measurements with tracer gas and anemometer was 2%. It was also discovered that if the same airflow was measured two times in the same value, the measurement result using the tracer gas method was different. For example, in the case of the fresh air radiator the first ACR was 1.09 h^{-1}, and in the second test, the result was 0.89 h^{-1}. As the airflow was measured with the flow hood at the beginning of the test, this phenomenon might be caused by the influence of wind. The ACR values of the tracer gas measurements were lower than the measurements with the flow hood. The average ACR of all measurements was 1.03 h^{-1} with the tracer gas and 1.18 h^{-1} with the flow hood. To make the values comparable, the infiltration ACR is added to the flow hood measurement result. The average variety of two different type of measuring method is 18%.

Table 8. Airflow measurement results of laboratory tests.

Tested unit	Nr. of test	Fan speed, %	ACR with tracer gas, h^{-1}	Measured ACR, h^{-1}
Pair-wise	K2	60	1.07	1.18
	K4	60	1.11	1.11
	K6	25	0.80	0.69
	K7	25	0.68	0.69
	K8	50	0.98	1.14
	K9	50	1.00	1.14
Monoblock	K10	50	0.89	1.09
	K11	30	0.65	0.89
	K12	50	1.02	1.33
	K13	30	0.74	1.30
Ventilation radiator	K10	50	0.89	1.09
	K11	30	0.65	0.89
	K12	50	1.02	1.33
	K13	30	0.74	1.30

3.1.3 Measurements of ACR using tracer gas method in test apartments

In the test apartment one and two the ACR was measured using the concentration decay method with both artificially and metabolically increasing the concentration of tracer gas. In Table 9, the ACR of the bedroom and the other part of the apartment are pointed out. If the bedroom door is opened, then the airflow in the bedroom and other parts of an apartment varies up to 3%. In the situation when the bedroom door was closed, the ACR in the bedroom of second test-apartment was 36% higher. Although the correlation coefficients of ACR calculation are over 0.99, then the calculated ACR in case of artificially and naturally added tracer gas varies up to 29%. The main reason for the high variation is the effect of the wind and that the tests were not done at the same time. To sum up, the concentration decay method with metabolically increasing the concentration of tracer gas is possible to use in field measurements, but the results vary greatly.

To study the performance of the calculation methods on the wider scale, four apartments where the indoor air CO_2 level was previously already measured were also analysed. If the bedroom door is closed, then the air in other parts of the apartment is not ideally mixed. That is why the effective volume is only the bedroom volume. However, if the door is opened, then the effective volume is the whole apartment or part of the apartment. The average ACR of all the measurements was 0.28 h^{-1} with the metabolic CO_2 method and 0.26 h^{-1} with the concentration decay method. The average variety between the two methods was 6.3%. The biggest difference comparing the ACR of used methods was 25%. The moderate average variety of the methods shows that these CO_2 based tracer gas methods are suitable for evaluating the performance of ventilation in apartment buildings. At the same time, it is a more reliable way to calculate the ACR values with both methods. High uncertainty of airflow measurements is the main reason why the CO_2-based tracer gas method is used in this study only in case of NV and SRVUs. If other methods than tracer gas method could be used for ACR measurements, this was done.

Table 9. Measured ACR in in test apartments.

Code of apart-ment	Position of the bedroom door	ACR, 1/h				
		Artificial decay		Metabolic decay		Metabolic method
		General	Bedroom	General	Bedroom	Bedroom
1	Opened	0.21	0.20	0.25	0.26	0.28
	Closed	0.25	0.16	-	0.17	0.21
2	Opened	0.48	0.46	0.45	0.46	0.40
	Closed	0.44	0.38	0.37	0.27	0.32
3	Opened	-	-	-	0.29	0.33
4	Opened	-	-	-	0.12	0.16
5	Opened	-	-	-	0.23	0.30
6	Opened	-	-	-	0.30	0.24

3.1.4 Measurements of ACE using tracer gas method in test apartments

ACE was measured in two naturally ventilated apartments. Tests were made in the heating period and in warm period. The special focus was to determine how the position of the inner doors affect the ACE in the apartment. Figure 26 shows the CO_2 concentration change in the bedroom and bathroom of apartment 2 during two days. The bedroom door was closed during the first night and opened during the second night. The CO_2 concentration in the bedroom was 500 ppm higher than in the bathroom during the first night, while during the second night the concentrations were practically even. It proves that the CO_2 generated by the occupants spread and diluted in the whole apartment, if the bedroom door was open.

The whole apartment was considered as one zone during the concentration decay tests and local air change indexes were measured in every room of the apartment. The measured nominal time constants and local air change indexes are shown in Table 10. Nominal time constants were calculated based on the concentration decay in the extract grille. The local air change index was the lowest in the bedroom of the second apartment when the door was closed. The value was 57% while 100% expresses fully mixed ventilation. The local air change index was 61% with same conditions in apartment no. 1. As both values were clearly under 100%, it can be noted that the air flow in the apartments was not fully mixed, if the bedroom door was closed. On the contrary, if the bedroom door was open, the local air change indexes in apartment no. 1 were 97%–101% and in apartment no. 2 90%–106%, which indicated that the air flow in both apartments was quite uniform.

The ACE values outside the heating period were measured only in second apartment. If the bedroom door was closed, the local air change index was 97%–130%. If the bedroom door was closed the local air change index was only 53% in bedroom. At the same time in other rooms the index varied from 95% to 102%.

Air distribution was also analysed according to the CO_2 decay patterns that compiled using the linear interpolation method (Figure 27). CO_2 patterns compiled only to apartment no. 2. Room air patterns are analysed in heating period with opened bedroom door, in heating period with closed door and in warm period with opened door. It can be concluded that closing the bedroom door ensures uniform CO_2 concentration in a room. At the same time, the local air change index in bedroom is lower than in other parts of the apartment. If the inner door was open, the air distribution was not uniform and the local ACR was higher near to the fresh air valve. The local air change index was the lowest in the upper part of the inner door. In the lower part of the door, the local ACR was slightly higher which corresponds to the theory that the air is moving into another room from there.

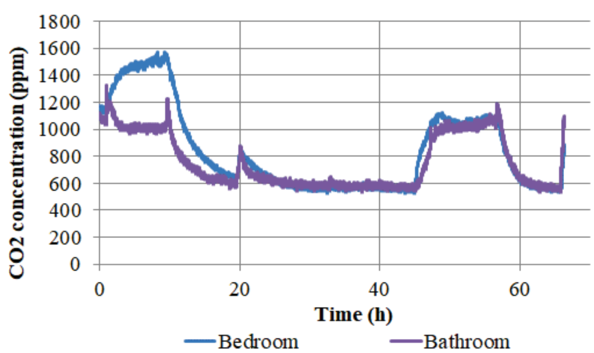

Figure 26. Indoor air CO_2 concentration in apartment 2.

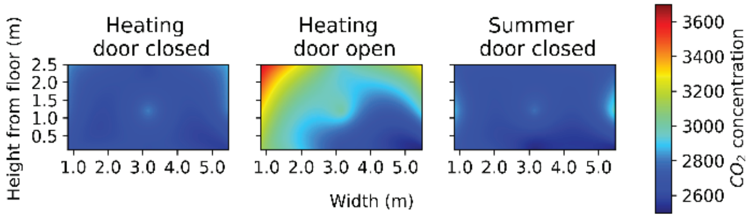

Figure 27. Room air distribution of apartment 2 with opened and closed door.

Table 10. Local air change indexes in apartments.

Apartment no./ Period	Door position	Nominal time constant (h)	Local air change index (%)					
			Bed-room	Living-room	Kitc-hen	Bath-room	Toilet	Corri-dor
1/heating	Open	4.78	97	100	99	100	99	101
1/heating	Closed	3.55	61	85	108	97	118	-
2/heating	Open	1.64	90	-	98	106	-	105
2/heating	Closed	2.01	57	-	94	100		104
2/summer	Open	2.20	97	-	98	98	-	130
2/summer	Closed	2.12	53	-	102	98	-	95

3.2 ACE of SRVUs and ventilation radiator

Three SRVUs were tested in nearly-zero energy test building in Tallinn University of Technology. The decay curve had very good correlation with theoretical curve as the correlation was at least 0.99 during all the tests in heating period and at least 0.98 in warm period. The results of the measurements of SRVUs in heating period are shown in Table 11 and Figure 28 and outside the heating period in Table 12.

Pair-wise unit was tested in heating period and outside the heating period in different fan speeds. The room and supply air temperature differences were from –4.8 °C to –2.2 °C. In heating period the mean age of air in tests K5 and K6 were 1.25 h and 1.47 h, respectively. Despite the same fan speed, the difference was 15%. That was possibly caused by the wind or the difference between supply air and room temperature. If the fan speed was 50%, the difference of the results was very small as the mean age of air values were 1.02 h and 0.99 h.

Pair-wise units were also tested outside the heating period with fan speed 25%, 50% and 75%. The mean age of air in tests were 1.25 h (M1), 0.96 h (M2), 0.58 h (M3) and 0.65 h (M4). The room and supply air temperature differences were from –0.9 °C to -2.1 °C. The values of ACE were 46%–51%. It can be concluded that the ACE is lower outside the heating period as the room and supply air temperature difference is lower. The temperature difference is lower outside the heating period as it is not possible to turn off the HR and the heat is recovered also during the warm period.

Secondly, monoblock ventilation unit was tested. In heating period the mean age of air values were 1.54 h and 1.35 h with 30% fan power, and 1.13 h and 0.98 h with 50% fan power. As the difference of nominal time constant was in the same magnitude and the ACE values were 48%–50%, it can be concluded that the air flow rates were different during the tests. The air flow rate was most likely affected by the pressure differences caused by wind and the difference of inside and outside temperatures.

Outside the heating period the mean age of air values were 1.1 h with 30% fan power and 1.13 h with 50% fan power. The room and supply air temperature difference were –1.1 °C and –1.2 °C. The values of ACE were 47% and 48%. In the same way, as pair-wise units, the ACE of monoblock units is lower outside heating period. The main reason is the high supply air temperature.

Thirdly, ventilation radiator was tested in combination with mechanical extract ventilation. Tests were done during heating and warm period. The air flow rates were chosen to be similar to the values of the bedroom of a common apartment. The difference between room temperature and supply air temperature were –7.9 °C (K13), –5.6 °C (K14), –6.7 °C (K15) and –6.0 °C (K16). In heating period the ACE values were 49%–50%.

In summer period two different tests were made and the difference between room temperature and supply air temperature were –8.1 °C (M7) and –7.7 °C (M8). The airflows were similar to the heating period values. The ACE values outside the heating period were 54% in both test. The ACE is higher in warm period because the heating system is turned off and the supply air is not heated.

The ACE in the test room was 48%–52% during all the heating period tests with all three units (Table 11). As 50% ACE value expresses ideal mixing flow, the air flow can be considered fully mixed with all three devices. It was also noted that the alteration of air flow rate did not have any impact on the ACE which means that even if the air flow rate was lower, the fresh air still reached every part of the test room. The ACE values outside the heating period were 46%–54% (Table 12). In case of pair-wise and monoblock units the ACE values are higher in heating period and in case of fresh air radiators the ACE values are higher outside the heating period. The reason for that trend is different supply air temperature. In case of pair-wise and monoblock unit the supply air temperature was close to the room temperature during the warm period. At the same time in case of ventilation radiator the supply air temperature was lower.

Table 11. Test Results of room-based ventilation units in heating period.

Ventilation Unit	Pair-wise				Monoblock				Ventilation radiator			
Test No.	K5	K6	K7	K8	K9	K10	K11	K12	K13	K14	K15	K16
Fan speed (%)/Air flow rate (l/s)	25	25	50	50	30	30	50	50	7.5	7.5	10.9	10.7
Room and supply air temperature difference (°C)	-4.8	-2.9	-2.2	-2.6	-7.2	-10.5	-8.7	-10.0	-7.9	-5.6	-6.7	-6.0
Mean age of air (h)	1.25	1.47	1.02	0.99	1.54	1.35	1.13	0.98	0.92	1.13	0.75	0.77
Nominal time constant (h)	1.25	1.46	1.04	1.02	1.52	1.30	1.13	0.98	0.89	1.12	0.75	0.77
Air change efficiency (%)	50	50	51	52	49	48	50	50	49	50	50	50

Table 12. Test Results of room-based ventilation units outside heating period.

Ventilation Unit	Pair-wise				Monoblock		Ventilation radiator	
Test No.	M1	M2	M3	M4	M5	M6	M7	M8
Fan speed (%)/Air flow rate (l/s)	25	50	75	75	30	50	7.7	7.9
Room and supply air temperature difference (°C)	-1.7	-2.1	-0.9	-1.3	-1.1	-1.2	-8.1	-7.7
Mean age of air (h)	1.35	0.93	0.63	0.69	1.17	0.86	1.12	1.09
Nominal time constant (h)	1.25	0.96	0.58	0.65	1.10	0.82	1.21	1.19
Air change efficiency (%)	46	51	46	47	47	48	54	54

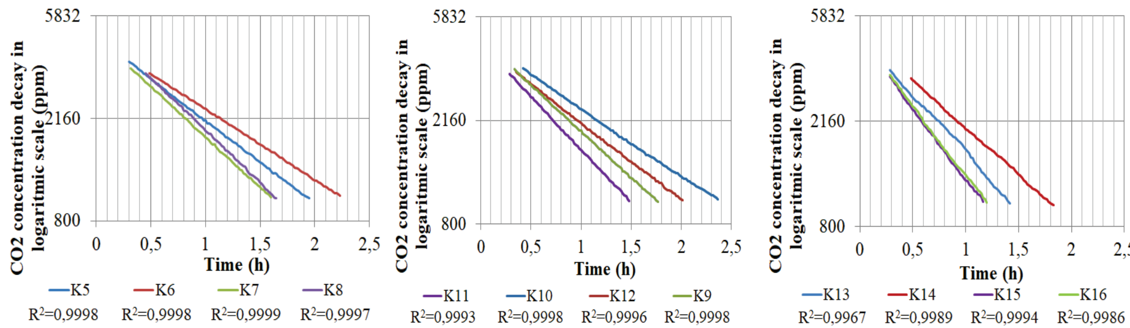

Figure 28. CO_2 concentration decay using pair-wise (left), monoblock (centre) and ventilation radiator units (right).

3.3 CO_2 levels and ACR in old apartment buildings

The average indoor air CO_2 level in Estonian apartments during the occupancy time in the heating period was 1102 ppm and in summer period 913 ppm. The average human presence in apartments during the heating period was 68% and 55% in summer period. In the case of concrete and brick apartment buildings, the average level of CO_2 during occupancy period was 1265 ppm. The average CO_2 concentration in apartments with NV (<1990) was 1225 ppm, and in apartments with ME ventilation (>2000) 788 ppm (Figure 29).

During the occupied time in the heating period, the CO_2 concentration indoors in old apartments with NV corresponded to ICC III class in 65% of the cases and in new apartments with mechanical ventilation corresponded to ICC II class in 67% of the cases. During the occupied time in summer period, the CO_2 concentration indoors in old apartments with NV corresponded to ICC III class in 79% of the cases and in new apartments with mechanical ventilation corresponded to ICC II class in 67% of the cases.

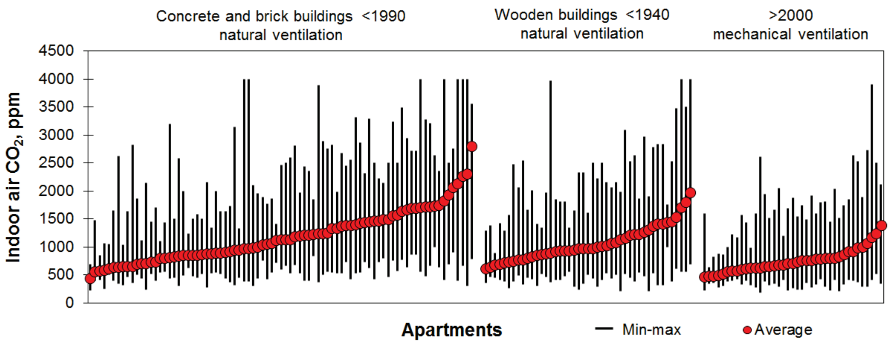

Figure 29. CO_2 concentration in apartments during the occupied heating period.

The airflow in bedrooms was calculated using the metabolic CO_2 concentration by Equation 3, with the average value of seven day periods. The average airflow of panel and brick buildings with NV was 4.4 l/s (2.9 l/s per person) during the heating period and 6.2 l/s (5.2 l/s per person) in the summer period. The same airflows in wooden buildings with NV but leakier building envelope were 6.6 l/s (3.7 l/s per person) during the heating period and 7.8 l/s (3.9 l/s per person) in the summer period. In new apartment buildings with mechanical ventilation, the average airflow was 10.7 l/s (7.1 l/s per person) during the heating period and 12.4 l/s (6.0 l/s per person) in the summer period.

According to EN 15251 [31] criteria of airflow in bedrooms, 22% apartments in the old panel and brick buildings with NV corresponded to ICC III during heating and 44% during the summer period. In old wooden apartment buildings with NV the correspondence to ICC III criteria was 37% during the heating period and 47% during the summer period. In new apartment buildings with mechanical ventilation correspondence to ICC II criteria was 35% during the heating period and 31% during the summer period. The average ACR according to the metabolic CO_2 method is 0.51 h^{-1} both in summer and winter season in bedrooms of the old panel and brick buildings. In wooden buildings, the average ACR of bedrooms was 0.56 h^{-1} in the heating period and 0.79 h^{-1} in summer period. In new apartment buildings with mechanical ventilation the ACR of bedrooms was 1.1 h^{-1} in the heating period and 1.4 h^{-1} in summer. The airflows in bedrooms per person are shown in

Figure 30. It can be concluded that in all three types of buildings the air change in summer period is higher. The main reason for that trend is the possibility to open the windows without compromising on thermal comfort.

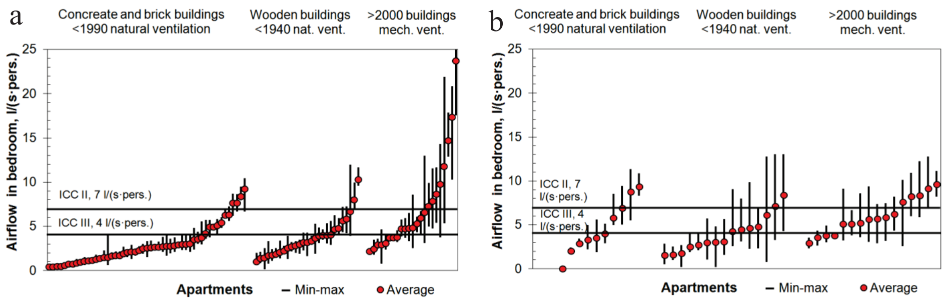

Figure 30. Airflow in bedrooms calculated according to metabolic CO_2 method during the heating period (left); Airflow in bedrooms calculated according to metabolic CO_2 method during the summer period (right).

Extract airflows were measured in kitchen, bathrooms and toilets (Figure 31). In concrete and brick apartment buildings with NV, the average exhaust airflow (momentary measurements in heating period) was 9.1 l/s, the average total ACR of apartments was 0.24 h^{-1}, and airflow per floor area of the apartment was 0.17 l/(s·m^2). In only 5% of the apartments, total exhaust airflow corresponded to the target values of ICC III. In new apartment buildings with NV, the average extract airflow was 18 l/s, the average total ACR of apartments was 0.42 h^{-1}, and airflow per floor area of the apartment was 0.30 l/(s·m^2). In only 7% of the apartments, total extract airflow corresponded to the target values of ICC II.

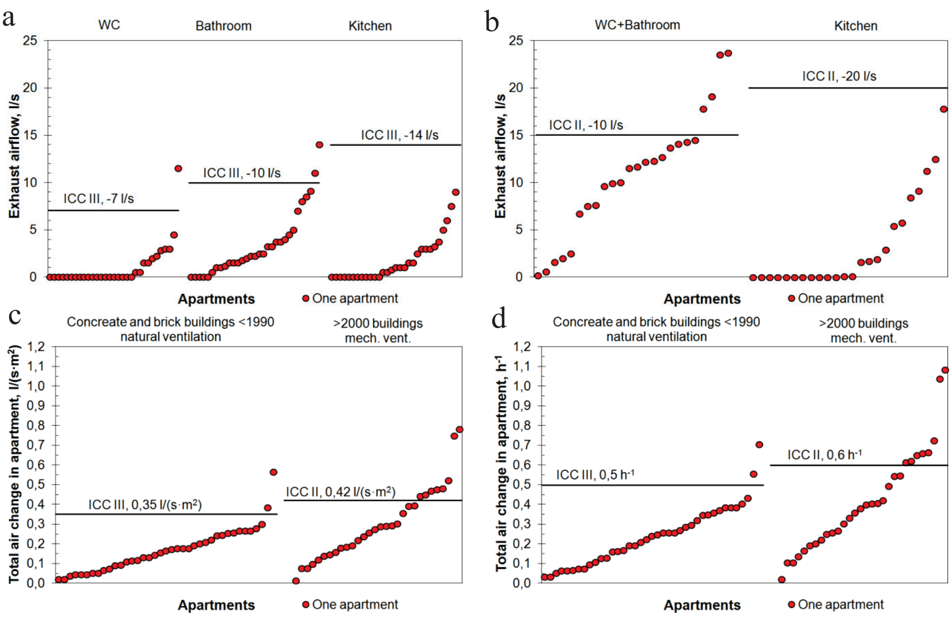

Figure 31. Extract airflows from old apartments with NV (a); Extract airflows from new apartments with mechanical ventilation (b); Total ACR in apartments per floor area (c); Total ACR in apartments per internal volume (d).

3.4 CO_2 levels and ACR in renovated apartment buildings

3.4.1 Development of ventilation requirements during the grant schemes

The airflow rate and CO_2 measurement results are compared for ventilation systems used in the renovation. In principle, the same EN-15251 ICC II requirement applied for both grant schemes, but in grant II the requirements were wrote out and supervision was strengthened (Table 13). Complementing the requirements in second grant scheme affected the selection of ventilation systems, however, EAHP and HRV were used in both grants enabling the performance comparison of the same system under different conditions. Grant II requirements specified room-based airflow rates, airflow measurement report was made mandatory, and third party inspection for design documentation was conducted before the funding decision. Also, requirements to preheat the intake air, general ventilation principle that the ventilation system should serve all rooms in an apartment (outdoor air to bedrooms and living rooms, and extract from wet rooms and kitchen), and continuous ACR in apartments at least 0.5 h^{-1} were added. Ventilation airflow rate design according to the grant II requirements for typical apartments is shown in Table 14.

Table 13. Overview of the requirements for indoor climate and ventilation when renovating apartment buildings using state financial support.

Period	Requirements for indoor climate and ventilation
2010 – 2014 first grant	No specific requirements, but in accordance with the indoor climate requirements according to EN-15251 (2007) ICC II
2014 – 2018 second grant	All grant levels: • Continuous ACR for apartment at least 0.5 h^{-1} + see Table 14 • Sound pressure levels in bedrooms and living rooms 25 dB(A) • Third party inspection of design documentation • Mandatory airflow measurement report • Indoor climate according to the EN-15251 (2007) ICC II requirements or following ventilation requirements specified in the grant scheme • 40% grant level (most popular, 80% of buildings): in addition to aforementioned: • HR ventilation system serving all rooms in an apartment • Preheating the intake air with VRs in EAHP system • Ventilation units should be without electric preheating coils

Table 14. Ventilation airflow rate calculation for model apartments according to the II grant requirements, 2014–2018.

Apartment type	Floor area, m^2	Extract airflow rate, l/s				Supply airflow rate, l/s					ACR
		WC	Bathroom	Kitchen	Total	Living	Bed1	Bed2	Bed3	Total	h^{-1}
Single room	35	-	10	6	16	10+6[1]	-	-	-	16	0.63
1 bedroom	55	-	15	8	23	10+2[1]	10+1[1]	-	-	23	0.58
2 bedrooms	70	10	15	8	33	10+2[1]	10+1[1]	10	-	33	0.65
3 bedrooms	80	10+2[1]	15+1[1]	8+2[1]	40	10	10	10	10	40	0.69

[1]values marked with "+" indicate the requirement to balance airflows

Technical conditions of second grant made it impossible to continue the use of NV systems. Similarly, the requirement that the heat recovery ventilation should serve all rooms in an apartment together with 25 dB(A) sound requirement blocked the use of SRVUs. These systems have therefore not been used in the second grant period.

3.4.2 CO_2 levels in renovated apartment buildings

Indoor air CO_2 concentration in the studied apartment buildings varied during the first grant scheme from 346 to 6714 ppm and during the second grant scheme from 401 to 3645 ppm. The average CO_2 concentration of all apartments during the occupancy period was 970 ppm during the first scheme and 837 ppm during the second scheme. The average human presence in the apartments during the heating period was 61% and 63%, respectively. The average, minimum, and 95% percentile levels of the CO_2 measurements of renovated apartments during the occupancy period are shown in Figure 32 and Figure 33. According to the standard in CEN/TR 16798-2:2019, the CO_2 level of indoor air may exceed the specified limit values by 6% (II ICC) of the annual use of the building daily, weekly, monthly, or yearly. CO_2 concentration in the bedrooms fulfilled the requirements of the II ICC in 41% and 58% of the measured grant and second grant apartments, respectively. In different ventilation systems, CO_2 concentration in first grant scheme corresponded to the values in EVS-EN 16798 II ICC during the following percentage of the occupancy time:

- 44% of apartments in the case of NV without fresh air valves;
- 35% of apartments in the case of NV with fresh air valves;
- 30% of apartments in the case of EAHP;
- 45% of apartments in the case of SRVU;
- 100% of apartments in the case of HRV.

In second grant scheme CO_2 concentration corresponded to EVS-EN 16798 II ICC values:

- 43% of apartments in the case of ME ventilation without HR;
- 75% of apartments in the case of EAHP;
- 62% of apartments in the case of HRV.

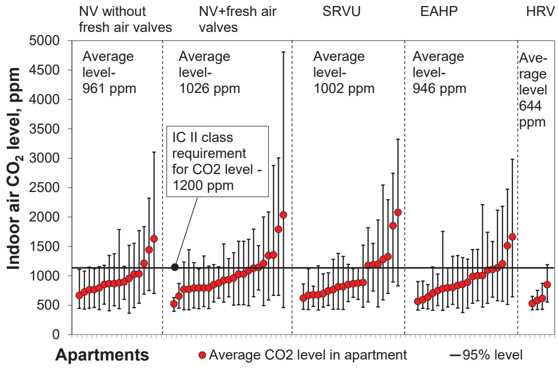

Figure 32. Occupancy period CO_2 concentration of studied ventilation renovation measures in the first grant.

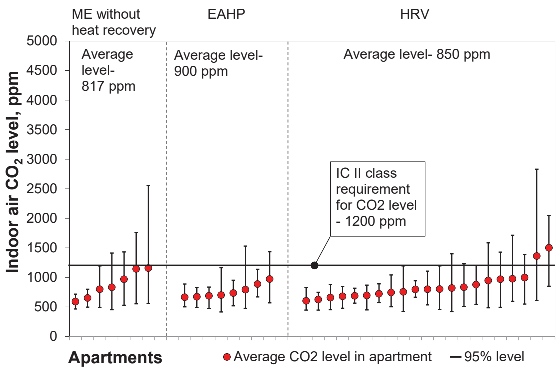

Figure 33. Occupancy period CO_2 concentration of studied ventilation renovation measures in the second grant.

3.4.3 ACRs in renovated apartment buildings

For evaluating the performance of ventilation renovation measures in both grant periods, the ACRs in apartments were calculated from measured airflow rates and the volume of apartments. The average extract airflows in different ventilation systems and apartments are shown in Figure 34 and Figure 35. The ACR fulfils the requirements of the support grant (0.5 h^{-1}) in 4.8% and 55% of the apartments in the first and second grant periods, respectively. The average ACR of all measured apartments was 0.17 h^{-1} and 0.57 h^{-1} in the first and second grant periods, respectively.

During the first grant period, the ACR was the lowest in apartments with NV without fresh air intake and in apartments with SRVUs. Measured ACRs and total measured extract airflows from the WC, kitchen, and bathroom are shown in Figure 35. In apartments where the NV with or without fresh air intakes and SRVUs were installed, no apartments fulfilled the minimum requirement of support grants. The total average extract airflow from the WC, bathroom, and kitchen was 5.2 l/s. Extract airflows are extremely low in apartments with SRVUs. The main reason for this phenomenon was that the extract grilles were closed to improve the indoor and outdoor pressure conditions of the SRVUs. These results led to changes in the technical conditions for second grant period.

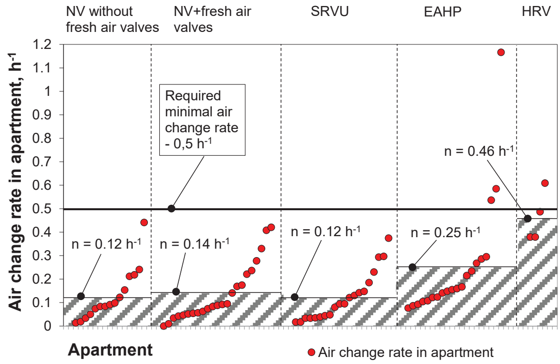

Figure 34. The ACR in apartments during first grant period.

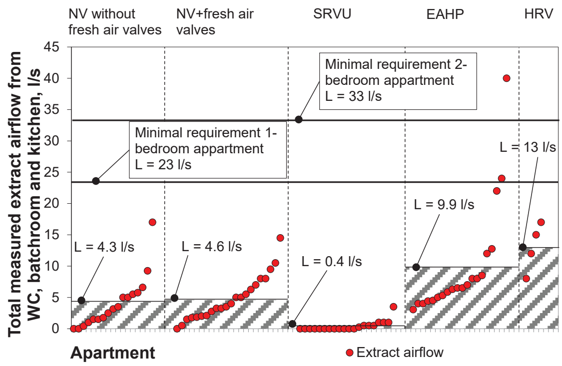

Figure 35. The extract airflows of the studied apartments during first grant period.

During the second grant period, the average ACR of HRV ventilation was 0.73 h^{-1}, and the average ACR of ME without HR and EAHP systems was 0.32 h^{-1} (Figure 36). In the case of HRV ventilation in 88% of the apartments, ACR was ensured. ACR was not required in any of the studied apartments with EAHP or ME without an HR ventilation system. The measurement results of ACRs in apartments indicate that the HRV ventilation ensured approximately two times higher ACR than EAHP or ME without HR. Because the airflow of all studied systems fulfilled the requirements during the commissioning airflow measurement, airflows of the EAHP and ME without HR ventilation systems decreased during operation.

Conditions of the second renovation grant established the requirements for the extract air airflows from bathrooms, toilets and kitchens. Therefore, the room extract airflows in apartments were also analysed (Figure 37). Total extract airflow from the bathroom, WC, and kitchen was 26 l/s in HRV, 10.8 l/s in EAHP and 11.3 l/s in ME without HR. In the case of HRV, the designed extract airflow was ensured in 21% of bathrooms, 78% of toilets and 88% of kitchens. In the case of EAHP, the designed extract airflow was ensured in 13% of bathrooms and in none of the toilets or kitchens. The extract airflow was not ensured in any of the rooms measured in the ME without HR.

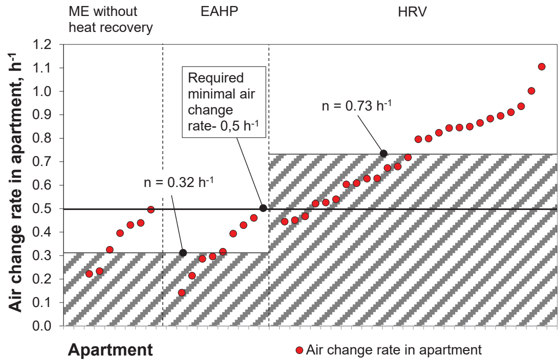

Figure 36. ACR in apartments of the studied ventilation systems during the second grant period.

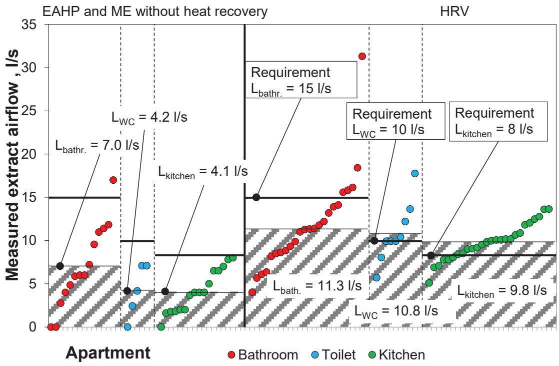

Figure 37. Extract airflows of the studied ventilation systems during the second grant period.

Supply airflows in living rooms and bedrooms were measured only in the case of the HRV ventilation system (Figure 38). According to the requirements of the renovation grant, the supply airflow in living rooms and bedrooms must be at least 10 l/s and 6 l/(s*person). The average supply airflow of the measured living rooms was 9.0 l/s and in the bedrooms 8.2 l/s. Considering the uncertainty of airflow measurement, 61% of the studied apartments fulfilled the requirements of the support grant. The average supply airflow was reduced in five apartments, where the supply valves were almost closed or sealed with tape.

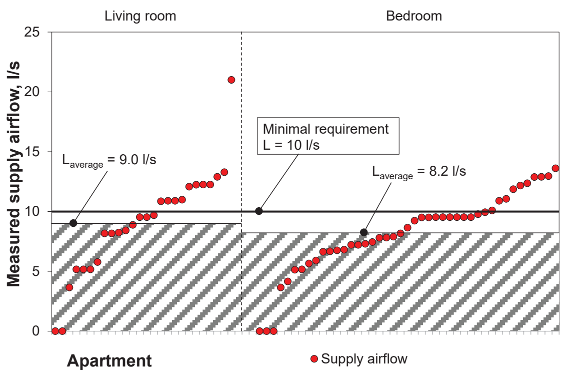

Figure 38. Measured supply air airflows of HRV in living- and bedrooms during second grant period.

3.4.4 Supply air temperatures in renovated apartment buildings

Supply air temperatures were measured in every building with HRV during the second grant scheme measurements. The results of the supply air temperature measurements are shown in Figure 39. The lowest measured temperature in the supply air was 6.6 °C. This temperature was measured in a building in which the heating coil was not installed. The supply air temperature setpoints were between 15 and 20 °C. The measurement results in Figure 39 show that the majority of the measured supply air temperatures fulfilled the setpoint values if the outdoor air temperature was over 2–4 °C. In the case of one ventilation unit, electrical preheating coils were used. The measurement results show that control of the preheating coil was implemented incorrectly, which caused the supply air temperature to be high in the apartments.

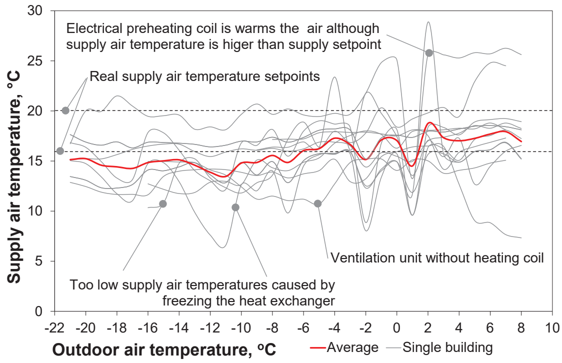

Figure 39. Measured supply air temperatures of HRV in living- and bedrooms during second grant period.

3.5 Performance analysis of SRVUs

The analyses of ACR rates in renovated apartment buildings which were equipped with SRVUs indicated that the performance of these units does not meet the expectations. That is the main reason why the additional studies were performed to analyse the problems related to this renovation solution. In addition, during the studies of renovation measures of grant period 1, a question of ACE of SRVUs arose. Thus, performance of SRVUs is analysed in more detail.

3.5.1 Field measurements of pressure difference of the building envelope

The results of field measurements showed that the pressure difference across the building envelope was negative during the entire measurement period in the first floor apartment and mostly negative in the fifth floor apartment (Figure 40). The occasional peaks toward zero-pressure difference are most likely caused by using the cooker hood, opening the windows or external doors to the balcony or staircase, the peaks and periods toward greater difference indicate the wind-induced effect. Pressure difference caused by wind can be dominant also for longer periods. The results indicate that the pressure difference is mostly caused by the stack effect being strongly dependent on the outdoor temperature in the bottom floor apartment, whereas on the top floor the dependence is weak due to the smaller height of the shaft. The measured indoor temperature during the measurement period in both apartments was roughly between 20 and 22 °C.

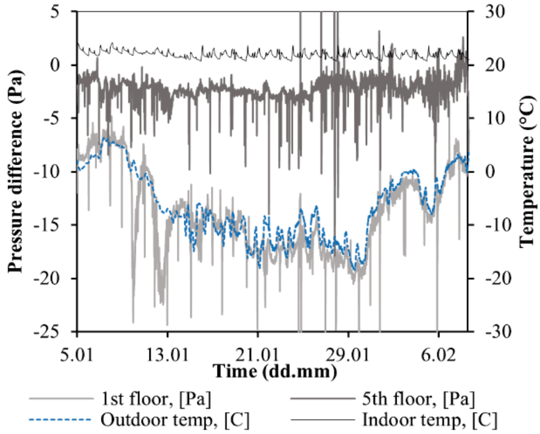

Figure 40. The measured indoor and outdoor pressure differences in the first and fifth floor apartments in the heating season during a one-month period.

3.5.2 The laboratory measurements of SRVUs

Based on the results of laboratory measurements the fan performance and HEX temperature efficiency of observed AHUs were studied. The measurement results of the performance of the unit with ceramic HEX are shown in Figure 41 left. In the beginning of the tests the value of underpressure in room was –2 Pa which means that supply and extract airflows were equal. After the pressure difference increased the extract air flow decreased and supply airflow increased at the same time. As results indicate, the supply and extract airflows are equal only at very low pressure differences. The greater the difference, the more the air flows differ. It can be seen that in case of 75% fan power, with differential pressure over –20 Pa the extract airflow is close to zero and the supply airflow around 60 m^3/h (Figure 41 right). The supply-exhaust cycles, which are presented in Figure 41, show quick drop of the supply air temperature after the cycle change. During the tests, the outdoor air temperature was close to –5 °C. If the supply and extract airflows are equal, the supply air temperature was about 7 °C but if the pressure difference was increased from 0 Pa–20 Pa in test room, the supply air temperature at the end of the supply working cycle was about –2 °C.

The fan performance curves were constructed for the fan speed levels of 25%, 50%, 75%, and 100% (Figure 42 left). The fan performance curves show how the supply and extract airflows of the ventilation units are related to the in-and outdoor pressure difference. It is also possible to present how the pressure difference is related to the temperature efficiency of studied ventilation units (Figure 42 right). The results indicate that if the pressure difference rises then the temperature efficiency decreases. The same trend appears for all tested fan speeds. For example, in case the 50% speed level, the temperature efficiency is over 0.5 if the pressure difference is smaller than 4 Pa.

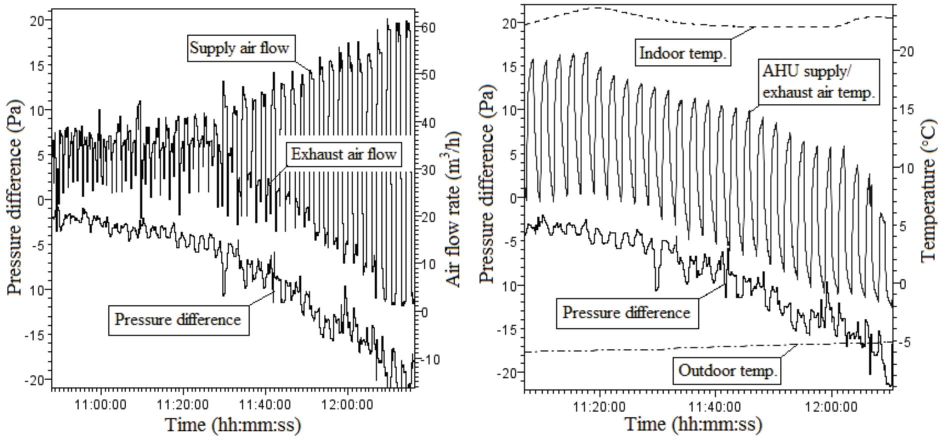

Figure 41. The results of the laboratory measurements of performance of the SRVU with regenerative HEX at 75% fan power: pressure difference and air flows (left); pressure difference and supply/exhaust air temperature (right).

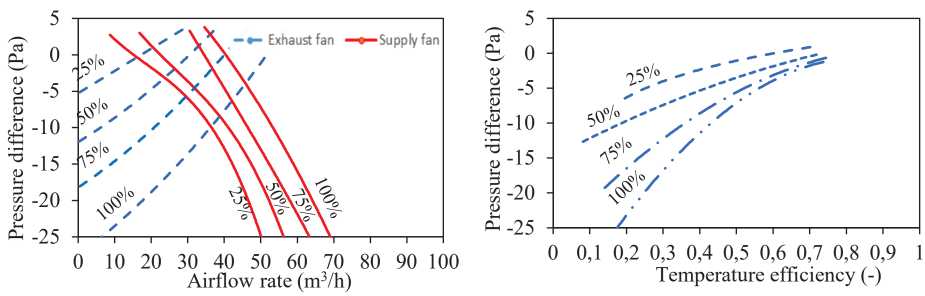

Figure 42. Measurement based fan performance curves of SRVU with ceramic regenerative HEX (left); measurement based temperature efficiencies of SRVUs with ceramic regenerative HEX (right).

The fan performance curves and temperature efficiency graphs were also constructed for the VU with recuperative HEX (Figure 43). The fan performance curves were constructed for the fan speed levels 25%, 50%, 75%, and 100%. Compared to the VUs with regenerative HEX, the units with recuperative can perform effectively in case of higher pressure differences between indoor and outdoor air. At the same time, if the pressure difference is -20 Pa at fan speed level 50%, the supply airflow is about 15% higher than exhaust airflow. The temperature efficiency of ventilation units with recuperative HEX is presented in Figure 43 right. Compared to units with regenerative HEX, the temperature efficiency of studied VUs is significantly better at higher pressure difference conditions. The pressure difference influences the temperature efficiency the most in lower fan speed levels.

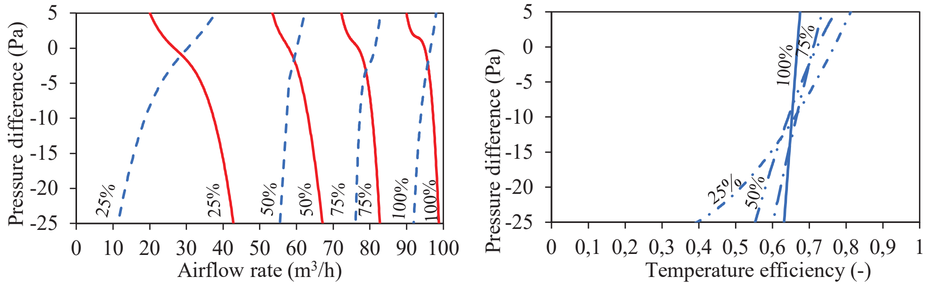

Figure 43. Measurement based fan performance curves of SRVUs with recuperative cross-flow plate HEX (left); measurement based temperature efficiencies of SRVUs with recuperative cross-flow plate HEX (right).

3.5.3 Simulation results of SRVUs

The simulation results achieved in the validation process are in good concordance with the field measurements (Figure 44 left), considering the fact that approximate wind pressure coefficients, performance of natural exhaust ventilation and wind data from an off-site weather station was used. The whole-year simulation results are presented in Figure 44 right. The results show that the whole building is under negative pressure for 63% of the year (5521 h per year). In the first-floor apartments, the pressure difference is below −10 Pa for 22% (1927 h per year) and lower than –20 Pa for 2% of the year (180 h per year). The pressure difference across the exterior wall during the heating season in the 5-story building can be as high as –30 Pa on the first floor, –20 Pa on the third floor and –15 Pa on the fifth floor. Although the performed whole-year simulations has been done according to only one building and some simplifications have been done during the simulation process, the results confirm the fact that SRVU systems in 5-story buildings have to cope with the pressure difference which is more than –20 Pa.

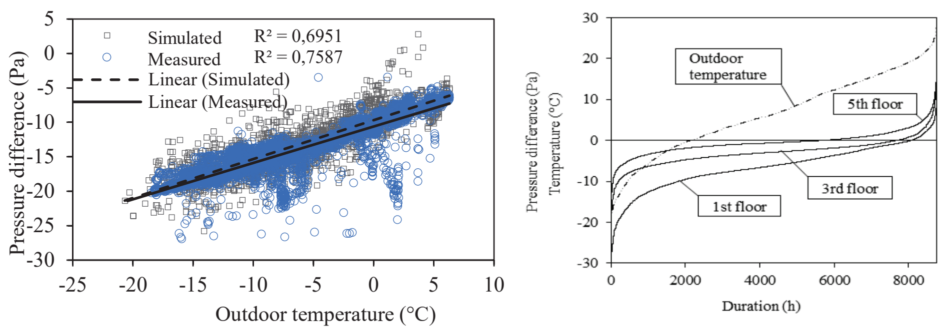

Figure 44. Dependence between measured and simulated indoor and outdoor pressure differences on the indoor-outdoor temperature difference in the first-floor apartment (left); The outdoor temperature and simulated whole-year pressure difference in the top, middle and bottom floor apartments of the 5-story apartment building (right).

The simulations of the SRVUs with the regenerative ceramic HEX were made using the same calibrated model of 5-story apartment building which was used in whole-year pressure difference simulations. The performance data of the fans and HEX has been taken from the results of laboratory tests that are described in previous subchapter. As the studied VUs have to ensure the low noise level in living room and bedroom, the unit can only work in 30–50% speed level. An example of supply air temperature and airflow rates simulation results of the SRVUs with ceramic HEX, located in first floor, are shown as duration curves in Figure 45 top. During heating season, supply air temperature is relatively close to the outdoor temperature (Figure 45 top) and supply airflow rate is much higher than exhaust airflow rate (Figure 45 bottom).

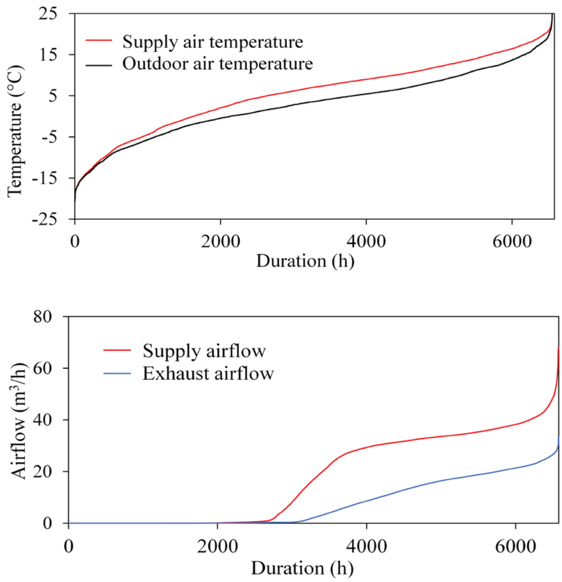

Figure 45. Simulated supply air temperature (top) and airflow rates duration curves for SRVUs during heating period in 1st floor apartment (September–May) (bottom).

4 Discussion

4.1 IAQ and ACR measurements in Estonian apartment buildings

The analysis shows that the ventilation systems of studied panel and brick and wooden buildings needed to be updated. At the same time, the installation of fresh air valves and retrofitting the other parts of old NV system does not guarantee the best possible indoor climate in apartment buildings. In dimensioning the NV systems, the calculated outdoor air temperature was taken to be +5 °C. That is the reason why NV systems do not guarantee the sufficient extract airflows at higher outdoor air temperatures even in theory. Another reason for the reduction of the compensation airflow is related to the renovation of building envelopes and replacement of old windows with tighter ones.

Based on this study, we can see a trend that in the case of mechanical exhaust ventilation with the fresh air valves in the new buildings, the extract airflows are also reduced. Although the average extract airflow in new buildings is two times higher than in buildings with NV, then in many apartments the fans are maintained in minimal possible airflow. Due to the low-temperature compensation airflow from fresh air valves, the airflow is decreased and the CO_2 level increases in winter period. Thus, when renovating the NV systems in old apartment buildings or constructing new ventilation systems, the mechanical supply-exhaust system with effective heat recovery should be preferred, or the compensation air from the fresh air valves should be preheated in the case of mechanical exhaust ventilation with heat pump HR.

As ventilation airflows in new apartment buildings with mechanical ventilation were below standard criteria, and the CO_2 level was over criteria, there is something wrong with the current design and installation practice of ventilation. One of the main reasons could be that designers design ventilation airflow, not the real performance. Usually, the side effects, like too noisy ventilation, draft and high energy use prevent using ventilation in design level. Better design, installation and maintenance guidelines are needed to avoid presented errors in the performance of ventilation in the future. At the same time, mechanical ventilation ensures statistically significantly lower indoor air CO_2 level than NV in old panel and brick or wooden buildings.

4.2 Performance of ventilation in renovated apartment buildings

4.2.1 Measured ACR and CO_2 levels in renovated apartment buildings

According to Paper I the average indoor air CO_2 level in old Estonian concrete and brick buildings during the occupancy period was 1265 ppm. The Paper V shows that during the first grant period, the average CO_2 level was 970 ppm, and during the second period, 837 ppm. These values show the trend that IAQ during the second grant period is considerably better than during the first grant period. Leivo et al. stated that after the ventilation retrofit, the average CO_2 level during the measurement period was 715 ppm, which is much lower than that measured in this study for the second grant scheme [135]. Because the CO_2 levels in this study were calculated for the occupancy period, they could not be directly compared with those of other studies. The average CO_2 levels of the whole measuring period for the first and second grants periods were 886 ppm and 789 ppm, respectively. Because the average CO_2 level depends on the occupants' presence, the occupancy period values were more informative. However, it should be noted that the CO_2 measurement results are sensitive to a number of factors such as infiltration, variation in human CO_2 generation, window opening, apartment door positions, and ventilation schedule effects. In this study, none of the measured apartments had gas stoves, so all CO_2 has human origin. Therefore, CO_2 measurements show the combined effect of ventilation, occupancy, and occupant behaviour. For this reason, airflow rate measurements are straightforward in the ventilation system performance assessment.

According to Paper I the average ACR in old Estonian concrete and brick buildings had been measured and was 0.24 h^{-1} and in new buildings with ME ventilation without HR 0.42 h^{-1}. During the first grant period, the average ACR of renovated apartments decreased to 0.17 h^{-1}. During the second grant period, the average ACR of all studied apartments was 0.57 h^{-1}. Leivo et al. analysed the influence of the renovation of ventilation systems in cold climates and pointed out that after renovation, the ACR was 0.48 h^{-1} [135]. Kamendere et al. also [62], [136] measured the ACR in renovated apartments and observed that ACRs were 0.39 h^{-1}-0.52 h^{-1}. During the second grant scheme, ventilation airflows in the studied buildings were close to the designed values (minimal required ACR 0.5 h^{-1}), and similar results have been shown also in other studies [62], [135], [136]. Additionally, during the first grant scheme, the measured ACR in apartments was lower than the same value in old Estonian concrete and brick buildings. Some ventilation renovation measures used in the first grant scheme did not work for various reasons, which are discussed in chapter 4.3.

4.2.2 Impact of the technical requirements of the renovation grant on the ventilation renovation measures

Comparing the performance of different ventilation renovation measures during both grant periods, ACRs of HRV systems significantly improved from 0.46 h^{-1} to 0.73 h^{-1}. The main reasons for the improved performance of these systems were stricter requirements for airflows and sound levels, third-party inspection of design documentation, and mandatory airflow measurement reports. These systems were designed more carefully which together with commissioning improved the quality. Airflow measurements and observations of the supply and extract valves showed that the airflow measurement reports were correct. In only five apartments, the positions of the valves were different from those in the measurement reports. These changes were made by occupants. One of the most positive aspects during the second grant period was the outstanding performance of the HRV ventilation system. ACR was ensured in 88% of apartments with HRV. This result is better than in new apartment buildings, according to the Paper I.

After the first grant period, when the average ACR of EAHP systems was only 0.25 h^{-1}, new technical conditions were added to the requirements of the support grant. In the second grant period, the average ACR increased to 0.32 h^{-1}. In the first grant scheme, there was only one building with an EAHP system and VRs. Additionally, the average ACR of that building was much higher (0.61 h^{-1}) than in other buildings with an EAHP system (0.16 h^{-1}). Thus, preheating the supply air had a significant impact on ACRs. In the case of the EAHP system, there could have been some influence of the requirement of third-party inspection for design documentation. The requirement for the mandatory airflow measurement report did not influence ACRs because, in the case of this system, the airflow measurement report was also performed in buildings studied during the first grant scheme. Using SRVUs to renovate old NV systems was unsuccessful because these units did not guarantee sufficient ACR. The results were so poor that the SRVUs were banned in the second grant scheme. This was a result of the requirement that the HR ventilation should serve all rooms of an apartment, and more importantly 25 dB(A) sound requirement and room based supply and extract airflow requirements which made it impossible to use SRVUs in the second grant period.

ME ventilation systems without HR were used only for renovations with a 25% grant. During the first grant scheme, local extract fans were designed for the WC, kitchen, and bathrooms to ensure the correct extract airflows from these rooms. Because the airflows of these fans were not measured, the requirement for the mandatory airflow measurement report changed the technical solution of this system. Designers and builders realised that the extract fans were noisy and did not guarantee the required airflow rates. Thus, central extract fans mounted on roofs or between ducts were used during the second grant period. This is the main reason why the measured airflows of the ME system during the second grant scheme were at the same level for EAHP (0.32 h^{-1}). In the first grant period, NV was used in some buildings, and thus fresh air intakes were added, but the improvement in ACR from 0.12 h^{-1} to 0.14 h^{-1} was minimal. This was conducted together with cleaning and retrofitting old exhaust shafts. Neither of these measures increased the ACR of the NV. Another reason for the reduction is the infiltration reduced by the renovation of building envelopes and replacement of old windows with tighter ones. This study revealed that adding fresh air intake does not solve this problem.

4.2.3 Performance of studied ventilation renovation solutions

To compare the performance of the ventilation systems used during both grant periods, the occupancy period average CO_2 levels of all measured renovated apartment buildings are summarised in Figure 46 left. The occupancy period average CO_2 level for all measured buildings was 928 ppm, for HRV 818 ppm, ME without HR and EAHP systems 891 ppm, SRVUs 1002 ppm, and NV 1000 ppm. The statistical analysis (t test) of measured CO_2 levels and calculated p values are shown in Figure 46 right. The calculated p values show a statistically significant difference between HRV and NV (t test: $p = 0.0091 < 0.05$) and between HRV and SRVUs (t test: $p = 0.049 < 0.05$). At the same time, there is not statistically significant difference between HRV and EAHP and ME without HR (t test: $p = 0.27 > 0.05$).

To compare the performance of the ventilation systems used during both grant periods, the average ACRs are summarised in Figure 47 left. HRV ventilation ensured the average ACR 0.70 h^{-1} as the average of both grant periods, ME without HR and EAHP systems 0.32 h^{-1}, SRVUs 0.12 h^{-1}, and NV 0.13 h^{-1}. The statistical analysis (t test) of measured ACRs in the case of different renovation measures and calculated p values are shown in Figure 47 right. The calculated p values show a statistically significant difference between HRV and all other ventilation renovation measures (t test: $p = 1.2 \cdot 10^{-11} < 0.05$).

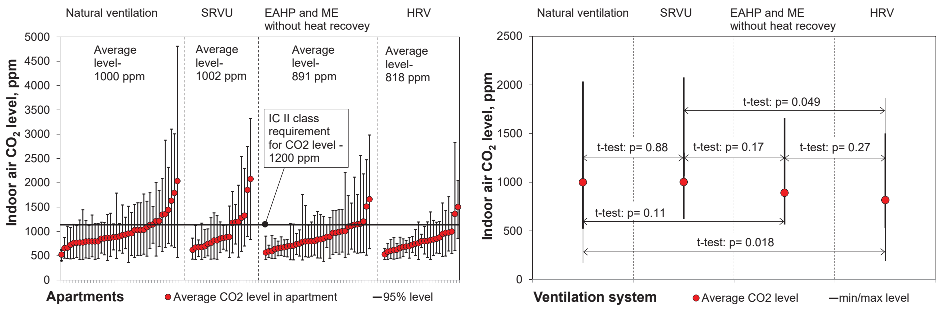

Figure 46. Occupancy period CO_2 concentration in different ventilation systems (left) and the statistical analyse (t-test) of average CO_2 levels of these systems (right).

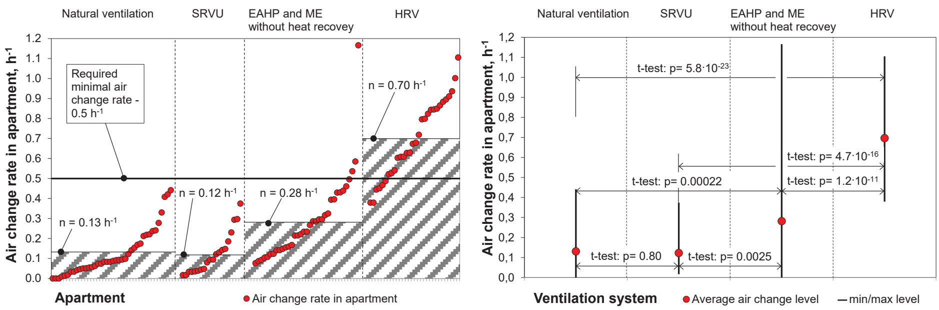

Figure 47. ACR of different ventilation systems (left) and the statistical analyse (t-test) to compare the performance of the systems (right).

Although the average ACR for the EAHP system was lower than the requirement, in some cases (mostly for tall buildings), this solution is the only possible technical solution to provide the extract air HR. This is the main reason why this solution can be recommended for buildings for which HRV cannot be technically used or is economically not viable. Khadra et al. [60] analysed the EAHP system with VRs in Swedish multifamily buildings and concluded that the EAHP renovation measure was the most cost-effective alternative to HRV. Kuusk et al. showed that EAHP had better energy performance than HRV in the central Europe climate, but in the cold Estonian climate, HRV showed better energy performance [137]. In Estonian climate, primary energy saving was 55% with HRV and 46% with EAHP which are close to observed values in practise [137].

Using SRVUs to renovate old NV systems of apartment buildings was unsuccessful because these units did not guarantee sufficient ACR and did not ensure extract airflow from toilets and bathrooms.

The analysis indicated that adding fresh air intakes to renovate the old NV systems did not ensure sufficient ACR in apartments. The main reason for this failure was the dimensioning of NV systems in old apartment buildings in Estonia, in which the design outdoor air temperature was +5 °C. Therefore, passive stack ventilation cannot guarantee sufficient annual extract airflows from apartments, even in theory.

In this thesis, the studies of ventilation renovation measures have been conducted in the conditions of old Estonian apartment buildings and Estonian outdoor climate. The ventilation systems of old apartment buildings in neighbouring countries of Estonia are quite similar to the technical solutions used in Estonia. Based on this, there is a clear potential to use the described ventilation renovation solutions in other Eastern European countries as well.

4.2.4 Main technical issues that influence the performance of ventilation in studied buildings

In the case of the SRVU, there was a problem with undersized fans. These units were designed to work at the highest possible airflow, but working at the highest speed level generated such high sound pressure levels that occupants switched these units to 30% of the maximum airflow [8], [122]. Mikola et al. in Paper IV and Vasileios et al. [138] have stated that the pressure differences across building envelopes due to wind and stack effects had a negative impact on the HR and supply air temperatures to SRVUs equipped with axial fans. Because of the negative pressure on the lower floors, extract airflow decreased, and the HR efficiency of the unit decreased to 30%; thus, the supply air temperature was too low to ensure thermal comfort [126]. This was also a reason why the speed of SRVUs was decreased.

In the case of the EAHP and ME ventilation systems, airflow was reduced by decreasing the fan speed. One reason why the fan speed was reduced was to save energy during operation. Additionally, it shows that users potentially misunderstand the operation principle of the EAHP system as the lower speed limits the heat source and HR in this system. One common problem was related to old extract air grilles not being replaced with modern extract air valves, causing the ventilation system to be unbalanced between apartments. If the old NV shafts were used for the mechanical exhaust systems, the technical conditions of the exhaust shafts were not improved by the installation. According to onsite observations and airflow measurements of the EAHP and ME systems, old ventilation shafts cannot be used without installing new ventilation ducts inside the old channels. The best solution for ventilation ductwork is performing the installation inside the insulation layer on the façade (Figure 48 right).

Renovated NV systems did not have transfer air grilles in the kitchens, toilets, and bathrooms, and the technical condition of the exhaust shafts remained poor. Deficiencies in the maintenance services of ventilation systems were also detected. For example, filters were not changed as often as necessary, the heat pump was not working to recover the heat from the extract air, or the systems were not monitored to find the critical errors. VR systems also had problems with cold floors near the radiator, caused by the incorrect connection of the intake air duct.

Although the HRV system performed well, there were technical problems that required solutions. One of the most common problems was that the supply air valve had been installed without the sector plate, which caused the cold draught reported by the residents (Figure 48 left). The same problem was pointed out by Thomsen et al. in renovated Danish apartment buildings [57]. One of the most notable limitations to the measurements was frost formation inside the plate HEXs of AHUs. Frost formation occurs if the surface temperature of the exhaust side of HEX is below the freezing point (<0 °C). Problems with frost formation in the case of plate HEXs in cold climate apartment ventilation were also reported by Alonso et al. [139]. The low supply air temperatures during the cold period (Figure 39) result in several problems related to ineffective frost prevention or defrosting of ice. Defrost measures must be used to avoid the freezing of condensed water vapour. The main techniques of frost prevention (preheating and bypassing the outdoor airflow) have been analysed in different studies [68], [69], [140].

Jedlikowski and Anisimov [69] concluded that the fully open bypass technique for frost prevention does not provide complete frost protection under sub-zero outdoor air temperature operating conditions. According to the supply air temperature measurement results in this study, the heating coil of the AHU is necessary in cold climates. Frost formation must be considered in the design phase and this issue requires further research and product development to develop the most energy-efficient measures to manage the problem. Frost protection solutions such as sectional defrosting, cold-corner control, and exhaust air dew point control are worth analysing in practical operation.

Figure 48. Supply air valve installed without sector plate (left) and apartment ventilation duct inside the insulation layer (right).

4.2.5 Improvements of grant schemes and the best practices for ventilation renovation

According to the analysed technical issues of the second grant scheme, new recommendations to improve technical conditions of ventilation renovation measures are proposed:

- First, the solution against frost formation inside the plate HEXs of the AHUs should always be used in the design stage.
- Second, the post-heating coil of the AHU with plate HEX is necessary.
- Third, supply air valves installed on the wall should always be designed for wall mounting.
- The last recommendation is to install new ventilation ducts in the old NV channels or install new ductwork inside the insulation layer on the façade.

According to the results of the studies of ventilation renovation in apartment buildings, it is possible to point out that the design and installation quality of ventilation systems plays an important role in energy performance of buildings, and it is very important to ensure the best possible solutions [9], [27]. Problems of renovation are often associated with installation quality, project changes without consulting ventilation designer, control systems of VUs, and service life maintenance. The possible solutions for these problems would be separate educational requirements for inspection officers and improvement of legislation in field of commissioning, maintenance and inspections. The problems, and possible solutions regarding the quality of residential systems are described in Table 15.

Table 15. Summary of problems observed regarding the quality of Estonian residential ventilation systems and schemes that have been implemented or that are under development to overcome these problems [9].

Topic	Major causes of quality problems	Existing quality schemes or incentives
Design	No consideration of noise levels, no ventilation sound attenuators between the apartments, VUs are designed on max speed, the use of old ventilation shafts without installing new ducts, supply valves are designed without sector plates	Residential ventilation standards, Governmental orders and laws, existing studies [12], [28], [141] about the renovation of ventilation systems of old apartment buildings
Installation	The quality of installation is poor, installations are not made by the ventilation project, supply valves are installed without sector plates	Finnish LVI RYL, by EVS-EN 60947-1:2001/A2:2002, Directive 71/305/EEC
Products	Control systems of AHUs are not working properly, product documentation is not translated	EU regulation No 305/2011, Governmental orders and laws
Commissioning	Commissioning specialist is not specialist in a field of ventilation	Estonian Building Law, Governmental ordinance No 11
Maintenance	Maintenance is not done by the regulations and product guidelines	EVS 830:2003, Governmental ordinance No 55, product guidelines

4.3 Performance of SRVUs as a ventilation renovation measure

The field measurements show that the pressure difference between the indoor and outdoor air in the bottom floor apartment depends heavily on the outdoor temperature, indicating the influence of the stack effect, whereas on the top floor, due to the smaller height of the exhaust ventilation shaft, the dependence is weak. Similar results have been also shown in other studies [142], [143]. Kiviste and Vinha [142] have studied different Finish buildings and found that in some cases there can be large underpressure conditions (<–15 Pa) between in-and outdoor environments. Kalamees et al. [89] showed that in most critical cases, the air pressure across the building envelope may rise up to 30 Pa and the main reason for that is airtight building envelope with unbalanced ventilation. This study confirms that in renovated 5-stories apartment buildings with natural exhaust ventilation, the pressure difference across the building envelope can rise up to 20–30 Pa. Analysing the fan performance of SRVUs with regenerative HEX, it can be concluded that the pressure differences over the envelope were caused by the NV and density differences between the indoor and outdoor air. The SRVUs itself did not play a significant role to increase the pressure drop across the building envelope.

During the analysis of the pressure difference measurement results and calibrating the model, the occasional peaks toward zero-pressure difference. These peaks are most likely caused by opening the windows or external doors to the balcony or staircase, the peaks and periods toward greater difference indicate the wind-induced effect. As the kitchen hoods and exhaust fans were installed in some apartments of studied buildings, the peaks can also be caused by these components of MV. Pressure difference caused by wind can be dominant also for longer periods. Although the wind-induced component varies in a wide range and depends on multiple variables, its contribution to the pressure conditions can be considerable, and thus special attention needs to be paid to buildings in wind exposed locations. Kalamees et al. [89] found that wind primarily influence the peak air pressure values and comparing the average values, the influence of wind is small. Despite the wind effect and other uncertainties during the pressure measuring and model compilation, we can see that dependence between measured and simulated indoor and outdoor pressure differences is quite strong. In the first floor the value of linear correlation coefficient of simulated data is 0.6951 and the correlation coefficient of measured data is 0.7587. The values of correlation coefficients, together with the similarity in results of simulation and measurement indicates that the calibration of the model was successful.

The laboratory measurement results of the studied SRVUs show that supply and extract airflows are equal only at very low pressure differences. The greater the gap, the more the airflows differ. It can be seen, that the unit with plate HEX is performing considerably better, mainly due to centrifugal fans, but also because of the constant airflows. In case of the unit with regenerative HEX, the pressure difference is causing low-pressure axial fan to perform poorly: smaller volumes of exhaust air to flow through the unit during exhaust cycle, lowering the heat quantity accumulated in the HEX and leaving the outdoor air heating insufficient. The effect escalates with lower outdoor temperatures and higher pressure differences, in which case the heat transfer in the unit degrades and larger volumes of cold air are entering the ventilated space. It means that the pressure difference across the building envelope is closely related to the temperature efficiency of studied ventilation systems.

The performance of SRVUs have also been monitored in previous studies. Smith et al. have developed the VUs with plastic rotary HEX [86], [129]. They have made airflow measurements of the tested units using the tracer gas method. The main conclusion of this study was that the temperature efficiency of studied unit on equal supply and exhaust airflows is about 0.83–0.84 [86]. As these tests were not performed in different indoor and outdoor pressure conditions, it is not possible to make the conclusion, how these units would perform in apartment buildings in cold climate region.

Based on the simulation results, the pressure difference across the exterior wall during the heating season in a five-story building can be as high as –30 Pa on the first floor, –20 Pa on the third floor, and –15 Pa on the fifth floor. Comparing the simulated pressure conditions and the measured characteristics of the VU, poor performance of the unit can be expected. The simulation results of SRVUs with regenerative HEX show that during heating season, supply air temperature is relatively close to the outdoor temperature and that supply airflow rate is much higher than exhaust airflow rate. At the same time the unit with recuperative HEX can ensure the temperature efficiency of the unit over 0.5 even under negative pressure as high as –25 Pa, making it possible to use the device in first floor apartments.

In case of both studied SRVUs, the only possible way to protect the HEX from freezing in cold climate is to reduce the supply airflow. As proven in this study, the exhaust airflow can be very small if the air pressure difference across the building envelope is high. That is the reason why there is high risk of ice formation in HEX, which complicates using these units in rooms with high humidity.

4.4 Air distribution of SRVUs and ventilation radiator

The air distribution of SRVUs and ventilation radiator is possible to analyse according to the calculated local air change indexes. The corresponding results are shown in Figure 49 and Figure 50. The values of local air change indexes of the pair-wise units were 93%–110% during the heating period. The values of ACE were 50%–51% and no stagnant zone was detected in the room. The local air change indexes outside the heating period were 86%–106% in tests M1 and M2 and 86%–101% in tests M3 and M4.

The local air change indexes of monoblock units in winter period were 93%–102% that proved the ACR was uniform in the whole room. The local air change indexes outside the heating period were 91%–101% in test M5 and 93%–109% in test M6.

During the heating period, the values of air change indexes of ventilation radiator were close to 100% in all areas of the room. This proves that the supply air mixed with the room air in effective way. Outside the heating period, the local air change indexes were 100%–113% in test M7 and 90%–129% in test M7.

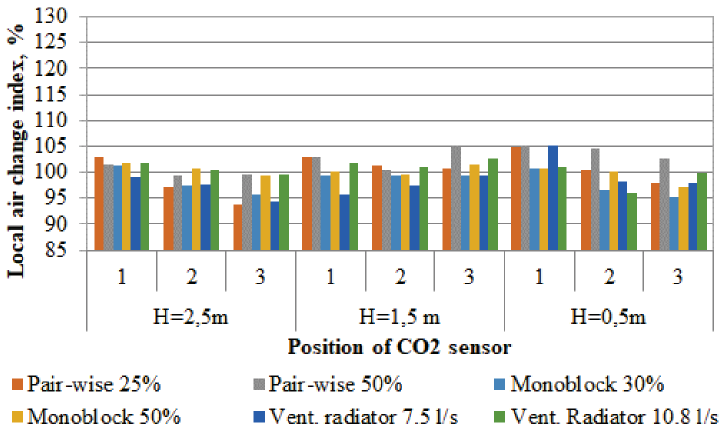

Figure 49. Local air change indexes of room based ventilation units in heating period.

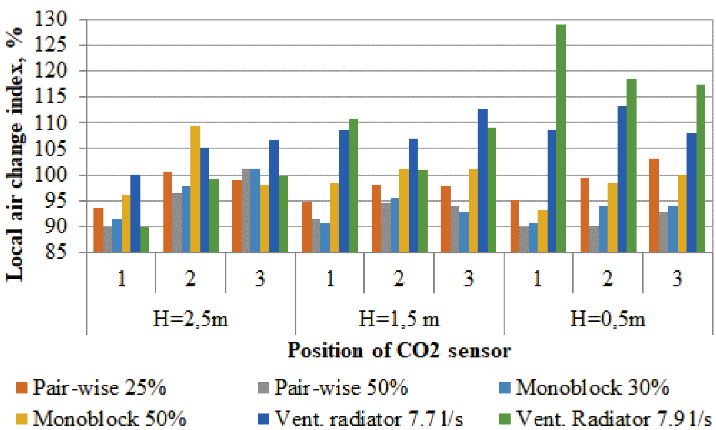

Figure 50. Local air change indexes of room based ventilation units in warm period.

Air distribution was also analysed according to the CO_2 decay patterns. The sections of the room pattern in NZEB laboratory are shown in Figure 13 (section A–B). The air distribution patterns compiled using the linear interpolation method. The room air distribution patterns are in Figure 51 (heating period) and Figure 52 (warm period). To compare the different decays, the patterns demonstrated in similar CO_2 levels around 2100–2800 ppm. Analysing the patterns, the most important conclusion is that local air change indexes are highest in the middle of room. This conclusion is the same for all the studied systems in both measuring period.

In case of pair-wise system the closer corner to the unit is with higher local ACR in warm period. At the same time, the closer and the farther corner are performing in similar way in summer. In case of monoblock units, the air pattern during both period is similar. The main difference of the air patterns of pair-wise and monoblock units is related to the different supply jets. The pair-wise unit gives the supply jet across the air distributor (360 degrees). At the same time the supply airflow of monoblock unit is directed only into the upper part of the room. This aspect can also be seen in Figure 52, where the local ACR of monoblock unit is higher in the bottom part of the room.

In case of ventilation radiator, the air pattern in heating period is quite uniform, but at the same time the local ACR in upper part of the room is lower than in other part of the room. The main reasons for this kind of pattern is quite cold supply air from the lower part of the room. In heating period the air is mixed by the convective air flow from the hot radiator, but the radiator was not turned on during the warm period. That is the main reason, why the ACE value is high and the concentration of CO_2 level is higher in upper zone.

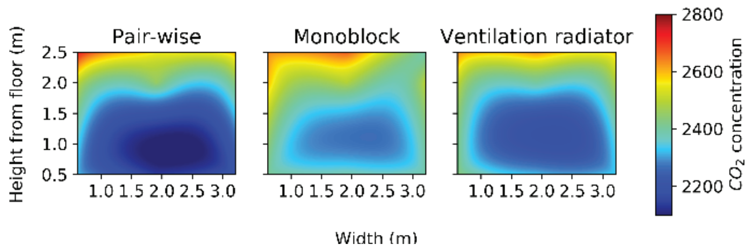

Figure 51. Room air distribution of room based ventilation units in in heating period (A-B).

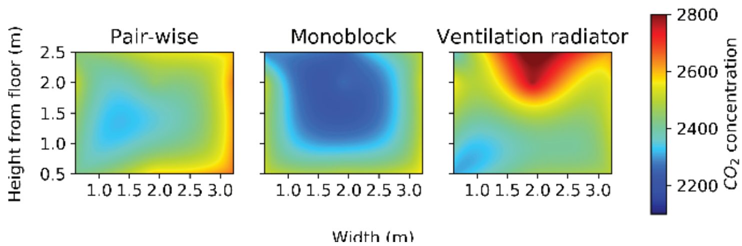

Figure 52. Room air distribution of room based ventilation units in in warm period (A-B).

5 Conclusions

5.1 Ventilation in old Estonian apartment buildings

It was shown that the average ACR in old apartments with NV was as low as 0.24 h^{-1} and it was possible it to worsen if not properly renovated. In contrast, the average actual ACR in new apartment buildings with mechanical exhaust ventilation was 0.42 h^{-1}. We can see a trend that in the case of mechanical exhaust ventilation with fresh air valves in new buildings, the exhaust airflows are reduced because of draught problems.

The technical inspection of studied ventilation systems of old apartment buildings shows that NV systems are in poor condition. Main problems have to do with insufficient installation quality of channels and exhaust devices, and lack of compensation airflow from air building leakages.

5.2 Performance of different ventilation renovation measures

Renovation with Estonian renovation grants shows that the ventilation system is a major obstacle in the apartment building renovation process. The results demonstrate that the IAQ and ACR in renovated apartments depended strongly on the technical specifications of renovation grants. The first Estonian renovation grant period without specific ventilation requirements resulted in the average ACR as low as 0.17 h^{-1} in studied apartments. The second grant period with detailed ventilation requirements increased the average ACR to 0.57 h^{-1}. A higher ventilation rate remarkably reduced the maximum CO_2 concentration in the bedrooms. Therefore, we have shown that it is possible to renovate old NV systems by using proper technical solutions, either the HRV or EAHP, and supporting the process with governmental subsidies.

The results allow to draw the following conclusions on the performance of ventilation systems:

- Comparing the performance of ventilation renovation measures during two grant periods, we observe that ACRs of the HRV systems built on the basis of stricter requirements, have significantly improved from 0.46 h^{-1} to 0.73 h^{-1}. That was due to the more detailed requirements for airflow rates and noise level, and the third-party inspection for design documentation.
- Average ACR of EAHP systems in the first grant period was 0.25 h^{-1} and in second grant period it increased to 0.32 h^{-1} due to requirement of preheating intake air. EAHP achieved the required ventilation rates in measurement reports of commissioning, but the main problem of this system was related to the reduction in fan speed in the operation. The reduction in fan speed was performed to save energy in operation, which indicates the potential misunderstanding of the operation principle of EAHP, as the lower fan speed will reduce the heat source and HR.
- The best ventilation performance was achieved with centralized HRV with a ductwork installation on the façade. HRV ensured the necessary ACR in actual operation in 88% of the measured renovated apartments. This system was the most widely used renovation measure for renovation up to 5-storey apartment buildings in Estonia. Although the average ACR operation of the EAHP system was lower than in the requirements, this system can also be recommended, and is, in some cases (mostly for tall buildings), the only feasible technical solution to provide the extract air HR.

- The renovation of old NV systems, or using SRVUs, did not guarantee sufficient ACR. Because of major problems, these ventilation renovation solutions were banned and were not used in the second grant period.

The ACR and CO_2 measurements during the first grant period show that only the general requirement to ensure Indoor Climate Category II does not guarantee the compliance. Lesson learnt in the first grant period led to detailed ventilation requirements with room-based airflow rates and noise levels implemented in the II grant period. The measurement results revealed that the most important technical conditions of the renovation grant are mandatory airflow and sound pressure level measurement reports, and third party inspection for design documentation. We also conclude that there is a need to specify the required room-based outdoor and extract airflow rates and ventilation noise levels in the technical conditions of the renovation grant to make the requirements and the design process transparent.

5.3 Performance of SRVUs in apartment buildings

The performance of two different SRVUs was studied: one of the units was a device with a recuperative cross-flow plate HEX and two centrifugal fans, and another with a regenerative ceramic HEX and an axial fan. In both cases of the studied SRVUs, pressure differences generated large differences in the supply and exhaust air flow rates. Because of the higher pressure rise, the airflow balance difference was much smaller in case of the unit with centrifugal fans compared to the unit with axial fan. This resulted in the smaller change in HR efficiency of the recuperative HEX, compared to the regenerative HEX case which practically lost its HR because of dominating stack effect pressure.

The simulation results show that in cold periods, apartments in the first floor can be under negative pressure as high as –20 Pa for longer periods of time. In ventilation system design, values of –10 Pa on the fifth floor, –15 Pa on the third floor and –20 Pa on the first floor apartments can be recommended to be used as design values for ventilation units. The simulation results of SRVUs with regenerative HEX show that during heating season, supply air temperature was close to the outdoor temperature, and that supply airflow rate was much higher than exhaust airflow rate, showing that the unit operated as air intake. Due to the differences in supply and exhaust airflows, there is a risk of freezing the heat exchanger, which excludes using studied ventilation units in rooms with high humidity.

The laboratory measurement results confirmed, that the axial fan used in the ventilation unit was not capable of working in typical pressure conditions occurring in multi-story building in cold periods to achieve sufficient ACR, HR, and supply air temperature, with noise levels under acceptable limits. In the case of the unit with recuperative HEX, under the same circumstances, the temperature efficiency of the unit remained higher than 0.5 even under negative pressure as high as –25 Pa, making it possible to use the device in first floor apartments. However, the toilet, bathroom and kitchen exhaust ventilation was unresolved with both SRVU units.

5.4 ACE of SRVUs and ventilation radiator

The ACE measurement method using the CO_2 based concentration decay method was validated in laboratory conditions. The test results for assessing the ACE showed that nearly ideal mixed ventilation was achieved both for ventilation radiators and two types of SRVUs. The lower supply air temperature increased the air change effectiveness. If the supply air temperature was 16 °C, the ACE was 51–52%. In the case of supply air temperature of 21 °C, the ACE dropped to 43–46%. It can be concluded that in the case of lower supply air temperature the ACE is closer to the ideal mixing.

The tracer gas concentration decay method was applied to measure the ACE and local air change indexes in both laboratory and field tests. Three tested SRVUs all created nearly fully mixed room air flows, despite the fact that the position of the supply and extract openings could have been favourable for a short-circuit flow. The ACE values were 48%–52% in heating period and 46%–54% in warm period. The alteration of the airflow rate did not have any impact on the ACE. In case of pair-wise and monoblock units the ACE values are higher in heating period, and in case of fresh air radiators the ACE vales are higher outside the heating period. The reason for that trend is different supply air temperature. In case of pair-wise and monoblock units, the supply air temperature was close to the room temperature during the warm period. At the same time, in case of fresh air radiator the supply air temperature was lower.

Air distribution was also analysed according to the CO_2 decay patterns. The most important conclusion is that local air change indexes are highest in the middle of room. This conclusion is the same for all the studied systems in both measuring periods. According to the results of this study, these three tested solutions are well-compatible for residential ventilation that regards the aspect of ACE.

The experiments in naturally ventilated apartments showed that if the ventilation scheme required transfer air between the rooms, the positions of the inner doors had a significant impact on the ACE. The local air change index in the bedroom with the closed door was, in the worst case, 43% lower than it would have been with fully mixed airflow. The airflow was almost fully mixed in case of open bedroom doors.

5.5 Future research

In case of HRV ventilation system, the main limitations to be solved are frost protection and defrosting operation of AHUs. Our studies proved that frost formation inside the plate heat exchangers of residential AHUs is a real problem, and designers and manufacturers should take it seriously. Further scientific research should focus on the most energy efficient measures to solve the defrosting operation of plate heat exchangers.

Although the HRV system performed well, one of the most commonly observed problem was that the supply air valve was installed without a sector plate, which caused a cold draught and occupants to report their negative experiences with it. Another challenge is achieving the required ACR of EAHP systems in the operation phase. In order to achieve trouble-free operation of ventilation renovation measures, these topics definitely need further research.

The studies of SRVUs have shown that in case of this renovation measure there are several technical issues that should be resolved before implementing this solution. Most critical questions are related to correct dimensioning of the fans of SRVUs and ensuring a sufficiently low noise level in bedrooms and living rooms. The freezing process of HEXs of SRVUs was not analysed in detail during this study, so it would be beneficial to study this in the future. One way to save energy from grid-connected electrical appliances, like SRVUs would also be a real-time control strategy based on Model Predictive Control for the energy scheduling [144]. Chen et al. have presented the development of a model predictive control strategy for the hybrid ventilation solution [145]. As this model is still a prototype, it needs more testing to analyse the detailed possibilities of model predictive control strategies. Real-time control strategy-based operating of SRVUs is another issue that needs to be addressed in the future.

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Acknowledgements

Firstly I would like to thank my supervisors Professor Jarek Kurnitski and Professor Hendrik Voll for their continuous support and guidance throughout my studies.

Secondly, my sincere gratitude goes to Professor Emeritus Teet-Andrus Kõiv, who originally proposed this topic of the thesis and gave me the encouragement and inspiration I needed to start my PhD studies.

I would like to thank the Nearly Zero Energy Buildings Research Group at the Tallinn University of Technology, especially Raimo Simson, Anti Hamburg, Karl-Villem Võsa and Professor Targo Kalamees for their valuable help in this research. Also, my thanks goes to all my colleagues and friends at the Tallinn University of Technology.

I would like to thank Piret and Madis for helping me with the proofreading of the thesis.

And lastly I would like to thank my family for their utmost support over the years. Their faith in me gave me the strength I needed to finalise my PhD studies.

This research was supported by the Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts, ZEBE, grant 2014-2020.4.01.15-0016 funded by the European Regional Development Fund, by the Estonian Research Council, grant No. PRG483 and by the Academy of Finland, grant for DECARBON-HOME 335253.

The research has been conducted as a result of the "Nearly-zero energy solutions and their implementation on the deep renovation of buildings, IUT1−15" (financed by Estonian Research Council).

The study utilises the measuring data of the national research projects financed by Estonian Credit and Export Guarantee Fund, by the Ministry of Economic Affairs and Communications and Tallinn University of Technology. We would like to thank Fund Kredex for cooperation of our research work.

Appendix

Publication I

A. Mikola, T. Kalamees, and T. A. Kõiv, “Performance of ventilation in Estonian apartment buildings,” in Energy Procedia, 2017, vol. 132, pp. 963–968. https://doi.org/10.1016/j.egypro.2017.09.681.

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 132 (2017) 963–968

Energy Procedia

www.elsevier.com/locate/procedia

11th Nordic Symposium on Building Physics, NSB2017, 11-14 June 2017, Trondheim, Norway

Performance of ventilation in Estonian apartment buildings

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Abstract

In this study, the performance of ventilation and air change in Estonian apartment buildings with different ventilation systems is analysed by field measurements. 189 apartments from 107 buildings with natural and mechanical ventilation were under investigation. Airflow and CO_2 levels were measured in the heating period and summer period. The airflows in apartments were estimated using the metabolic CO_2 method. Measurements were carried out in the kitchen, toilet and bathroom.
The analyse shows that the average air change rate of concrete and brick buildings was 0.24 h^{-1} and average airflow per surface area of the apartment was 0.17 l/(s·m^2). The total exhaust airflow corresponded to the target values of indoor climate category II in none of the apartments, and in only 5 % of the apartments did it correspond to climate category III. The average air change rate of the newly built (>2000) apartment buildings was 0.42 h^{-1}, and average airflow per surface area of the apartment was 0.3 l/(s*m^2). In 7 % of the new apartments, total exhaust airflow corresponded with the target values of indoor climate category II and in 23 %, of climate category III.
The technical inspection of studied ventilation systems shows that natural ventilation systems are in poor condition. Main problems have to do with insufficient installation quality of channels and exhaust devices and lack of compensation airflow from air building leakages. The main reason for the reduction of the exhaust air flows is related to the low supply air temperatures in cold period. Finally, the principles for the renovation of ventilation systems to provide better indoor climate and energy performance, are also discussed.

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

Keywords: Performance of ventilation; indoor air CO_2 concentration; natural ventilation, metabolic CO_2 method

1. Introduction

The performance of the residential ventilation systems plays major role in healthy indoor air quality because most people spend a significant part of their lives at home. Based on the review of scientific papers, a multidisciplinary group of European scientists have agreed that ventilation is strongly associated with comfort, productivity and health [1–3]. Considering the importance of ventilation rate as an influencing factor for the quality of indoor air and health outcomes that may be influenced by indoor environmental quality, more studies would be valuable [4].

Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics
10.1016/j.egypro.2017.09.681

Previous cross-sectional national studies have shown that a significant proportion of dwellings are mainly with low ventilation rates [5–8]. Measurements of ventilation in dwellings exhibit random variations because of the differences in the building technologies, air tightness, occupancy, human behaviour, maintenance, weather, artistry and material ageing. As the topic is multidisciplinary, using probability-based design will give a guide to reliable alternatives and the associated economic analysis. For that purposes, stochastic data is also needed for the performance of ventilation.

As the real performance ventilation influences comfort, health and energy use in buildings, the topic is important for the public health and national energy saving purposes. In this paper, the actual performance ventilation in Estonian apartment buildings is presented based on field measurements in different types of buildings with different ventilation principles. Since many of the similar apartment buildings in Eastern and Northern Europe have been built using similar technologies as in Estonia, it is possible to draw conclusions of the entire region.

2. Methods

The cross-sectional study about the performance of ventilation was carried out in 189 apartments in 107 different types of apartment buildings. Wooden apartment buildings (45 apartments) built <1940 and concrete apartment and brick buildings built between 1955 and 1990 (83 apartments), had natural passive ventilation. Different structures apartment buildings built after 2000 (39 apartments) had mechanical ventilation. From each building, one to three apartments were selected for the indoor climate study. Typically an apartment was selected from one of the upper floors and the ground floor. Apartments consisted of one, two or three rooms, with a separate kitchen, entry, and sanitary rooms.

Exhaust airflows were measured with an anemometer. Indoor air CO_2 concentrations were measured with HOBO U12-013 together with TelAire 7001 CO_2 loggers. Air change rate in bedrooms was determined based on measurement of the dynamics and level of CO_2 produced by the occupants at 10 min. intervals during 2-3 week periods during winter and summer. Based on measurements of indoor CO_2 levels in bedrooms, the air change in bedrooms was estimated according to mass balance equation:

$$C_{(t)} = C_{ex} + \frac{E}{Q} + (C_{(0)} - C_{(ex)} - \frac{E}{Q})e^{-\frac{Q}{V}t} \quad (1)$$

where: V - effective volume of enclosure (m^3); C - concentration of tracer gas (g/m^3); C_{ex} - outdoor concentration of tracer gas (g/m^3); Q - internal/external exchange rate (m^3/h); t - time (s); E - tracer gas generation (g/h); $C_{(0)}$ - tracer gas concentration at start of decay (g/m^3); $C_{(t)}$ - tracer gas concentration at time "t" after start of decay (g/m^3). As the CO_2 emission varies on a wide scale in daytime, the night period when people are sleeping should be used in air change rate calculations. CO_2 emission of adults is taken 13 l/h and the emission of children up to 12 years 6.5 l/h.

For assessment criteria we use EN-15251 [9] indoor climate category (ICC) III (acceptable, moderate level of expectation, for old buildings) for old (<1990) buildings and ICC II (normal level of expectation, for new buildings and major renovations) for new (>2000) buildings. The measurement results of CO_2 level are brought out for occupancy time only. The average human presence in apartments during the heating period was 68 % and 55 % in summer period.

The air leakage rate of building fabric was measured with the standardised fan pressurisation method [10]. Old wooden apartment buildings were leakier (q_{50} = 10 $m^3/(h \cdot m^2)$; n_{50} = 13 h^{-1}) than old concrete and brick buildings (q_{50} = 4.1 $m^3/(h \cdot m^2)$; n_{50} = 5.8 h^{-1}). The new apartments were the most airtight (q_{50} = 1.7 $m^3/(h \cdot m^2)$; n_{50} = 2.3 h^{-1}).

3. Results

3.1. Indoor CO_2 levels and air change rates in apartments

The average indoor air CO_2 level in Estonian apartments during the occupancy time in the heating period was 1102 ppm and 913 ppm in summer period. In the case of concrete and brick apartment buildings, the average level during occupancy period was 1265 ppm. The average CO_2 concentration in apartments with natural passive stack ventilation (<1990) was 1225 ppm, and in apartments with mechanical ventilation (>2000) it was 788 ppm, see Fig. 1.

During the occupied time in the heating period, the CO_2 concentration indoors in old apartments with natural ventilation corresponded to ICC III class 65 % of the cases and in new apartments with mechanical ventilation corresponded to ICC II class 67 % of the cases. During the occupied time in summer period, the CO_2 concentration indoors in old apartments with natural ventilation corresponded to ICC III class 79 % of the cases and in new apartments with mechanical ventilation corresponded to ICC II class 67 % of the cases.

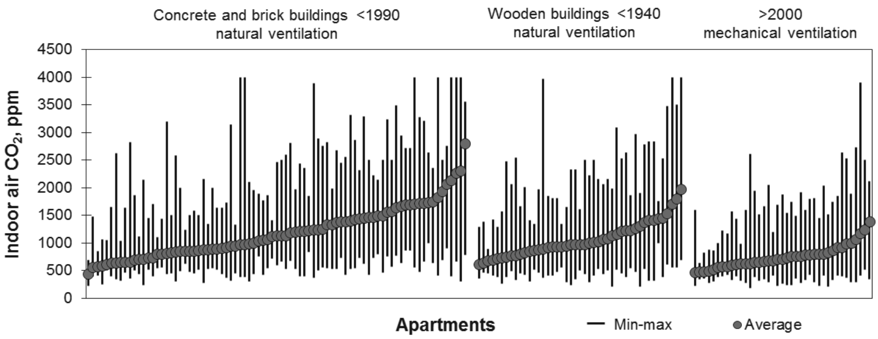

Fig. 1. CO_2 concentration in apartments during the occupied heating period.

3.2. Airflows in bedrooms

The airflow in bedrooms was calculated using the metabolic CO_2 concentration by Formula 1, as the average value of seven day periods. The average airflow of panel and brick buildings with natural ventilation was 4.4 l/s (2.9 l/s per person) during the heating period and 6.2 l/s (5.2 l/s per person) in the summer period. The same airflows in wooden buildings with natural ventilation but leakier building envelope were 6.6 l/s (3.7 l/s per person) during the heating period and 7.8 l/s (3.9 l/s per person) in the summer period. In new apartment buildings with mechanical ventilation, the average airflow was 10.7 l/s (7.1 l/s per person) during the heating period and 12.4 l/s (6.0 l/s per person) in the summer period.

According to EN 15251 [9] criteria to airflow in bedrooms, 22 % apartments in the old panel and brick buildings with natural ventilation corresponded to ICC III during heating and 44 % during the summer period. In old wooden apartment buildings with natural ventilation the correspondence to ICC III criteria was 37 % during the heating period and 47 % during the summer period. In new apartment buildings with mechanical ventilation correspondence to ICC II criteria was 35 % during the heating period and 31 % during the summer period. The average air change rate according to the metabolic CO_2 method is 0.51 h^{-1} both in summer and winter session in the old panel and brick buildings. In wooden buildings, the air change rate is 0.56 h^{-1} in the heating period and 0.79 h^{-1} in summer period. In new apartment buildings with mechanical ventilation the air change rate is 1.1 h^{-1} in the heating period and 1.4 h^{-1} in summer. The airflows in bedrooms per person are shown in Fig. 2. It can be concluded that in all three types of buildings the air change in summer period is higher. The main reason for that trend is the possibility to open the windows without compromising on thermal comfort.

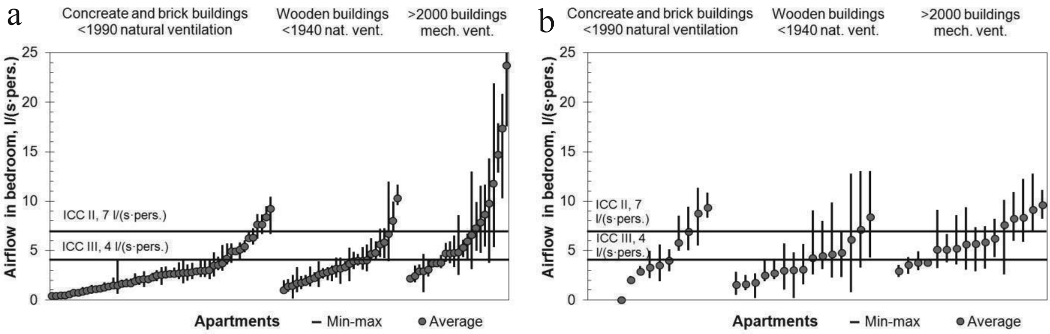

Fig. 2. (a) Airflow in bedrooms calculated according to metabolic CO_2 method during the heating period; (b) Airflow in bedrooms calculated according to metabolic CO_2 method during the summer period.

3.3. Exhaust airflows from kitchen, bathrooms and toilets.

Exhaust airflows were measured in kitchen, bathrooms and toilets, see Fig. 3. In concrete and brick apartment buildings with natural ventilation, the average exhaust airflow (momentary, during measurement in heating period) was 9.1 l/s, the average total air change rate of apartments was 0.24 h^{-1}, and airflow per floor area of the apartment was 0.17 l/(s·m^2). In only 5 % of the apartments, total exhaust airflow corresponded to the target values of ICC III. In new apartment buildings with natural ventilation, the average exhaust airflow was 18 l/s, the average total air change rate of apartments was 0.42 h^{-1}, and airflow per floor area of the apartment was 0.30 l/(s·m^2). In only 7 % of the apartments, total exhaust airflow corresponded to the target values of ICC II.

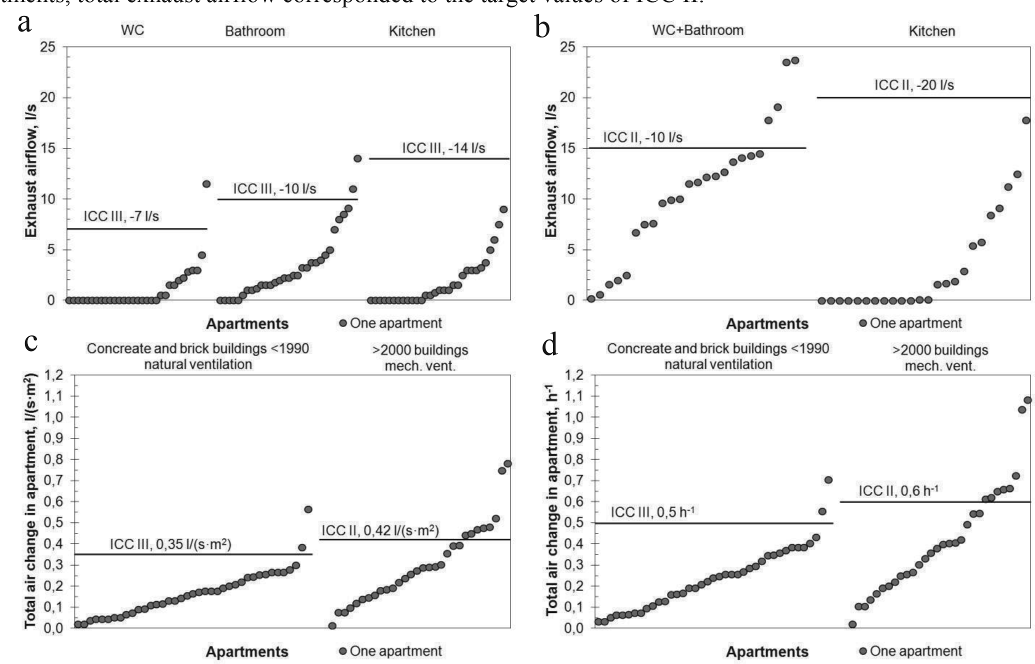

Fig. 3. (a) Exhaust airflows from old apartments with natural ventilation; (b) Exhaust airflows from new apartments with mechanical ventilation; (c) Total air change rate in apartments per floor area; (d) Total air change rate in apartments per internal volume.

3.4. Principles for renovation of ventilation in old apartment buildings

The main task of the renovation of a ventilation system is to ensure indoor air quality. Regardless of the type of the ventilation system, all rooms of the apartment must have continuous and adequate ventilation airflow. Thereby, fresh air inlets must not cause inconvenience by way of drafts and cooling. The current study showed that natural passive stack ventilation does not provide enough airflow in apartments and does not enable heat recovery. The main problems are related to insufficient installation quality of channels and exhaust devices and a lack of compensation airflow from air building leakages. Measurements in apartments with room based air handling units with regenerative ceramic heat exchangers have shown similar insufficient results because they fail to guarantee a continuous air change in apartments and do not comply with the energy efficiency requirements [11].

Based on current knowledge three main types of ventilation are most suitable for Estonian cold climate [12,13]:

- Apartment based supply and exhaust ventilation system with heat recovery, with unit located in apartment, in corridor or staircase.
- Centralized supply and exhaust ventilation system with heat recovery, with unit located on roof, pipes located in external wall or in apartment.
- Centralized exhaust ventilation system with fresh air radiators, heat pump heat recovery; each apartment has a single exhaust shaft, ventilation unit on the roof, or all apartments have joint exhaust shaft, ventilation unit on the roof.

4. Discussion

As ventilation airflows were below standard criteria, and the CO_2 level was over criteria, there is something wrong with the current design and installation practice of ventilation. One of the main reasons could be that designers design ventilation airflow, not the real performance. Usually, the side defects, like too noisy ventilation, draft and high energy use prevent using ventilation in design level. Better design, installation and maintenance guidelines are needed to avoid presented errors in the performance of ventilation in future. Mechanical ventilation ensures statistically significantly lower indoor air CO_2 level than natural ventilation in old panel and brick or wooden buildings. Natural ventilation does not guarantee sufficient air change rate and thermal comfort.

The analysis shows that the ventilation systems of studied panel and brick and wooden buildings need renovation. At the same time, the installation of fresh air valves and retrofitting the other parts of old natural ventilation system does not guarantee the best possible indoor climate in apartment buildings. In dimensioning the natural exhaust ventilation systems, the calculated outdoor air temperature was taken to be +5 ºC. That is the reason why natural exhaust system does not guarantee the sufficient exhaust airflows from apartments even in theory. Another reason for the reduction of the compensation airflow is related to the renovation of building envelopes and replacements of old windows with tighter ones.

Based on this study, we can see a trend that in the case of mechanical exhaust ventilation with the fresh air valves in the new buildings, the exhaust airflows are also reduced. Although the average exhaust airflow in new buildings is two times higher than in buildings with natural ventilation, then in many apartments the fans are maintained in minimal possible airflow. Due to the low-temperature airflow from fresh air valves, the airflow is decreased and the CO_2 level increases in winter period. Thus, when renovating the natural ventilation systems in old apartment buildings or constructing new ventilation systems, the mechanical supply-exhaust system with effective heat recovery should be preferred, or the compensation air from the fresh air valves should be preheated in the case of mechanical exhaust ventilation with heat pump heat recovery. The best possible solution to raise the supply air temperature of mechanical exhaust ventilation is to use the fresh air radiators.

Conclusions

The performance of ventilation in Estonian apartment buildings is distressing. The main problems are connected with too low airflow and high pollutant level. Even in new apartment buildings with mechanical ventilation, where airflows are significantly higher, standard criteria are still not fulfilled. The average indoor air CO_2 level of all the measurements during the occupancy time in the heating period was 1042 ppm, and the average level of occupancy period was 1102 ppm. The indoor air CO_2 concentration of old apartments with natural ventilation in the heating period corresponded to ICC III class 65 % of the occupied time and in new apartments with mechanical ventilation corresponded to ICC II class 67 % of the occupied time. During the occupied time in summer period the CO_2 concentration indoors in old apartments with natural ventilation corresponded to ICC III class 79 % and in new apartments with mechanical ventilation corresponded to ICC II class 67 %.

During the heating period, the average airflow from bedrooms of panel and brick buildings with natural ventilation is 2.9 l/s per person. In wooden buildings with natural ventilation and in case of leakier building envelopes, it was 3.7 l/s per person. In new apartment buildings with mechanical ventilation it was 7.1 l/s per person. The average total air change rate of old apartments with natural ventilation was 0.24 h^{-1}, and airflow per floor area of the apartment was 0.17 $l/(s \cdot m^2)$. The average air change rate of new buildings was 0.42 h^{-1}, and average airflow per surface area of the apartment was 0.30 $l/(s \cdot m^2)$.

For renovation of ventilation in old apartment buildings, we recommend quiet supply and exhaust ventilation with effective heat recovery. In addition to calculating required airflows, the better design of the real performance of ventilation system is also needed. Better design, installation, and maintenance guidelines are needed to avoid presented errors in the performance of ventilation in future.

Acknowledgements

The research has been conducted as a result of the “Nearly-zero energy solutions and their implementation on the deep renovation of buildings, IUT1−15“ (financed by Estonian Research Council). The study utilises the measuring data of the national research projects financed by Estonian Credit and Export Guarantee Fund, by the Ministry of Economic Affairs and Communications and Tallinn University of Technology.

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Publication II

A. Mikola, T. A. Kõiv, J. Rehand, and H. Voll, "The usage of CO2 tracer gas methods for ventilation performance evaluation in apartment buildings," in 10th International Conference on Environmental Engineering, ICEE 2017, 2017. https://doi.org/10.3846/enviro.2017.267.

"Environmental Engineering" 10th International Conference
Vilnius Gediminas Technical University
Lithuania, 27–28 April 2017
http://enviro.vgtu.lt

eISSN 2029-7092 / eISBN 978-609-476-044-0

Article ID: enviro.2017.267
DOI: https://doi.org/10.3846/enviro.2017.267

The Usage of CO_2 Tracer Gas Methods for Ventilation Performance Evaluation in Apartment Buildings

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Abstract. The purpose of the study is to investigate the potential of the CO_2-based tracer gas methods for the ventilation performance evaluation in apartment buildings. To test and elaborate the methods, the ventilation air change rate (ACR) and air change efficiency (ACE) measurements were performed. The methods were tested in laboratory conditions and apartments with natural ventilation, room-based ventilation units, exhaust ventilation and mechanical exhaust ventilation with fresh air radiators. Concentration decay method is applied with both artificially and naturally increasing the concentration of tracer gas. The ACR is also calculated using metabolic constant dosing method with the effective volume. As the traditional tracer gas methods give the correct result only in case of perfect mixed ventilation, then the ACE is also measured. To observe the effectiveness of the air change and the level of air mixing multiple CO_2 sensors placed in different positions. The tracer gas measurements were carried out in naturally ventilated apartments to study the influence of the inner doors to the ACE. The daily variation of CO_2 level in case the long-term CO_2 measurements gives us the possibility to calculate the ACR when inhabitants are sleeping or have left the apartment. Using the CO_2 as the natural tracer gas and the concentration decay method together with the metabolic constant dosing strategy, we can calculate the CO_2 concentrations according to the long-term CO_2 measurements without knowing the exact emission of inhabitants. The studied methods are inexpensive and at the same time sufficiently accurate for airflow measurements. Another reason for the study comes from the ventilation retrofit process in Estonia where the single room ventilation units are used. As these wall-mounted ventilation units are sensitive to in- and outside pressure differences the measurement of ventilation airflow in the traditional way can be inaccurate.

Keywords: Performance of ventilation, tracer gas methods, natural ventilation, metabolic CO_2 method.

Conference topic: Energy for Buildings.

Introduction

The performance of ventilation system is one of the main factors that influences the indoor air quality. During the last decade, the retrofitting process has increased the airtightness and energy efficiency of old apartment buildings in Estonia. At the same time, the indoor air quality is often poor as the air change rate (ACR) in apartments does not meet the requirements of Estonian (Mikola *et al.* 2016). In many studies, the key indicator for the assessment of indoor air quality and ventilation performance in buildings is CO_2 (Guo, Lewis 2007). CO_2 is often used as a passive tracer gas to determine human occupancy in the space and ACR in rooms is controlled by the level of CO_2 in rooms. However, CO_2 produced by people can also be used as a natural tracer gas for ACR measurements (Báránková *et al.* 2004). Tracer gas methods are a widely used practice for assessing the performance of ventilation systems in many countries as these do not request the air speed or pressure measurements from ducts (Cheong 2001). ACR is determined by adding a certain amount of tracer gas to the indoor air of tested zone. According to the change of tracer gas concentration in the air, it is possible to calculate the airflow. The process of ACR measurements are described in detail in the standard EN ISO 12569:2012. Various tracer gas techniques have been used to measure the ACR of buildings. The most often SF6 is used as a tracer gas (Chao *et al.* 2004). At the same time in some studies also other gases for example CO_2 is used (Cui *et al.* 2015). Traces gas techniques are also used to measure the airtightness of buildings (Labat *et al.* 2013). The transient tracer gas techniques for measuring the ACR in a single zone are simple decay, two-point decay, integral decay and charge up method. The steady-state methods to measure airflow are a pulse, constant injection, long-term integral and constant concentration (Sherman 1990). In the same study, it is also pointed out that the most common mistake made in tracer gas analyses, is the fact that, the measurements made under poorly mixed conditions. The best possible method depends on the specific characteristics of the measurement object. For example, the ACR measurements in five-room test-building have shown that only the constant concentration method is suitable for separate airflow calculations in rooms (Etheridge, Sandberg 1996). Other techniques are appropriate for whole house ACR calculations. Chao *et al.* compared the concentration decay and constant concentration methods in an office building with mechanical ventilation system with VAV-dampers and apartment buildings with the natural ventilation. They found that the difference in airflows was 16% which mean that there is a correlation between these methods. The study points out that one of the advantages in case of constant concentration method is the possibility to measure the airflows in the VAV type ventilation system (Chao *et al.* 2004). The tracer gas techniques have also used to assess the ACR in the case of natural (Labat *et al.* 2013) and different types of mechanical ventilation (Cui *et al.* 2015). Labat *et al.* used CO_2 as a tracer gas to obtain ACR measurements in a naturally ventilated building. The measurements were done using the concentration decay method, from October to January during different wind and thermal conditions. The ACR of the building measured from 3 to 18 h^{-1} (Labat *et al.* 2013). In across Catalonia the ACR in 16 single-family dwellings were measured using the tracer gas technique. CO_2 were released until the concentration in rooms were 1500 ppm, and the ACR were calculated using concentration decay method. The ACR of studied dwellings varied 0.074 to 0.541 h^{-1} (Montoya *et al.* 2011). You *et al.* calculated the ACR based on the measured CO_2 data. They used the decay model using non-linear regression analysis to minimise squared residuals for selected periods when a smooth decay curve in CO_2 levels was observed. Another possibility to evaluate the performance of ventilation system is to use the continuous monitoring strategy. It means that the level of CO_2 is measured during a longer period and afterwards the ACR in rooms is calculated according to the measurement results (You *et al*. 2012). Baránková *et al*. developed a method for ACR measurements in naturally ventilated dwellings. The method includes two parameters emission technique and one parameter decay technique. The two-parameter emission technique was used to calculate ACRs based on concentration build up measured in bedroom and guest room during the night when occupants were sleeping. Decay technique was used during the period after the occupants had left the building (Baránková *et al.* 2004).

The Estonian standard of the airflow measurements (EN-12599:2012 2012) says that the preferred way to calculate the ventilation airflows is measuring the air speed in ducts. At the same time in case of apartment buildings with natural ventilation, the air speed is not always possible to measure. The same problem is also with retrofitted apartment buildings were single room ventilation units had been used. As these wall-mounted ventilation units are sensitive to in- and outside pressure differences the measurement of ventilation airflow in the traditional way can be inaccurate. In some cases, it is possible to use the anemometer together with the flow hood, but this measurement method can give inaccurate results. In the USA the scientist has made several studies (Stratton *et al.* 2012) which show that the pressure loss in flow hood influence the measurement result.

The passive CO_2 method gives the correct values only in case of perfect mixed ventilation. The analyses show that the measurements results are not accurate in the case of poorly mixed conditions (Sherman 1990). That is the reason why the air change efficiency (ACE) in the case of different ventilation systems also studied in this paper. The main principles of ACE bases on the mean age of air which introduced by Sandberg (Sandberg 1981). Calculating the local mean age of air with tracer gas technique is described in international standard ISO 16000-8 (ISO 16000-8 2007). The ventilation efficiency is described in detail by REHVA (Mundt *et al.* 2004). Chung and Hsu measured the ventilation efficiency in case of different positions of air diffusers. They considered that the position of the supply and exhaust diffusers is critical and the contaminant removal effectiveness varied up to 39% (Chung, Hsu 2001). At the same time Manz *et al.* studied the room-based air handling units with recuperative and regenerative heat exchangers and measured the ventilation efficiency of both systems. They found that the position of the room-based ventilation unit did not influence the air change efficiency. The measured ventilation efficiency of these room-based solutions was approx 60% (Manz *et al.* 2000). Rojas *et al.* have studied the mechanical exhaust ventilation. The supply air gave to bedrooms, and the exhaust air diffusers were installed in kitchen and bathroom. In the living room, there were no air diffusers installed and ventilation airflow was supplied by the cascade ventilation. The measured ACE in the living room was from 30% to 40% (Rojas *et al.* 2015).

Methods

Description of measurements

As the main purpose of the study is to evaluate the performance of different ventilation systems using the CO_2-based tracer gas method, then laboratory and field measurements are conducted. The tracer gas methods were tested in case of natural ventilation, room-based ventilation units, exhaust ventilation and mechanical exhaust ventilation with fresh air radiators. Concentration decay method was applied with both artificially and naturally increasing the concentration of tracer gas. Tracer gas measurements were carried out in naturally ventilated apartments to study the influence of the position of the inner doors to the ACE. The flowchart of used measuring and the analysing process is pointed out in Fig. 1. Firstly, the CO_2 based ACE measurement method was validated in laboratory conditions. The validation process took place in Mektory ventilation laboratory where different possibilities of air distribution and airflows can be set. The frozen CO_2 used for tracer gas dosing. To observe the effectiveness of the air change and the level of air mixing, multiple CO_2 sensors placed in different positions have been used during the measurements. A total of 10 CO_2 sensors were located at a different high of test-room as showed in Fig. 2a. The Evikon CO2-RH-T E2228L loggers were used. The ventilation airflow and pressure difference measured with Testo 435-4 measuring unit and Testo 410 flow hood. Supply air temperature measured with HOBO UX100-014M Type K thermocouple. The measurements were conducted on the fixed air supply rate with various supply air temperatures and in the case of mixing and short-circuit types of flow. During the test process, the frozen CO_2 was evaporated from the hot water source until the level of the CO_2 was 5000 ppm. The air mixed with the fan to ensure the same CO_2 level at every point of the room. After that the ventilation systems were started with the constant airflow and CO_2 sensors began to record the

CO_2 level in the test-room. The recording interval of CO_2 logger was 1 second. During the test, people were not present in the room. The test ended when the level of CO_2 dropped below 1000 ppm. The values of ACE were calculated using concentration decay method. The supply air temperatures were changed to see if the tested method is consistent with the theory that the ACE increases when the lower supply air temperature used. If the airspace is fully mixed, then the concentration of contaminants is the same at every point of the room and also in exhaust air. It means that the ACE is 50% in case of ideal mixing conditions. In the case of short-circuiting flow, the ACE is below 50%. If the value of ACE does not meet the requirements of the flow type or the ACE is not correlated to the variation of supply air temperature, then the other measuring scheme should be used, or the calculation principles should be corrected.

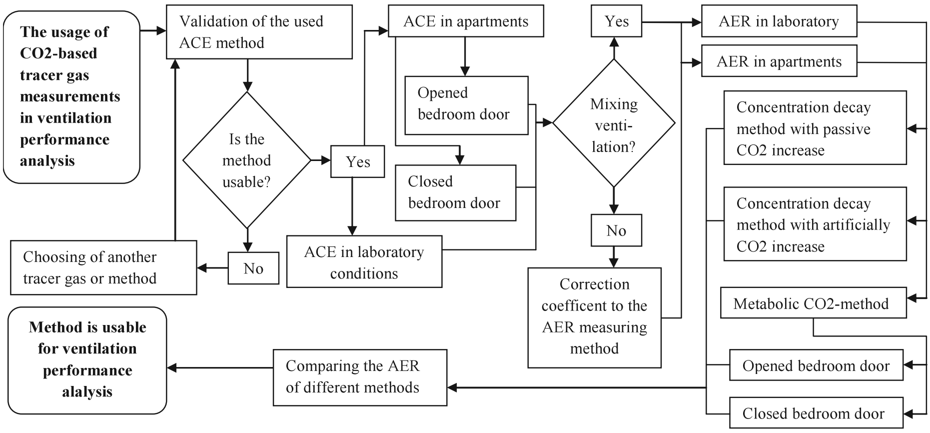

Fig. 1. The flow chart of the performed studies

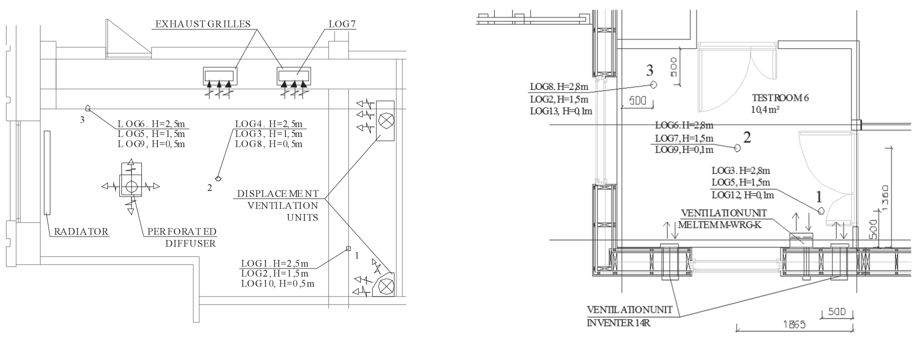

Fig. 2. The position of measuring devices and air diffusers in Mektory laboratory (2a) and Nearly zero energy test building (2b)

After the ACE measuring method is validated the next step of the study is to see the functioning of the method in apartment buildings and laboratory equipped with the various ventilation systems. In the laboratory, the value of ACE was measured in the case of room-based Inventer 14R and Meltem M-WRG-K air handling units and fresh air radiator. The ventilation radiator combined with mechanical extract ventilation. The same measurement devices used as in the previous step. The CO_2 sensors were located at a different high of test-room as showed in Fig. 2b. According to the results of the laboratory measurements the values of ACE were calculated in case 3 different ventilation solution. These results make possible to compare the ventilation efficiency of these systems and also give us the answer how to use the tracer gas method to calculate the ACR values. The ACE measurements were also carried out in 2 naturally ventilated apartments. The area of the first apartment was 43.3 m^2 and the area of the second one was 29.1 m^2. The both apartments locate in typical soviet-time built apartment buildings with natural exhaust valves in the kitchen, toilet and bathroom. The supply air is taken from fresh air valves in case of apartment number 2 and the cracks of the windows in the first apartment. The ACE measurements were done in 2 cases: the inner door closed and the inner door open. The methodology of the measurements and the principles of the ACE calculation were the same as in laboratory test. To imitate the common situation in the apartment, the doors of bathroom and toilet were closed in both cases. The apartment is watched as one zone, and for every room, the local air change index was calculated. The CO_2 measuring devices are installed in every room of the apartment and also near the both exhaust element. The recording interval of CO_2 logger was 1 minute. The nominal time constant was calculated as the average of 2 devices. According to measurement results in the apartment buildings, it is possible to see the influence of the of the inner doors to the value of ACE. If the bedroom door is closed, then the movement of transfer air is decreased. The main question is how the smaller ACR value of apartment influences the ACE. If the ACE value is significantly different from 50%, then we have to correct the mass balance equation with the correction factor.

The ACR value of the laboratory tests was calculated using the concentration decay method. The frozen CO_2 was used for tracer gas dosing. Multiple CO_2 sensors placed in different positions in the same way as ACE studies (see Fig. 2b). After the CO_2 was released, people left the room and during the tests the air was not mechanically mixed. The ACR was calculated according to the average level of all used CO_2 sensors. The values of ACR were calculated according to the Eq. (2). ACR was calculated in case of room-based air handling units and fresh air radiator. As the tracer gas method gives the whole AER of the room which consist of ventilation airflow and the in- and exfiltration airflow, the in- and exfiltration airflow was measured with the same method when the ventilation units were stopped. The calculated values of the airflow measurements were compared with the results based on the anemometer and pressure difference.

The ACR of the studied apartments was measured with three different subdivision of tracer gas method. These methods are the concentration decay method with using the occupant created CO_2, the concentration decay method with using the artificially added CO_2 and metabolic CO_2 method. In case the artificially added CO_2 method the dry ice was used in the same way as in laboratory tests. The CO_2 sensors were installed in bedrooms, and the measurements were done with opened and closed bedroom door. There is also a possibility is to use the concentration decay method with the occupant generated CO_2 as the tracer gas. As in case the natural ventilation the level of CO_2 increases in sleeping period and after the people have left the apartment in the morning the airflow can be calculated according to the decay period. As the increase of the tracer gas concentration is usually lower in occupant generated case, then this method can be more inaccurate. Also if the people are present all the time, then this method cannot be used as there is any decay period. The ACR of the studied apartments was also calculated with the metabolic CO_2 method. The measurements of the CO_2 level were performed at night time when people were sleeping. The CO_2 sensors were installed in bedrooms, and the measurements were done with opened and closed bedroom door. The ACR were calculated using the least squares method. The ACR values of all three used tracer gas methods were compared with each other. If the results of the measurements are not similar, then the methodology is corrected. To study the performance of the calculation methods in wider scale four additional apartments where the indoor air CO_2 level was previously already measured was analysed. The sizes of the apartments were 38–62 m^2 and there lived 1–2 occupants. The AER in these apartments were calculated according to the concentration decay method with using the occupant created CO_2 and metabolic CO_2 method. The door between bedroom and other apartment were opened in all the time.

Methods of finding the air change efficiency

The ACE describes the speed of the room air change compared to the fastest possible air replacement at the same airflow (Mundt *et al.* 2004). This indicator is used when the sources of pollution are not known, or they are constantly changing. That is the reason why this figure can also be used in case of apartment buildings where the main source of pollution is people whose position in the room may constantly change. The ACE is defined as the ratio of the shortest possible air change time to the actual air change time, as in:

$$\varepsilon^a = \frac{\tau_n}{\tau_r} \cdot 100 = \frac{\tau_n}{2 \cdot \langle \tau \rangle} \cdot 100 \,, \tag{1}$$

where: ε^a – the ACE, %; τ_n – nominal time constant, h; τ_r – air change time for all the air in the room, h; $\langle\tau\rangle$ – the room mean age of air, h (Mundt *et al.* 2004). The shortest possible average air change time is $\tau_n/2$ and it is possible only in case the ideal piston flow. In the case of the ideal mixing ventilation, the ACE is 50%. In the case the displacement ventilation the value of ACE is between 50 to 100% and short-circuit below 50%.

To characterise the ventilation effectiveness of certain room point the local air change index is used. It is defined as the ratio of the nominal time constant and local mean age of air, as in:

$$\varepsilon_p^a = \frac{\tau_n}{\tau_p} \cdot 100 \,, \tag{2}$$

where ε_P^a – local air change index in point P, %; τ_p – local mean age of air in point P, h (Mundt *et al.* 2004). In the case of the ideal mixing ventilation, the local air change index is 100% at every point of the room air, and the mean age of air is equal to the nominal time constant at every point of the zone.

Tracer gas methods for the determination of air change rate

Lawrence and Braun have shown that a quasi-static model for CO_2 levels in buildings is sufficiently accurate for evaluation the performance of ventilation in small commercial buildings. A general equation of CO_2 concentration in a well-mixed room is based on mass balance equation for the tracer gas, as in:

$$V\frac{dC}{dt} = QC_{ex} - QC + E - R\ , \tag{3}$$

where: V – effective volume of enclosure (m^3); C – concentration of tracer gas (g/m^3); C_{ex} – outdoor concentration of tracer gas (g/m^3); Q – internal/external airflow (m^3/h); t – time (s); E – tracer gas generation (g/h); R – tracer gas removal rate by means other than ventilation (Lawrence, Braun 2007).

If we assume that the tracer gas removal rate by other processes than ventilation is zero, then R = 0. In case the concentration decay method the injection of the tracer gas is stopped, and the rate E also becomes zero. Integration of Eq. (1) yields the equation:

$$C_{(t)} = C_{ex} + (C_{(0)} - C_{(ex)})e^{-\frac{Q}{V}t}\ , \tag{4}$$

where: $C_{(0)}$ – tracer gas concentration at start of decay (g/m^3); $C_{(t)}$ – tracer gas concentration at time "t" after start of decay (g/m^3) (Guo, Lewis 2007).

If tracer gas is released at a constant rate, Eq. (1) becomes:

$$C_{(t)} = C_{ex} + \frac{E}{Q} + (C_{(0)} - C_{(ex)} - \frac{E}{Q})e^{-\frac{Q}{V}t}\ . \tag{5}$$

In some studies the CO_2 emissions from people are observed as the average value of 24 h period and the CO_2 emission is calculated based on the normal metabolism of the same period. In the other studies, the CO_2 emissions are brought out during the sleeping period. As the CO_2 emission varies in wide scale in daytime, the night period when people are sleeping should be used in ACR calculations (Guo, Lewis 2007). In earlier studies of the indoor air quality in Estonian apartment buildings, the night time emissions are used for ACR calculations with metabolic CO_2 method (Mikola *et al.* 2016). The CO_2 emission of adults is taken 13 l/h and the emission of children up to 12 years 6.5 l/h. At the same time in various studies have pointed out that the emission of CO_2 can vary in large scales. In this study, the least squares method as an alternative possibility is observed. The main idea of the least squares method is to find the values of airflow, CO_2 emission to the room and effective volume of the zone in a way that the cure of real CO_2 measurements would be as close as possible to the theoretical curve of the CO_2 variation. The curve fitting process is done by using "Solver" function in Microsoft Excel. In the case of the real CO_2 measurements in apartments, we should also consider optimising the value of the effective volume of the zone.

Results and discussion

Laboratory measurement results

The described CO_2 based method of measuring ACE was tested and validated in Mektory laboratory. As every test was repeated two times, then two separate values of the air ACE were calculated. The nominal time constant was 0.25 h in all test cases. The nominal time constant equals to the mean age of air of the exhaust air. The mean age of air was calculated according to the concentration decay method. If the supply air temperature was 16 °C the ACE was 51.5% and 50.9%. In case the supply air temperature 21 °C the ACE was 43.1% and 46.1%. In case the lower supply air temperatures, the ACE is close to the ideal mixing. If the supply air temperature rises, then the efficiency falls. We also tested the layout of the diffusers which we assumed to short-circuit ventilation. In case the supply temperature of 16 °C the solution provided the ACE 44.4% and 40.1% and in case the temperature 21 °C, the ACE were 41.1% and 42.1%. The main overview of the efficiency measurements is pointed out in Table 1. The tests of mixing and short-circuit ventilation showed that the used method is in good correlation to the theory.

Table 1. The overview of the ACE measurements

Type of air distribution	Mixing ventilation				Short-circuit ventilation			
Nr. of test	K14	K19	K15	K20	K12	K16	K13	K18
Supply temperature, °C	16	16	21	21	16	16	21	21
Ventilation airflow, l/s	100	100	100	100	100	100	100	100
Mean age of air, h	0.24	0.25	0.29	0.27	0.28	0.31	0.30	0.30
Nominal time constant, h	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Air change efficiency, %	51.3	50.9	43.1	46.1	44.4	40.1	41.1	42.1

The ACE was also studied in case 2 type of room-based ventilation units and exhaust ventilation with fresh air radiators. Inventer 14R type of ventilation devices were tested in 25% and 50% speed of maximum value. In these speeds, the sound pressure level in apartment buildings is below the 30 dB(A). The calculated mean age of air and nominal time constant are pointed out in Table 2. The ACE is from 50% to 52%. It is possible to conclude that the values of the air change efficiency do not depend on the airflow of the unit and the unit ensures perfectly mixing ventilation. Meltem M-WRG-K ventilation units were tested in 30% and 50% speed levels. In these speeds, the sound pressure level in apartment buildings is below the 30 dB(A). The mean age of air was between 0.98 to 1.54 h, and the ACE was 48–50%. Although the variety in ACR was considerable, then the air ventilation was still mixing type. The main purpose for the difference on airflows was to study the influence of wind. The main parameters of the test cases are pointed out in Table 2. In the case of fresh air radiator, the ACR in the test room was set to 0.8 and 1.2 h^{-1}. The airflow was measured with the Testo flow hood. The ACE was in the range 49–50% which is close to the value of mixing ventilation. The main parameters of the test cases are pointed out in Table 2.

Table 2. The ACE in case the tested ventilation solution

Tested ventilation unit	Inventer 14R				Meltem M-WRG-K				Fresh air radiator			
Nr. of test	K6	K7	K8	K9	K11	K13	K10	K12	K14	K15	K16	K17
Speed of fan, %	25	25	50	50	30	30	50	50	7.5	7.5	10.9	10.7
Supply temperature, °C	24.2	20.5	22.5	23.4	14	12.1	16.8	11.7	15.8	17.5	15.2	16
Mean age of air, h	1.25	1.47	1.02	0.99	1.54	1.35	1.13	0.98	0.92	1.13	0.75	0.77
Nominal time constant, h	1.25	1.46	1.04	1.02	1.52	1.30	1.13	0.98	0.89	1.12	0.75	0.77
Air change efficiency, %	50	50	51	52	49	48	50	50	49	50	50	50

The air change efficiency analyses in laboratory conditions showed that ACE of all tested ventilation systems was close to 50%. The ventilation distribution is mixing type, and the tracer gas method can be used without any correction factors to Figure 3. The next step of the study was to measure the airflow using CO_2 as the tracer gas. The method is firstly tested in laboratory conditions, and the values of ACR are compared to the anemometer measured values. The level of CO_2 is increased artificially and each airflow two measurements were done. The values of ACR are compared in Table 3. The average variety of ACR measurements with tracer gas and anemometer was 2%. We also discovered that also the same airflow was measured two times in the same value, the measurement result using the tracer gas method were different. For example, in the case of the fresh air radiator the first ACR was 1,09 h^{-1}, and in the second test, the result was 0.89 h^{-1}. As the airflow was measured with the flow hood at the beginning of the test, this phenomenon might be caused by the influence of wind. The ACR values of the tracer gas measurements were lower than the measurements with the flow hood. The average ACR of all measurements was 1.03 h^{-1} with the tracer gas and 1.18 h^{-1} with the flow hood. To make the values comparable, the infiltration ACR is added to the flow hood measurement result. The average variety of result two different type of measuring method is 18%.

Table 3. Airflow measurement results of laboratory tests

Tested ventilation unit	Inventer 14R						Meltem M-WRG-K				Fresh air radiator			
Nr. of test	K2	K4	K6	K7	K8	K9	K10	K11	K12	K13	K14	K15	K16	K17
Speed of fan, %	60	60	25	25	50	50	50	30	50	30	lower		higher	
ACR with tracer gas, 1/h	1.07	1.11	0.80	0.68	0.98	1.00	0.89	0.65	1.02	0.74	1.09	0.89	1.33	1.30
Measured ACR, 1/h	1.18	1.11	0.69	0.69	1.14	1.14	–	–	–	–	0.87	0.87	1.26	1.23

Field measurements

The air change rate were also measured in the previously described apartments. The nominal time constants were calculated according to the decay concentration of exhaust grilles. The local air change index was the lowest in the closed-door bedroom of apartment nr. 1, where the index was 61%. In apartment nr. 2 the local air change index in the same conditions was 94%. In the case of ideal mixing the local air change indexes have to be 100%. It is possible to consider that the position of the bedroom is the key parameter which decreases the air change efficiency. In case the opened bedroom doors the local air change indexes were in range 97–101% in the first apartment and range 99–105% in the second apartment. If the bedroom door is opened, then we have the mixing type of ventilation. The nominal time constants and the local air change indexes in test apartments are described in Table 4. In test apartment one and two the ACR was measured using the concentration decay method with both artificially and naturally increasing the concentration of tracer gas. In Table 4, the ACR of the bedroom and the other part of the apartment are pointed out. If the bedroom door is opened, then the airflow in the bedroom and other parts of an apartment varies up to 3%. In the situation when the bedroom door was closed, the ACR in the bedroom of second test-apartment was 36% higher. Although the correlation coefficients of ACR calculation are over 0.99, then the calculated ACR in case artificially and naturally added tracer gas varies up to 29%. The main reason for the high variation is the effect of the wind and aspect that the tests were not done at the same time. To sum up, the concentration decay method with the naturally increasing the concentration of tracer gas is possible to use in field measurements.

Table 4. The nominal time constants and the local air change index in test apartments (number 1 and 2)

Code of apartment	Position of the bedroom door	Local air change index, %						ACR, 1/h				
								Artificial decay		Natural decay		Metabolic method
		Bed-room	Living room	Kit-chen	Bath-room	WC	Cor-ridor	Gene-ral	Bed-room	Gene-ral	Bed-room	Bedroom
1	Opened	97	100	99	100	99	101	0.21	0.20	0.25	0.26	0.28
	Closed	61	85	108	97	118	104	0.25	0.16	–	0.17	0.21
2	Opened	105	104	104	99	0.48	0.46	0.48	0.46	0.45	0.46	0.40
	Closed	94	98	103	93	0.44	0.38	0.44	0.38	0.37	0.27	0.32
3	Opened	–						–	–	–	0.29	0.33
4	Opened							–	–	–	0.12	0.16
5	Opened							–	–	–	0.23	0.30
6	Opened							–	–	–	0.30	0.24

To study the performance of the calculation methods on the wider scale, we also analysed four apartments where the indoor air CO_2 level was previously already measured. We know that if the bedroom door is closed, then the air in other parts of the apartment, is not ideally mixed. That is why the effective volume is only the bedroom volume. However, if the door is opened, then the effective volume is the whole apartment or part of the apartment. The average ACR of all the measurements were 0.28 h^{-1} with the metabolic CO_2 method and 0.26 h^{-1} with the concentration decay method. The average variety between the two methods was 6.3%. The biggest difference comparing the ACR of used methods was 25%. The moderate average variety of the methods shows that these CO_2 based tracer gas methods are suitable for evaluating the performance of ventilation in apartment buildings. At the same time, it is a more reliable way to calculate the ACR values with the both method.

Conclusions

Firstly, the ACE measurement method was validated in laboratory conditions. The test results for assessing the ACE showed that nearly ideal mixed ventilation was achieved. The lower supply air temperature increased the air change effectiveness. If the supply air temperature was 16 °C, the ACE was 51–52%. In case the supply air temperature 21 °C the ACE was 43–46%. It can be concluded that the lower supply air temperature the ACE is closer to the ideal mixing. The next step of validating the ACE measuring method was to measure the ACE values in apartment buildings and laboratory equipped with the various ventilation systems. As the values of the ACE were in the range 48% – 52%, the test results confirmed that all tested ventilation renovation solutions were capable of producing mixed ventilation. The ACE was not affected by the variation of the fan speed. It is also possible to find that the tracer gas method can be used without any correction factors. At the same time, it should be noted that high ACE is not the only criteria for providing good indoor air quality. The test results in apartments indicated that the position of the inner doors significantly affects the ACE. The local air change index in the bedroom with the closed door was up to 39% lower than it would have been in the case of fully mixed ventilation. When the bedroom door was open, the local air change indexes were the same throughout the whole apartment and in correlation with fully mixed ventilation. Based on that, it was concluded that the effective volume of the ventilated zone depends on the door position. Consequently, when calculating the ACR in the bedroom with closed or open door, the effective volume used in calculations should be only the volume of the bedroom and the volume of the whole apartment or part of the apartment, respectively.

The next step of the study was to measure the airflow using CO_2 as the tracer gas. The method was firstly tested in laboratory conditions, and the values of ACR were compared to the anemometer measured values. The ACR values of the laboratory tests were calculated using the concentration decay method. The average variety of ACR measurements with tracer gas and anemometer was 2%. The average ACR of all measurements was 1.03 h^{-1} with the tracer gas and 1.18 h^{-1} with the flow hood. The average variety of two different type of measuring method is 18%. The ACR of the studied apartments was measured using the concentration decay method with using the occupant created CO_2, the concentration decay method with using the artificially added CO_2 and metabolic CO_2 method. Although the correlation coefficients of ACR calculation are over 0.99, then the calculated ACR in case artificially and naturally added tracer gas varies up to 29%. All three methods produced comparable results, which confirmed the applicability of the studied techniques for measuring the ACR. Unlike other measuring procedures, metabolic methods, which utilise the daily fluctuation of CO_2 concentration in apartments, have the advantage of having no impact on the everyday life of tenants. In summary, the studied CO_2 based tracer gas methods are suitable for the airflow measurements in apartment buildings with studied ventilation systems.

Funding

The research has been conducted as a result of the "Nearly zero energy solutions and their implementation on the deep renovation of buildings" [IUT1−15] (financed Estonian Research Council).

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Publication III

A. Mikola, J. Rehand, and J. Kurnitski, “Air change efficiency of room ventilation units,” in E3S Web of Conferences, 2019, vol. 111. https://doi.org/10.1051/e3sconf/201911101017.

E3S Web of Conferences 111, 01017 (2019) https://doi.org/10.1051/e3sconf/201911101017
CLIMA 2019

Air change efficiency of room ventilation units

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Abstract. The purpose of this study is to investigate the air change efficiency of commonly used residential room ventilation units with tracer gas concentration decay method. Carbon dioxide was used as a tracer gas in both laboratory and field measurements. The performance of room ventilation units was compared to the conventional mixing ventilation. Therefore, the laboratory measurements were conducted with horizontal supply air jet from the overhead air diffuser on the fixed supply airflow rate with various supply air temperatures. The test results showed that nearly fully mixing ventilation was achieved. Furthermore, lower supply air temperature increased the air change efficiency. In next step, the air change efficiency of three room ventilation systems were measured in the test room. Tested systems included pair-wise units, monoblock unit and ventilation radiator, which was combined with mechanical extract ventilation. The measurements were carried out both during the heating period and outside the heating period. The results confirmed that all three solutions were capable of producing fully mixed ventilation. The air change efficiency was not affected by the variation of the air flow rate. Finally, tracer gas measurements were carried out in naturally ventilated apartments and the air change efficiency of these measurements were compared with the results of rooms based ventilation units.

1 Introduction

Ensuring the healthy indoor climate is becoming more and more important during the process of constructing and refurbishing buildings. One of the most important components of healthy indoor climate is air quality, which can be controlled by providing sufficient air exchange rate (ACR) with the ventilation system. ACR is a quantitative value, which shows the ratio of supply and extract air flow rate to the volume of the room. The air change efficiency (ACE) has to be calculated to make sure that the air quality is equally good in all locations of the room. ACE is a value which describes how effectively fresh air is distributed in the room.

ACE can be calculated using tracer gas methods. A certain amount of tracer gas is added to the room air and the concentration alteration is examined. ACE is based on the mean age of air, which was first introduced by Sandberg in 1981 [1]. The calculation methods for the mean age of air using tracer gas methods are described in detail in international standard ISO16000-8 [2]. A thorough instruction for the calculation methods has been compiled by REHVA [3]. Chung and Hsu measured ventilation efficiency with different supply diffuser positions and concluded that position of the diffuser had a remarkable effect on the contaminant removal efficiency (CRE). The maximum difference of the CRE was 39% [4]. On the other hand, Mainz et. al. studied the efficiency, including ACE of room ventilation air-handling units with regenerative and recuperative heat recovery and came to an opposite result. ACE was not affected by the position of the air-handling unit and was uniformly high - the mean value was around 60%. ACE value for fully mixed ventilation is 50% [5]. Rojas, Pfluger and Feist studied ACE in a flat with cascade ventilation. The supply air was provided to the bedrooms, which were connected to the living-room through a corridor. The ACE of the living-room was low, between 30% and 40% with that solution [6]. Mikola, Kõiv and Rehand measured the ACE of mixed ventilation and concluded that lower supply air temperature resulted in higher ACE value [7].

2 Methods

2.1 Description of measuring methods

The main purpose of the study is to evaluate the performance of different ventilation strategies in different environments. Thus, both laboratory and field tests were conducted. Laboratory tests were conducted in the Mektory ventilation laboratory and nearly zero energy (nZEB) test building in Tallinn University of Technology (TalTech). Field measurements were carried out in two flats with natural ventilation in Tallinn. The measurements in the Mektory ventilation laboratory and nZEB test building were carried out both during the heating period and outside the heating period.

Concentration decay method was applied and CO_2 was used as a tracer gas. The advantages of CO_2 include easy measuring process and low risk on health. A

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relatively high concentration in the outdoor air can be considered as a disadvantage. The natural concentration of CO_2 was subtracted from the test values to minimize the impact on the results. Frozen carbon dioxide, also known as "dry ice" was used as a source. It was vaporized in hot water. Room air was mixed with fan to ensure uniform concentration in the room at the beginning of the experiment. People were not present in the test room during the experiment. The concentration of CO_2 in the room air was raised to 5000 ppm. The lower limit of the decay calculation was set to 1500 ppm. The calibration process of used CO_2 based concentration decay method is described in detail by Mikola, Kõiv and Rehand [7]. It is shown that the correlation between the real decay curve and the theoretical exponential decay decreases at lower concentration values [7].

Firstly, ACE was measured in Mektory ventilation laboratory using perforated overhead air diffuser with horizontal supply jet. Two different supply air temperatures were tested. The achieve the ideal mixing ventilation the mixing fan which was placed in the middle of the test room and it was used to verify the used methods. The setup of the test room in Mektory lab is shown in Fig. 1 The floor area of the test room was 33 m^2 and the effective volume was 90 m^3. A total of ten CO_2 sensors were placed in different positions in the test room, including one on the extract grille. The positions of the sensors are shown in Fig. 2. The objective was to cover the room evenly to measure air change efficiency in all areas of the room. Evikon CO2-RH-T E2228L CO_2 sensors/loggers were used.

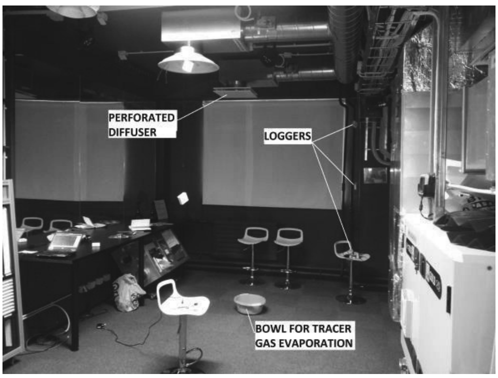

Fig. 1. The test room in Mektory ventilation laboratory.

Secondly, three different room-based ventilation systems were tested in nZEB laboratory of TalTech to determine the ACE provided by them. To to avoid the effects of the sun and other heat loads, the tests were made during stable outdoor climate conditions and cloudy periods and the curtains were in front of the windows. The area of the test rooms was 10.4 m^2 and volume 31.2 m^3 which is a similar size to the bedroom of a common flat in Estonia. The first examined room solution was pair-wise unit, which is a device with regenerative heat exchanger (see Fig. 3 left). The unit is equipped with only one fan, which operates cyclically both as supply and exhaust, and is located on the wall of the test room. Two units, which operated in the opposite direction, were installed in the test room. The air flow was directed upward along the wall.

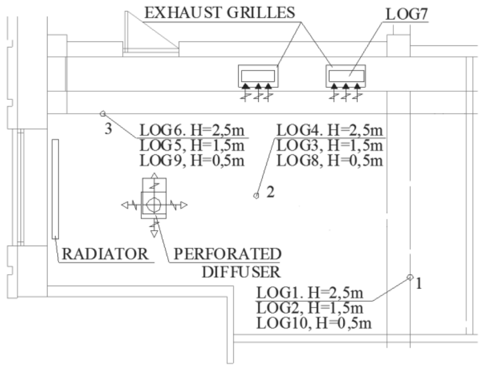

Fig. 2. The setup of CO_2 sensors and air diffusers in Mektory ventilation laboratory.

The second unit was a monoblock ventilation unit equipped with recuperative heat exchanger and supply and exhaust air fans (see Fig. 3 right). The device was placed on the wall of the test room. Supply and exhaust terminals are both located on the top of the device quite close to each other.

Finally, a ventilation radiator combined with mechanical extract ventilation was tested (see Fig. 3 bottom). The radiator was located under the window and the extract valve in the ceiling in the middle of the room. The same ten CO_2 sensors with a similar setup were used for concentration decay measurements. The layout of the test rooms is shown in Fig. 4.

Fig. 3. Tested pair-wise, monoblock and ventilation radiator units in nearly zero energy test building.

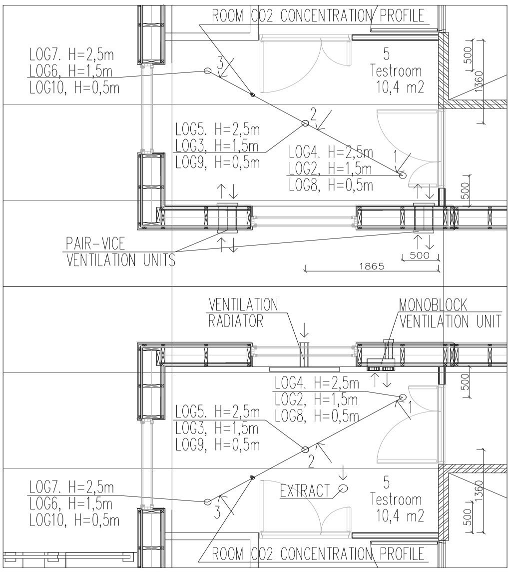

Fig. 4. The setup of CO_2 sensors and air diffusers in nearly zero energy test building.

As room ventilation units have been widely used to renovate the ventilation systems of old apartment buildings, the objective was to determine whether these ventilation solutions are capable of providing fresh air to all areas of the room and therefore create a mixed air flow which is recommended solution for a common flat. All three devices were tested on two different fan speeds to verify, if the air distribution in the room was affected by the air flow rate. Fan power levels were chosen the way that the sound pressure levels in the room would be under 25 dB(A) and 30dB(A), which are maximum recommended and allowed values respectively according to Estonian regulations [8], [9].

As a next step, field measurements were conducted. The air change efficiency was determined in two flats. Both of the apartments were located in a non-refurbished soviet-time building. The flats were equipped with natural ventilation with extract grilles in bathroom, WC and kitchen. No specific air intakes were installed. Such buildings represent an old not renovated building stock in Estonia. The floor areas of the flats were 43.3 m^2 and 29.1 m^2. The apartments were occupied by two and one persons, respectively. The floor plans of the flats are shown in Fig. 5.

Providing sufficient ventilation is especially important in the bedroom of the apartment because occupants spend the most time there. In the flats where intake and extract openings are positioned in different rooms, the air change efficiency can be significantly affected by the position of the inner doors, because pressure differences of natural ventilation are small. Therefore, tests were conducted in two different situations - with open and closed bedroom door. The doors of bathroom and toilet were closed to imitate the most common situation. CO_2 sensors were placed in each room and also on each extract grille. Nominal time constant was calculated based on the average concentration decay of the extract grilles. The logging interval of the concentration was one minute. The whole apartment was considered as one air zone. Therefore, local air change index, which describes the ventilation efficiency can be calculated for each room separately.

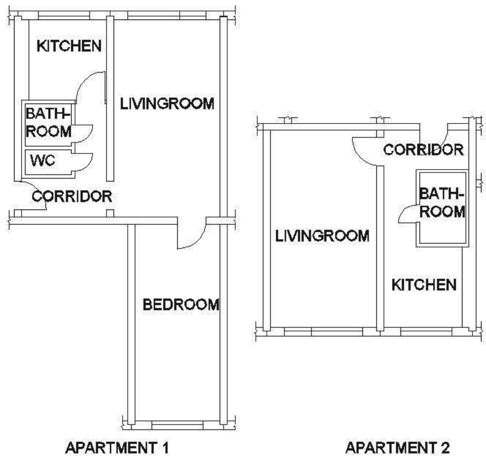

Fig. 5. The layout of the tested apartments.

2.2 Methods for calculating the air change efficiency

To calculate the ACE, the concept of mean age of air has to be introduced. Mean age of air is a statistical figure which is based on the age distribution of air components in a certain point and it is expressed in time units. The counting of the age starts at the moment when air enters the room. Air in certain point consists of components which have covered different distance in the room and also spent different period of time there. Local mean age of air τ_p is the statistical average value of those components. The mean age of air $\langle\tau\rangle$ in the whole room is the average local mean age of air of all the points in the room. In case of fully mixed ventilation, τ_p is equal in all room points. On the contrary, in case of short-circuit flow, the local mean age of air is low in the short-circuit zone and high in the stagnant zone. According to the definition, τ_p in the extract air is always equal to the nominal time constant τ_n of the room, which is the minimal possible time for the exchange of all room air [3].

$$\tau_n = \frac{V}{L} \tag{1}$$

where: τ_n - nominal time constant, h; V - volume of the room, m^3; L - ventilation air flow rate, m^3/h.

The mean age of air was calculated according to the international standard ISO-16000-8 [2]. Although the standard provides methodology for the calculation of local mean age of air, it can be expanded to the whole room based on the definition shown above. To calculate the mean age of air in the room, the average concentration of all measured room points on each minute was plotted in logarithmic scale in relation with time. If the relation between the two values is exponential, the curve will be a straight line. The absolute value of the depression angle of the curve shows the average air change rate and the reciprocal of which is the mean age of air in the room [2].

$$\tau = \frac{1}{\lambda} \quad (2)$$

where: τ - mean age of air, h; λ - average air change rate and depression angle of the function, 1/h.

Air change efficiency is defined as a ratio between the shortest possible air change time and the actual air change time τ_r. It can also be described as the ratio between the shortest possible mean age of air and the actual mean age of air. The shortest possible mean age of air in the room is $\tau_n/2$ which occurs in case of the ideal piston flow [3].

$$\varepsilon^a = \frac{\tau_n}{\tau_r} \cdot 100 = \frac{\tau_n}{2 \cdot \langle \tau \rangle} \cdot 100 \quad (3)$$

where: ε^a - ACE, %; τ_n - nominal time constant, h; τ_r - actual air change time in the room, h; ‹τ› - mean age of the room air, h. ACE is expressed as a percentage with the maximum value 100% which occurs during piston flow. The ACE of ideally mixed flow is 50%, displacement flow between 50% and 100% and short-circuit flow under 50% [3]. The ACE value 50% is normal for an occupied room [10].

A concept of local air change index ε_p^a is defined to measure the ACE in a certain room point. It is defined as a ratio between nominal time constant and local mean age of air [3].

$$\varepsilon_p^a = \frac{\tau_n}{\tau_p} \cdot 100 \quad (4)$$

where: ε_p^a - local air change index in point P, %; τ_n - nominal time constant, h; τ_p - local mean age of air in point P, h.

3 RESULTS AND DISCUSSION

3.1 Laboratory test to verify the concentration decay method

The CO_2 concentration decay method was used in Mektory ventilation laboratory to verify the presumed ACE of mixed ventilation. Firstly, the conditions of ideal mixing ventilation laboratory was tested, used the mixing fans. The results of ACE were close to ideal mixing. To analyse the influence of supply air temperature, two different supply air temperatures were tested and two separate measurements were carried out on each setting. The nominal time constant during all the tests was 0.25 h which calculated based on the fixed air flow rate of the ventilation unit. Fig. 6 shows that the actual CO_2 concentration decay during all the tests correlated very well with the theoretical exponential decay curve that proved the accuracy of the method. The correlation was at least 0.99 in all four experiments. The steeper depression angle on Fig. 6 expresses bigger ACR and lower mean age of air in the room air. Results of mixed ventilation tests are shown in Table 1. According to the definition, the mean age of air in the extract air is equal to the nominal time constant. The maximum difference in the test results was 15%.

If the supply air temperature was 16 °C, the ACE values were 51.3% and 50.9% and if the supply temperature was 21 °C, the ACE values were 43.1% and 46.1%. This shows that the ventilation in the test room with 16 °C supply temperature can be considered fully mixed. The mixing was less efficient during tests K3 and K4, when the supply temperature was 21°. ACE values were 43.1% and 46.1%, respectively. As both supply diffuser and extract grille were on the ceiling, the most important factor in terms of high ACE was the supply air jet throw length to reach to the floor. A visual test with smoke was also conducted. The observation verified that the supply air with lower temperature reached the floor with higher velocity. The local air change index values were constantly higher with the lower supply temperature as well. The correlation with theoretical decay was at least 0.98 for all the loggers. The local air change indexes were between 93% and 109% in tests K1 and K2 and between 82% and 92% in tests K3 and K4. No stagnant zone was detected based on the local measurements.

Table 1. Test results of mixed ventilation.

Test no.	K1	K2	K3	K4
Room and supply air temperature difference (°C)	-6.0	-6.9	-1.1	-2.2
Mean age of air (h)	0.24	0.25	0.29	0.27
Nominal time constant (h)	0.25	0.25	0.25	0.25
Mean age of air in extract air(h)	0.25	0.25	0.29	0.28
Air change efficiency (%)	51.3	50.9	43.1	46.1

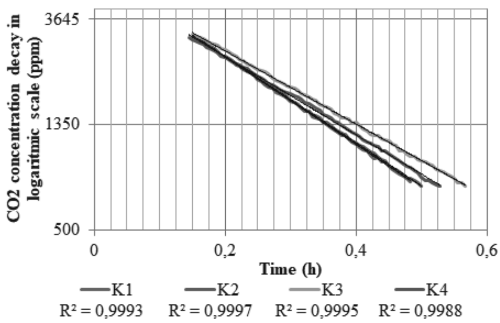

Fig. 6. Concentration decay in mixed ventilation tests.

3.2 Laboratory test results

Three room-based ventilation solutions were tested in nearly-zero energy test building in TalTech. The decay curve was very good correlation with theoretical curve as the correlation was at least 0.99 during all the tests in heating period and at least 0.98 in warm period. The results of the measurements of room-based units in heating period are shown in Table 2 and Fig. 7 and outside the heating period are shown in Table 3.

Firstly, pair-wise unit was tested in heating period and outside the heating period in different fan speeds. The room and supply air temperature differences were from -4.8 °C to -2.2 °C. In heating period the mean age of air in tests K5 and K6 were 1.25 h and 1.47 h, respectively. Despite the same fan speed, the difference was 15%. It was possibly caused by the wind or the difference between supply and room temperature. If the fan speed was 50%, the difference of the results was very small as the mean age of air values were 1.02 h and 0.99 h.

Pair-wise units were also tested outside the heating period with fan speed 25%, 50% and 75%. The mean age of air in tests were 1,25 h (M1), 0.96 h (M2), 0.58 h (M3) and 0.65 h (M4). The room and supply air temperature differences were from -0.9 °C to -2.1 °C. The values of ACE were 46% – 51%. It can be concluded that the ACE is lower outside the heating period as the room and supply air temperature difference is lower. The temperature difference is lower outside the heating period as it is not possible to turn off the heat recovery and the heat is recovered also during the warm period.

Secondly, monoblock ventilation unit was tested. In heating period the mean age of air values were 1.54 h and 1.35 h with 30% fan power, and 1.13 h and 0.98 h with 50% fan power. As the difference of nominal time constant was in the same magnitude and the ACE values were 48% - 50%, it can be concluded that the air flow rates were different during the tests. The air flow rate was most likely affected by the pressure differences caused by wind and the difference of inside and outside temperatures.

Outside the heating period the mean age of air values were 1.1 h with 30% fan power and 1.13 h with 50% fan power. The room and supply air temperature difference were -1.1 °C and -1.2 °C. The values of ACE were 47% and 48%. In the same way, as pair-wise units, the ACE of monoblock units is lower outside heating period. The main reason is in high supply air temperature.

Thirdly, ventilation radiator was tested in combination with mechanical extract ventilation. Tests were done during heating and warm period. The air flow rates were chosen to be similar to the values of the bedroom of a common apartment. The difference between room temperature and supply air temperature were -7.9 °C (K13), -5.6 °C (K14), -6.7 °C (K15) and -6.0 °C (K16). In heating period the ACE values were 49% – 50%.

In summer period two different test were made and the difference between room temperature and supply air temperature were -8.1 °C (M7) and -7.7 °C (M8). The airflows were similar to the heating period values. The ACE values outside the heating period were 54% in both test. The air change efficiency is higher in warm period because the heating system is turned off and the supply air is not heated.

The ACE in the test room was 48% – 52% during all the heating period tests with all three of the units (see Table 2). As 50% ACE value expresses ideal mixing flow, the air flow can be considered fully mixed with all three devices. It was also noted that the alteration of air flow rate did not have any impact on the ACE which means that even if the air flow rate was lower, the fresh air still reached every part of the test room. Fig. 8 shows the local air change indexes in the test room with all three room based units.

The ACE values outside the heating period were 46% – 54% (see Table 3). In case of pair-wise and monoblock units the ACE values are higher in heating period and in case of fresh air radiators the ACE vales are higher outside the heating period. The reason for that trend is different supply air temperature. In case of pair-wise and monoblock units the supply air temperature was close to the room temperature during the warm period. At the same time in case of ventilation radiator the supply air temperature was lower.

Table 2. Test Results of room-based ventilation units in heating period.

Ventilation Unit	Pair-wise				Monoblock				Ventilation radiator			
Test No.	K5	K6	K7	K8	K9	K10	K11	K12	K13	K14	K15	K16
Fan speed (%)/Air flow rate (l/s)	25	25	50	50	30	30	50	50	7.5	7.5	10.9	10.7
Room and supply air temperature difference (°C)	-4.8	-2.9	-2.2	-2.6	-7.2	-10.5	-8.7	-10.0	-7.9	-5.6	-6.7	-6.0
Mean age of air (h)	1.25	1.47	1.02	0.99	1.54	1.35	1.13	0.98	0.92	1.13	0.75	0.77
Nominal time constant (h)	1.25	1.46	1.04	1.02	1.52	1.30	1.13	0.98	0.89	1.12	0.75	0.77
Air change efficiency (%)	50	50	51	52	49	48	50	50	49	50	50	50

Table 3. Test Results of room-based ventilation units outside heating period.

Ventilation Unit	Pair-wise				Monoblock		Ventilation radiator	
Test No.	M1	M2	M3	M4	M5	M6	M7	M8
Fan speed (%)/Air flow rate (l/s)	25	50	75	75	30	50	7.7	7.9
Room and supply air temperature difference (°C)	-1.7	-2.1	-0.9	-1.3	-1.1	-1.2	-8.1	-7.7
Mean age of air (h)	1.35	0.93	0.63	0.69	1.17	0.86	1.12	1.09
Nominal time constant (h)	1.25	0.96	0.58	0.65	1.10	0.82	1.21	1.19
Air change efficiency (%)	46	51	46	47	47	48	54	54

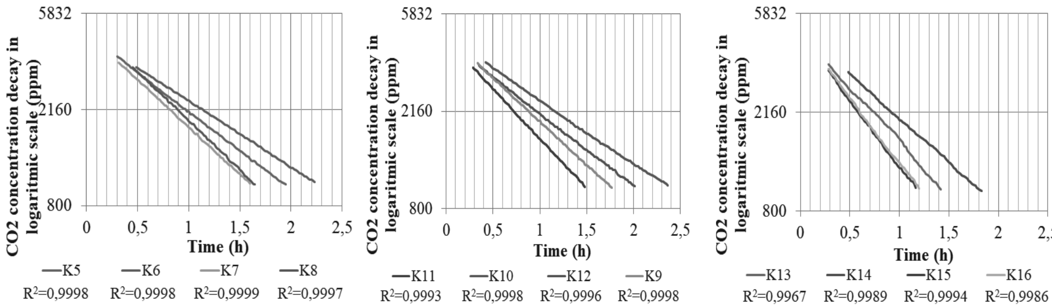

Fig. 7. CO_2 concentration decay using pair-wise, monoblock and ventilation radiator units.

3.4 Air distribution of room based ventilation units

The air distribution of room based ventilation units is possible to analyse according to the calculated local air change indexes. The corresponding results are shown in Fig. 7 and Fig. 8. The values of local air change indexes of the pair-wise units were 93% – 110% during the heating period. The values of ACE were 50% – 51% and no stagnant zone was detected in the room. The local air change indexes outside the heating period were 86% – 106% in tests M1 and M2 and 86% – 101% in tests M3 and M4.

The local air change indexes of monoblock units in winter period were 93% – 102% that proved the air change rate was uniform in the whole room. The local air change indexes outside the heating period were 91% – 101% in test M5 and 93% – 109% in test M6.

During the heating period, the values of air change indexes of ventilation radiator were close to 100% in all areas of the room. This proves that the supply air mixed with the room air in effective way. Outside the heating period, the local air change indexes were 100% – 113% in test M7 and 90% – 129% in test M7.

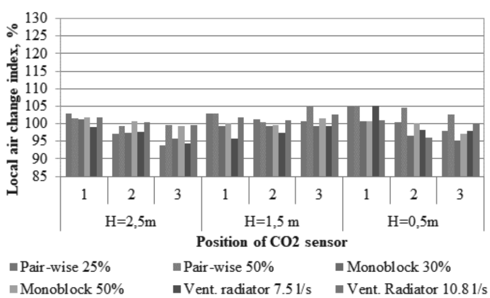

Fig. 7. Local air change indexes of room based ventilation units in heating period.

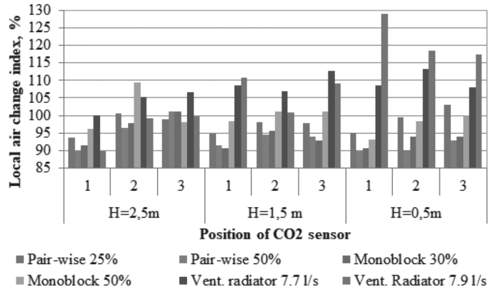

Fig. 8. Local air change indexes of room based ventilation units in warm period.

Air distribution was also analysed according to the CO_2 decay patterns. The sections of the room pattern in nZEB laboratory are shown in Fig. 4 (section A-B). The air distribution patterns compiled using the linear interpolation method. The room air distribution patterns are in Fig. 9 (heating period) and Fig. 10 (warm period). To compare the different decays, the patterns demonstrated in similar CO_2 levels around 2100 – 2800 ppm. Analysing the patterns, the most important conclusion is that local air change indexes are highest in the middle of room. This conclusion is the same for all the studied systems in both measuring period.

In case of pair-wice system the closer corner to the unit is with higher local air change rate in warm period. At the same time, the closer and the farther corner are performing in similar way in summer. In case of monoblock units, the air pattern during both period is similar. The main difference of the air patterns of pair-wice and monoblock units is related to the different supply jets. The pair-wice unit gives the supply jet across the air distributor (360 degrees). At the same time the supply airflow of monoblock unit is directed only into the upper part of the room. This aspect can also be seen in Fig. 10, where the local air change rate of monoblock unit is higher in the bottom part of the room.

In case of ventilation radiator, the air pattern in heating period is quite uniform, but at the same time the local air change rate in upper part of the room is lower than in other part of the room. The main reasons for this kind of pattern is quite cold supply air from the lower part of the room. In heating period the air is mixed by the convective air flow from the hot radiator, but the radiator was not turned on during the warm period. That is the main reason, why the ACE value is high and the concentration of CO_2 level is higher in upper zone.

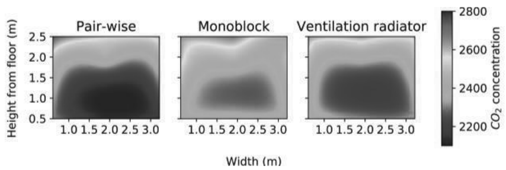

Fig. 9. Room air distribution of room based ventilation units in in heating period (A-B in Fig. 4).

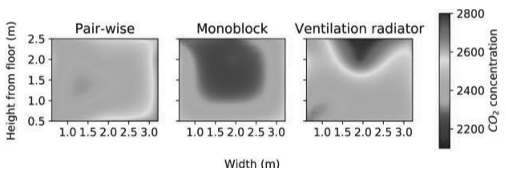

Fig. 10. Room air distribution of room based ventilation units in in warm period (A-B in Fig. 4).

3.3 Field test results

Air change efficiency measured in two naturally ventilated apartments. Tests made in the heating period and in warm period. The special focus was to determine how the position of the inner doors affects the ACE in the apartment. Fig. 11 shows the natural CO_2 concentration change in the bedroom and bathroom of apartment 2 during two days. The bedroom door was closed during the first night and open during the second night. The CO_2 concentration in the bedroom was 500 ppm higher than in the bathroom during the first night, while during the second night the concentrations were practically even. It proves that the CO_2 generated by the occupants spread and diluted in the whole apartment, if the bedroom door was open.

The whole apartment was considered as one zone during the concentration decay tests and local air change indexes were measured in every room of the flat. The measured nominal time constants and local air change indexes are shown in Table 3. Nominal time constants were calculated based on the concentration decay in the extract grille. The local air change index was the lowest in the bedroom of the second flat when the door was closed. The value was 57% while 100% expresses fully mixed ventilation. The local air change index was 61% with same conditions in flat no. 1. As both values were clearly under 100%, it can be noted that the air flow in the apartments was not fully mixed, if the bedroom door was closed. On the contrary, if the bedroom door was open, the local air change indexes in flat no. 1 were 97%-101% and in flat no. 2 90%-106%, which indicated that the air flow in both apartments was quite uniform.

The ACE values outside the heating period were measured only in second apartment. If the bedroom door was closed, the local air change index was 97% - 130%. If the bedroom door was closed the local air change index was only 53% in bedroom. At the same time in other rooms the index varied from 95% to 102 %.

Air distribution was also analysed according to the CO_2 decay patterns that compiled using the linear interpolation method (see Fig. 12). CO_2 patterns compiled only to flat no. 2. Room air patterns are analysed in heating period with opened bedroom door, in heating period with closed door and in warm period with opened door. We can conclude that closing the bedroom door ensures uniform CO_2 concentration in room. At the same time, the local air change index of bedroom is lower than in other parts of the apartment. If the inner door was open the air distribution was not uniform and the local air change rate was higher near to the fresh air valve. The local air change index was the lowest in the upper part of the inner door. In the lower part of the door, the local air change rate was slightly higher which corresponds to the theory since the air is moving into another room from there.

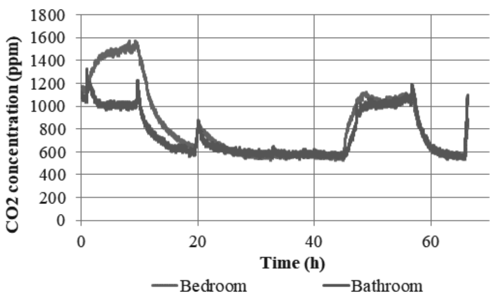

Fig. 11. Natural CO_2 concentration in apartment 2.

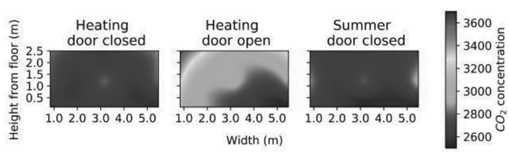

Fig. 12. Room air distribution of flat no. 2 with opened and closed door.

Table 3. Local air change indexes in apartments.

Flat no./ Period	Door position	Nominal time constant (h)	Local air change index (%)					
			Bedroom	Living-room	Kitchen	Bathroom	WC	Corridor
1/heating	Open	4.78	97	100	99	100	99	101
1/heating	Closed	3.55	61	85	108	97	118	-
2/heating	Open	1.64	90	-	98	106	-	105
2/heating	Closed	2.01	57	-	94	100		104
2/summer	Open	2.20	97	-	98	98	-	130
2/summer	Closed	2.12	53	-	102	98	-	95

4 Conclusions

The tracer gas concentration decay method was applied to measure the air change efficiency and local air change indexes in both laboratory and field tests. After the injection and mixing of the tracer gas has stopped, the concentration of it should decrease exponentially. The results showed that the correlation with theoretical exponential decay curve was at least 0.98 in most cases which proves that the tests were conducted methodically right and that the air flow in the room was uniform.

According to the definition, the air change efficiency of the fully mixed ventilation is 50%. This was achieved with perforated ceiling diffuser and 16 °C supply temperature resulting in the ACE of 51%. When the supply temperature was 5 °C higher, the ACE dropped to 45%, which confirmed that if the fresh air was supplied from the ceiling, it should be slightly cooler than the room temperature to ensure penetration and mixing in the whole room.

Three tested room ventilation units all created nearly fully mixed room air flows, despite the fact that the position of the supply and extract openings could have been favorable for a short-circuit flow. The ACE values were 48% - 52% in heating period and 46% - 54% in warm period. The alteration of the air flow rate did not have any impact on the ACE. In case of pair-wise and monoblock units the ACE values are higher in heating period and in case of fresh air radiators the ACE vales are higher outside the heating period. The reason for that trend is different supply air temperature. In case of pair-wise and monoblock units the supply air temperature was close to the room temperature during the warm period. At the same time in case of fresh air radiator the supply air temperature was lower.

Air distribution was also analysed according to the CO_2 decay patterns. Room air patterns compiled using the linear interpolation method. The most important conclusion is that local air change indexes are highest in the middle of room. This conclusion is the same for all the studied systems in both measuring period. According to the results of this study, these three tested solutions are well-compatible for residential ventilation that regards the aspect of air change efficiency.

The experiments in naturally ventilated apartments showed that if the ventilation scheme required transfer air between the rooms, the positions of the inner doors had a significant impact on the air change efficiency. The local air change index in the bedroom with the closed door was in worst case by 43% lower than it would have been with fully mixed air flow. The air flow was almost fully mixed in case of open bedroom doors.

Air distribution in apartment no. 1 was also analysed according to the CO_2 decay patterns that compiled using the linear interpolation method. This analyse showed that the bedroom door ensures uniform CO_2 concentration in room. At the same time, the local air change index of bedroom is lower than in other parts of the apartment.

Acknowledgement

This research was supported by the Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts, ZEBE, grant 2014-2020.4.01.15-0016 funded by the European Regional Development Fund.

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Publication IV

A. Mikola, R. Simson, and J. Kurnitski, “The Impact of Air Pressure Conditions on the Performance of Single Room Ventilation Units in Multi-Story Buildings,” Energies, vol. 12, no. 13, 2019. https://doi.org/10.3390/en12132633.

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Article

The Impact of Air Pressure Conditions on the Performance of Single Room Ventilation Units in Multi-Story Buildings

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Received: 30 April 2019; Accepted: 27 June 2019; Published: 9 July 2019

Abstract: Single room ventilation units with heat recovery is one of the ventilation solutions that have been used in renovated residential buildings in Estonia. In multi-story buildings, especially in a cold climate, the performance of units is affected by the stack effect and wind-induced pressure differences between the indoor and the outdoor air. Renovation of the building envelope improves air tightness and the impact of the pressure conditions is amplified. The aim of this study was to predict the air pressure conditions in typical renovated multi-story apartment buildings and to analyze the performance of room-based ventilation units. The field measurements of air pressure differences in a renovated 5-story apartment building during the winter season were conducted and the results were used to simulate whole-year pressure conditions with IDA-ICE software. Performance of two types of single room ventilation units were measured in the laboratory and their suitability as ventilation renovation solutions was assessed with simulations. The results show that one unit stopped its operation as a heat recovery ventilator. In order to ensure satisfactory indoor climate and heat recovery using wall mounted units the pressure difference values were determined and proposed for correct design.

Keywords: single room ventilation unit; building pressure condition; stack effect; wind pressure; ventilation renovation; decentralized ventilation unit

1. Introduction

In Estonia, multi-story apartment buildings constitute about 60% of the whole dwelling stock, and the majority (75%) of the buildings were built primarily in 1961–1990 [1]. Due to the increase in the price of energy, the energy policies of the European Union [2], the age, construction quality, and poor thermal insulation of the buildings, as well as both morally and technically outdated, obsolete heating and ventilation systems, there is an increasing need for retrofitting [3–7]. Part of the building stock built before the 1990s has already been renovated but for many apartment buildings this process is yet to start [6,8].

Typical multi-story apartment buildings have been built with natural ventilation, where fresh outdoor air enters through leaks or openings of the windows and doors, mixes with the warm room air, and leaves the building through shafts in the bathroom and kitchen. With retrofitting the building envelope, in order to achieve necessary thermal insulation for reducing the energy consumption for space heating, the air tightness of the building increases and the air flow through cracks and leaks is reduced, which makes the air change with natural ventilation very poor and does not provide the required air change rate [9]. Several analyses on the performance of ventilation in old Estonian dwellings [3,4,8] show that average indoor air CO_2 in occupied period is 1225 ppm which means the air change rate is too low to ensure good indoor air quality. As concluded in previous studies [10–16], there is a strong correlation between ventilation and health. With the renovation of old apartment buildings, the improvement of ventilation is unavoidable in order to provide healthy indoor environment for the occupants [17].

During the period 2010 to 2014 a total number of 663 apartment buildings were renovated using the renovation grant scheme [18]. The main principle of this grant schemes was to improve indoor air climate and energy efficiency of Estonian apartment buildings. There were 3 different grant levels, but in order to qualify for the highest financial support of 35% of the renovation costs provided by the state, the designed ventilation system was required to include heat recovery. Few solutions used in new buildings are suited for retrofitting purposes, mainly for construction-technological reasons. Other factors that affect the choice of suitable system are the cost of the system, the volume of construction work, aesthetics, adjustability and the costs of maintenance and operation. The impact of ventilation on the energy use of buildings can be between 30–60% for new and retrofitted buildings [5,8,19], thus heat recovery from the exhaust air is inevitable. Depending on the type of the heat exchanger (HEX) used in the air handling unit (AHU), it is possible to recover either sensible and latent heat or only sensible heat from the exhaust air [20,21].

The need for electricity to move the air increases at higher ventilation rates, becoming in some cases the main factor of increase in the final energy demand [22–24]. Ductless systems with room-based air handling units tend to have the lowest construction and operation costs, and to be simplest in design and most aesthetic [25]. The lack of ducts is a clear advantage since the most common problems are caused by the poor installation quality of ducts and inadequate project design [4]. It is also essential for the ventilation unit to have a low electric power consumption, suitable acoustic properties [26] and sufficient energy saving performance, which is strongly related to outdoor climatic conditions, the enthalpy efficiency, fan power consumption and necessary fresh air change rate [27].

One way to save energy from grid-connected electrical appliances would also be a real-time control strategy based on Model Predictive Control for the energy scheduling [28]. Chen et al. have presented the development of a model predictive control strategy for the hybrid ventilation solution [29]. As this model is still a prototype, it needs more testing to analyze the detailed possibilities of Model Predictive Control strategies.

The two most commonly used types of room-based devices used to renovate ventilation systems of apartment buildings during the retrofits 2010–2014 are: unit with recuperative plate HEX and centrifugal fans (Figure 1a) and unit with regenerative ceramic HEX and an axial fan (Figure 1b). The single-fan-based unit works in cycles, switching between the supply and exhaust mode every 60–70 s. During the exhaust cycle, the heat from the warm exhaust air is accumulated in the ceramic comb-like HEX and is then used to heat up the cold outdoor air during the supply cycle.

Figure 1. Types of room-based ventilation units used in the renovation of old apartment buildings: (**a**) with recuperative cross-flow plate HEX and (**b**) with regenerative ceramic heat exchanger (HEX).

Since the ventilation units are mounted inside the exterior wall of the building, the performance of the units is directly affected by the pressure differences between indoor and outdoor air across the building envelope. During the ventilation renovation in 2010–2014, the natural exhaust ventilation system was often not replaced. It means that the room-based ventilation units had to operate together with the natural ventilation system. The pressure difference in buildings with natural ventilation is caused mainly by the wind and the stack effect. There are numerous studies on both the stack effect [30–34] and the wind-induced pressure [35–37] in different building types with variable height, geometry and location. Wind conditions depend on the location and surroundings of the building. The stack effect depends on the height of the building and the temperature difference between indoor and outdoor air. The temperature differences of the air cause density differences that induce buoyancy force; the warm indoor air rises and is replaced by the colder outdoor air through the building envelope during the heating season. Studies indicate larger air pressure difference over the building envelope in more airtight buildings [19,38]. Shafts, staircases and other vertical openings, but also leaks through the cracks in floors, walls and ceilings can contribute considerably to the stack effect [39].

Indoor air quality measurements in Estonian renovated apartment buildings have shown that room-based ventilation units are not ensuring the necessary air change rate [18,40]. To secure the success of the renovation work, it is necessary to find out the reasons why the air change rate is below the designed values. Based on the described practical need, the main aim of this study is to analyze the performance of room-based ventilation units in typical renovated multi-story apartment buildings. Mikola et al. [40] have measured the air change rate in apartment buildings with room-based ventilation units and pointed out that problem may be caused by the high indoor and outdoor pressure difference and incorrect dimensioning of the fans. Thus, present study allows a detailed examination of these hypotheses. The results of the study can provide an innovative overview of the performance of the room-based ventilation units in renovated apartment buildings.

2. Methods

The performance of the exterior wall mounted single room ventilation units with regenerative and recuperative HEX were studied. Firstly, the on-site measurements were made in a renovated five-story apartment building. In next step, the measurements of units with regenerative HEX and recuperative HEX were performed in laboratory conditions. The results of field and laboratory measurements were used to compile a simulation model of the studied renovated apartment building with regenerative ventilation units. The next step was to calibrate the simulation model according to the measured indoor-and outdoor pressure differences, indoor temperatures, airflows, and outdoor climate data. Then the simulations of indoor and outdoor pressure differences, fan performance curves and heat recovery were performed. Lastly, the simulation and measurement results of room-based AHUs were analyzed and the conclusions on the performance of room-based ventilation units in apartment buildings were outlined. The flow chart of the main methods of the study is described in Figure 2.

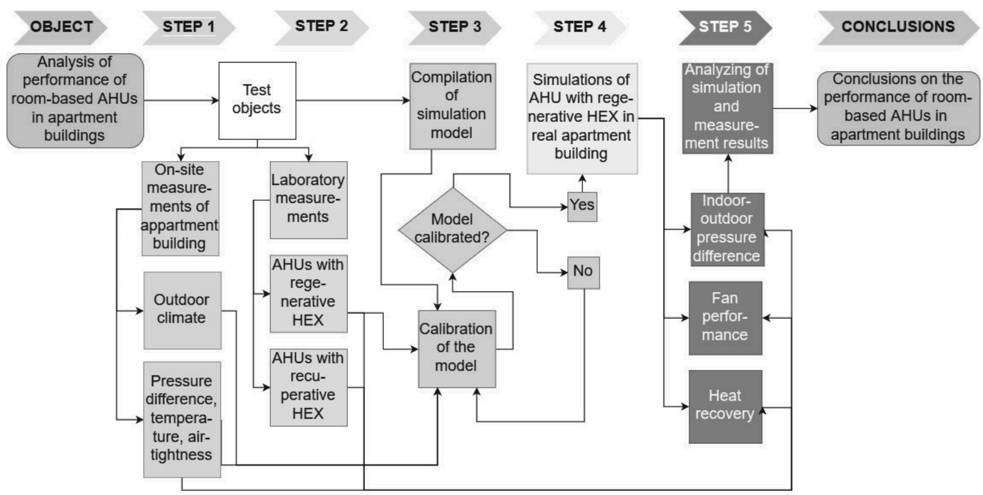


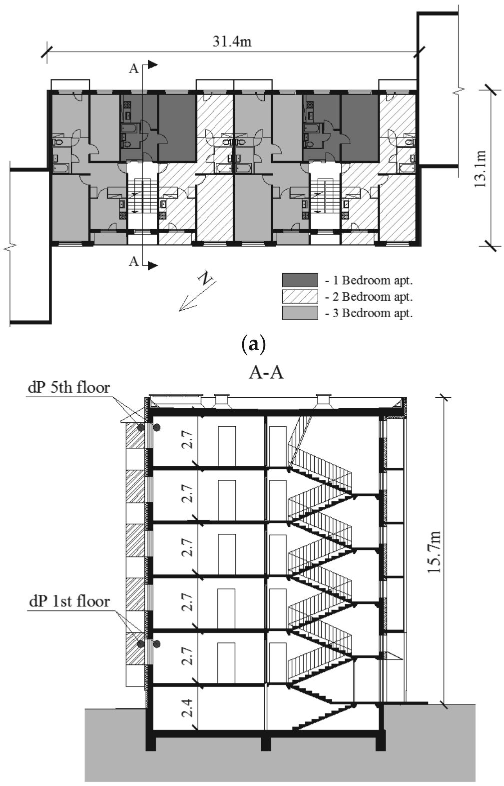
Figure 2. The flow chart of the performed studies. AHU: air handling unit.

2.1. Measurements

The pressure differences between the indoor and outdoor air across the exterior wall were measured during a 3-month period of the heating season in renovated 5-story apartment building. The fan performance and the temperature efficiency of room-based ventilation unit with regenerative and recuperative HEX were studied in TalTech technological facility.

2.1.1. The Studied Building

The studied building was a typical precast large concrete panel 5-story apartment building located in an urban area built in 1975 with 30 apartments, 2 staircases and a full cellar. The building is connected on both sides with two buildings of the same type. The height of stories is 2.7 m and the height of rooms is 2.5 m. The building is heated with water radiators by district heating. The floor plan of the building is shown in Figure 3a and cross-section in Figure 3b.



(**b**)

Figure 3. (**a**) Floor plan and (**b**) cross-section with pressure difference measurement point locations of the studied building.

The building was renovated in the years 2003 and 2012: the exterior walls, roof, and balconies were insulated, the windows were replaced; and the heating system was reconstructed. The thermal transmittances of the envelope before and after the retrofitting are presented in the Table 1. For ventilation, wall mounted regenerative HEX ventilation units were installed in the bedrooms and living rooms, in the bathrooms and kitchens natural exhaust ventilation was used (Figure 4). The diameter of the ventilation shafts with round cross-sections is 140 mm and height varies between

0.7 m and 12.6 m, depending on the story. All the units with regenerative HEX were controlled from the control center. It means that all the units worked in same speed and in same working cycle.

Table 1. Thermal transmittances of the envelope before and after retrofitting.

Part of the Thermal Envelope	Thermal Transmittance, W/(m^2·K)	
	Before	After
External walls	1.05	0.22
Roof	0.45	0.15
Doors	2.0	1.2
Windows	2.9	1.4

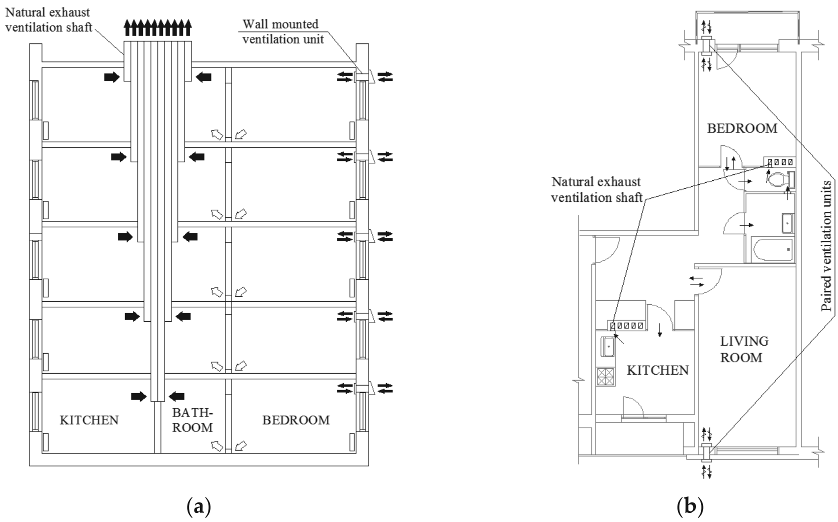


Figure 4. Principle solution of the ventilation system with room-based units: (**a**) cross-section and (**b**) floor plan of a typical apartment.

2.1.2. Field Measurements

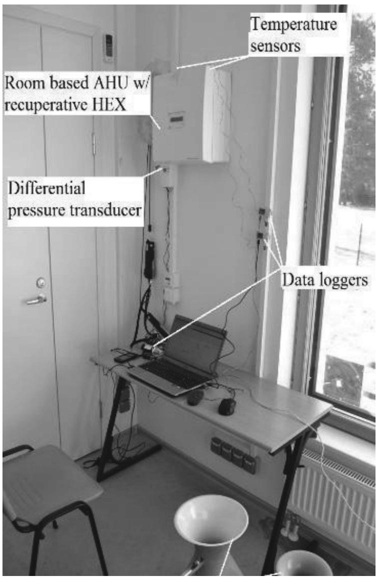
Pressure differences between the indoor and outdoor air across the exterior wall were measured during a 3-month period of the heating season (December 2013–February 2014) in 4 apartments located on different floors. Measurements were taken at the height of 2 m from the floor level (Figure 3b). For the outdoor pressure component, a plastic tube of 4 mm in diameter was planted through the window seal with one end connected to the pressure transducer. Diaphragm-type pressure transducers were used: Dwyer Magnesense MS-221 and Onset T-VER-PXU-L both with the measuring range of −50 to +50 Pa (output 0–10 VDC) and accuracy of 1% full scale output. Readings were taken in every 1 min and an average of the readings was saved with a 10-min interval using Onset Hobo U12 and Squirrel Q2010 data loggers. For environment measurements and data logging Hobo U12 devices were used with the temperature measuring range of −20 to +70 °C with accuracy ±0.35 °C and relative humidity 5% to 95% with accuracy ±2.5% of full-scale output.

2.1.3. Laboratory Measurements

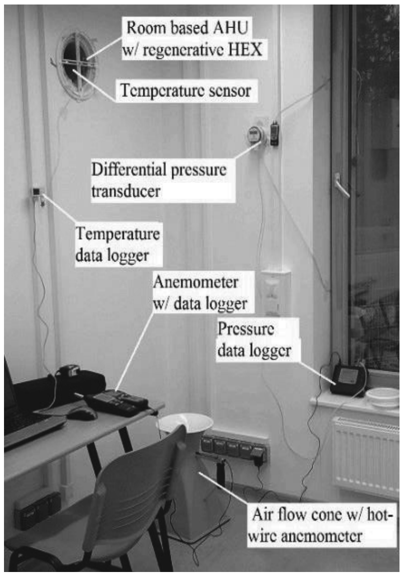
In the laboratory-controlled environment, performance and efficiency of two types of room-based ventilation units were studied. The core elements of the first unit are cross-flow plate HEX, centrifugal fan, supply and exhaust filters, transfer ducts and outdoor hoods (see Figure 1a). The second unit has a ceramic HEX, axial fan, mounting tube, outdoor hood, inner cover and air filter (see Figure 1b).

The first device is a constant flow ventilation unit compared to the latter, which works in cycles, switching with 70-s intervals between the supply and exhaust mode. During the exhaust cycle, heat from the warm exhaust air is accumulated in the ceramic comb and is then used to heat up the cold outdoor air during the supply cycle. Both devices are installed without the heating coil.

The setup of the experiment of recuperative units is shown in Figure 5a and setup of the regenerative HEX is shown in Figure 5b. In the case of the unit with regenerative HEX, the temperature sensor was placed in the center of the airflow behind the air distributor. To measure the room and exhaust air temperature, another temperature sensor was placed to the top of the room 0.3 m away from the ventilation unit. The outdoor air temperature was measured close to the fresh air grille. The measuring cone was placed over the inner cap of the unit and the air speed was measured inside the cone. To measure the outside pressure, the pressure sensor was installed through the window to outside. The inside and outside pressure were both measured at a height of two meters. In case of unit with recuperative HEX, the temperature sensors were installed on the top of the unit inside the supply and exhaust airflow. The airflow, fresh air temperature, and pressure difference were measured in the same way as described in case of unit with regenerative HEX.



(a)



(b)

Figure 5. Experimental setup with the studied room-based ventilation units: (**a**) with recuperative HEX and (**b**) regenerative HEX.

During the experiments, the pressure difference between the indoor and outdoor air, outdoor temperature, supply/exhaust air temperature and air speed inside the measuring cone were measured and logged in every second. The same temperature and pressure sensors and loggers were used as in field measurements. The measured air speed was used to calculate the volumetric air flow through the unit. Airflow measurements were carried out using Testo 435-4 measuring instrument/data logger with hot-wire anemometry probe (measuring range from 0 to 20 m/s, with accuracy 0.01 m/s and +4% of reading). The pressure conditions in the test room were achieved using a central air handling unit and by adjusting the supply/exhaust valves of the ventilation system.

2.1.4. Temperature Efficiency of Room-Based Units

The temperature efficiency was used to quantify the effect of heat recovery of the studied ventilation system. As the main purpose of the study is to evaluate the performance of the room-based ventilation units, then the temperature ratio (efficiency) η_{temp} is defined as [25,26]:

$$\eta_{temp} = \frac{\overline{t_{sup}} - t_{out}}{t_{exh} - t_{out}}, \quad (1)$$

where t_{out} is the outdoor air temperature and t_{exh} is the exhaust air temperature. The time-averaged value of the supply air temperature of ventilation units with the regenerative HEX, has to be used which is given by [26]:

$$\overline{t_{sup}} = \frac{1}{\tau}\int_{t=0}^{t=\tau} t_{sup}(t)\cdot dt \quad (2)$$

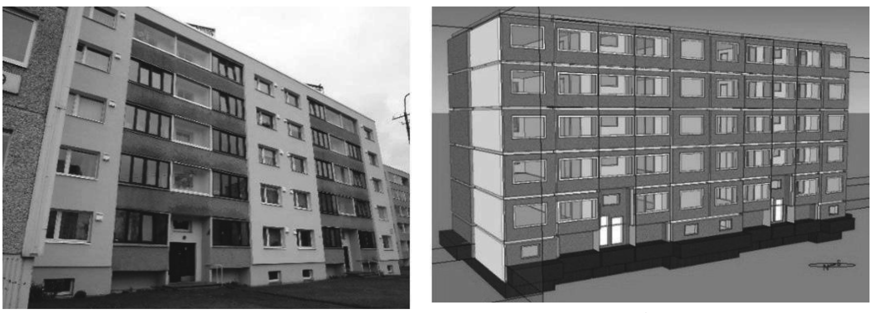
where t is the time and τ is the semi-period, which means the duration of the supply or extract process. In the case of the recuperative HEX, the process is in a steady state [26]:

$$t_{sup}(t) = \text{const.} \quad (3)$$

2.2. Computational Model

2.2.1. Description of Simulation Model

A model of the building was created and simulated using IDA Indoor Climate and Energy (IDA ICE) software version 4.6 developed by Equa Simulation AB (Figure 6). Each room of the composed building model is the separate zone. As there is common natural ventilation exhaust channel for the bathroom and toilet, these rooms were composed as a one zone. The building model was calibrated using the measured data from field studies. A custom climate file with hourly wind data, outdoor temperature and relative humidity of the measurement period from the local weather station located ~1 km from the site was used for the validation process. The orientation of the building is presented in Figure 3a.



(**a**) (**b**)

Figure 6. The studied (**a**) apartment building and (**b**) the simulation model.

For whole-year simulation, weather data from Estonian Test Reference Year (TRY) were used. The TRY is constructed using selected months from a number of calendar years, and may be used for many applications, such as indoor climate and energy simulations, HVAC system performance, or simulation of active or passive solar energy systems [41]. The air tightness of the building was defined with air leakage rate per envelope area at 50 Pa of pressure difference (q_{50}). A value of 3.0 $m^3/(h\cdot m^2)$ was used in the calibration process, as also achievable with the renovation of building envelope for pre-fabricated large-panel buildings [42].

The ventilation units were inserted according to the standard renovation solution that means 1 pair-wise ventilation system, which consist of 2 separate units, was added in every living room and bedroom. The natural exhaust ventilation system was not renovated and it continued the work as before. To modulate the natural ventilation system, the "chimney" component was used. Chimney takes into account the height and length of ventilation channels but also friction and minor pressure losses. Chimney elements were added to the kitchens and toilets or bathrooms. Two chimney components were added per each apartment. The airflows of natural exhaust systems were measured using hot wire anemometer with a cone. During the air flow measurements, the specific indoor and outdoor parameters were also measured and for the model calibration average values of airflow measurements were used.

The studied ventilation unit with regenerative HEX was modelled using IDA-ICE advanced modelling interface. The exterior wall leak module was used to calculate the differential pressure across the building exterior wall, which was used as an input for supply and exhaust air flow control accordingly to the laboratory measurements results. The main principles of the model are described in Figure 7. The pressure-airflow dependencies were inserted to the linear segment controller and connected to the respective air terminal. To model room-based units, some simplifications were made. Firstly, the standard ventilation unit macro was used and the control signal to the HEX was removed. The working cycle of the unit is 60 s in supply mode and after that the unit is turned off and the pairing device is switched on for 60 s in exhaust mode. Switching the units between supply and exhaust mode is achieved using the "gain" component. Regulating the supply and exhaust airflow was performed according to the differential pressure variable (DPA_S) of the exterior wall in "leak" component.

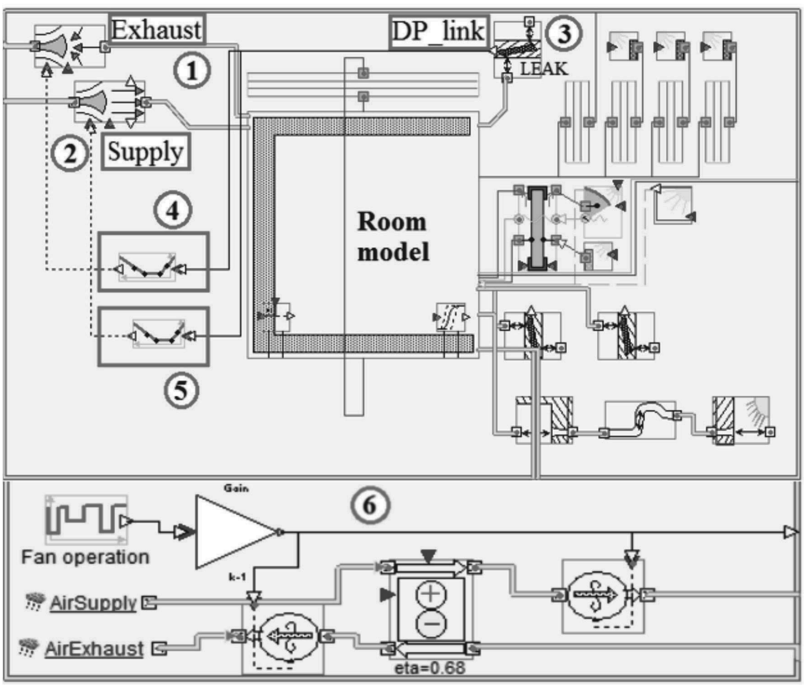


Figure 7. Schematics of the studied ventilation units modelling in IDA Indoor Climate and Energy (IDA ICE): (1) exhaust air terminal; (2) supply air terminal; (3) exterior wall leak module; (4) and (5) linear segment controllers; (6) ventilation unit module.

2.2.2. Air Pressure Calculations

The simulation model was calibrated according to the outdoor climate, indoor temperature, air change rate and air tightness measurements. During the calibration, the values of measured pressure difference were compared to the simulated data. The wind pressure distribution around the house is composed in way the wind flow is horizontal and an atmospheric boundary layer is neutral without vertical airflow [19]. The static wind pressure p_{wind} (Pa) outside the building facades is given by [19,43]:

$$p_{wind} = C_p \cdot \varrho_a \cdot U^2/2, \quad (4)$$

where C_p (dimensionless) is the pressure coefficient, ϱ_a is the air density (kg/m^3) and U (m/s) is the local wind velocity.

Pressure coefficients are empirically derived parameters determined either experimentally in a wind tunnel [44,45] or numerically using computational fluid dynamics [46,47]. In studied building model the wind-induced pressure conditions were simulated using constant wind-pressure coefficients defined at 45° intervals of a wind direction. Approximate values of wind pressure coefficients were used on external boundaries based on the exposure of the building. The pre-coded values of the "semi-exposed" option founded accurate enough (see Table 2).

Table 2. Facade average wind pressure coefficients used in the building simulation.

Facade	Orientation	Wind Angle (°)							
		0	45	90	135	180	225	270	315
Exterior wall	NE	0.4	0.2	−0.6	−0.5	−0.3	−0.5	−0.6	0.2
Exterior wall	SE	0.25	0.06	−0.35	−0.6	−0.5	−0.6	−0.35	0.06
Exterior wall	SW	0.4	0.2	−0.6	−0.5	−0.3	−0.5	−0.6	0.2
Exterior wall	NW	0.4	0.2	−0.6	−0.5	−0.3	−0.5	−0.6	0.2
Roof		−0.8	−0.8	−0.8	−0.8	−0.8	−0.8	−0.8	−0.8

The local wind velocity is calculated according to the simplified method for combining weather information with air tightness to calculate residential air infiltration (LBL method) recommended by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [43]. The local wind velocity at height h U(h) (m/s) is calculated by the equation:

$$U(h) = U_m \cdot k \cdot (h/h_m)^a, \quad (5)$$

where U_m (m/s) is the measured wind speed at the weather station (at a height of 10 m), h (m) the height from the surface of the ground, h_m (m) the height of the measurement equipment and constants k and a are the terrain coefficients. For the terrain coefficients k and a ASHRAE [43] recommended values for suburban terrain of 0.67 and 0.25 respectively were used. The LBL method, that is used in simulation model, has been proposed by Sherman and Grimsrud [48] and Modera et al. [49]. Modera et al. [49] have pointed out the typical values of terrain parameters for the standard terrain classes. The IV class is described as urban, industrial or forest areas and fitted the best with the conditions of tested apartment building. Sherman and Grimsrud [48] have pointed out that this method can also be used when the wind speed was not measured on-site.

The airflow Q (kg/s) through the bi-directional leakage opening is simulated in the building model with the empirical power law equation [19]:

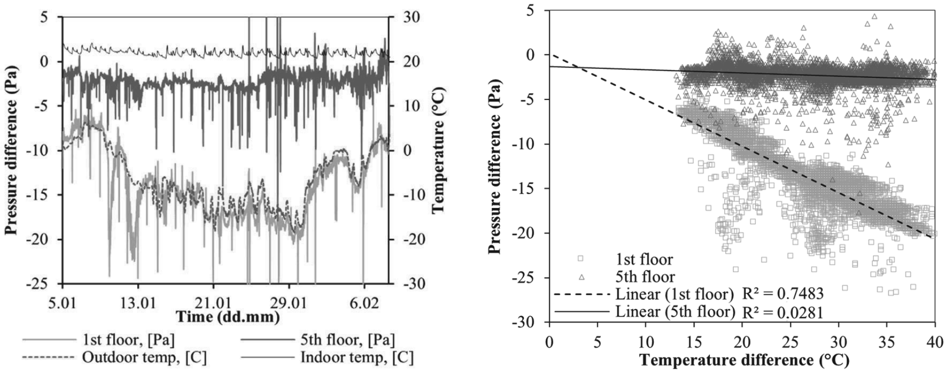
$$Q = C \cdot \Delta P^n, \quad (6)$$

where C (dimensionless) is a flow coefficient (related to the opening), ΔP (Pa) is the pressure difference over the opening and n is a flow exponent which is characterizing the flow regime. The infiltration air flow is calculated for the facade of every zone [19]. The leakage openings in model are distributed over the building model according to the total infiltration airflow.

3. Results

3.1. Field Measurements

The results of field measurements showed that the pressure difference across the building envelope was negative during the entire measurement period in the first floor apartment and mostly negative in the fifth floor apartment (see Figure 8a). The occasional peaks toward zero-pressure difference are most likely caused by using the cooker hood, opening the windows or external doors to the balcony or staircase, the peaks and periods toward greater difference indicate the wind-induced effect. Pressure difference caused by wind can be dominant also for longer periods. The results indicate that the pressure difference is mostly caused by the stack effect being strongly dependent on the outdoor temperature in the bottom floor apartment, whereas on the top floor the dependence is weak due to the smaller height of the shaft (see Figure 8a). The measured indoor temperature during the measurement period in both apartments was roughly between 20 and 22°C. The dependence between the indoor and outdoor pressure and temperature is shown in Figure 8b. In the first-floor apartment the value of linear correlation coefficient R^2 is 0.7483 and in fifth floor 0.0281.



(**a**) (**b**)

Figure 8. (**a**) The measured indoor and outdoor pressure differences in the first and fifth floor apartments, indoor and outdoor temperature in the heating season during a one-month period; (**b**) The dependence of pressure conditions on the indoor–outdoor temperature difference.

3.2. The Laboratory Measurements

Based on the results of laboratory measurements the fan performance and HEX temperature efficiency of observed AHUs were studied. The measurement results of the performance of the unit with ceramic HEX are shown in Figure 9a,b. In the beginning of the tests the value of underpressure in room was −2 Pa which means that supply and extract airflows were equal. After the pressure difference increased the extract air flow decreased and supply airflow increased at the same time. As results indicate, the supply and extract airflows are equal only at very low pressure differences. The greater the difference, the more the air flows differ. It can be seen that in case of 75% fan power, with differential pressure over −20 Pa the extract airflow is close to zero and the supply airflow around 60 m^3/h (Figure 9b). The supply–exhaust cycles, which are presented in Figure 9b, show quick drop of the supply air temperature after the cycle change. During the tests, the outdoor air temperature was close to −5 °C. If the supply and extract airflows are equal, the supply air temperature was about 7 °C but if the pressure difference was increased from 0 Pa–20 Pa in test room, the supply air temperature at the end of the supply working cycle was about −2 °C.

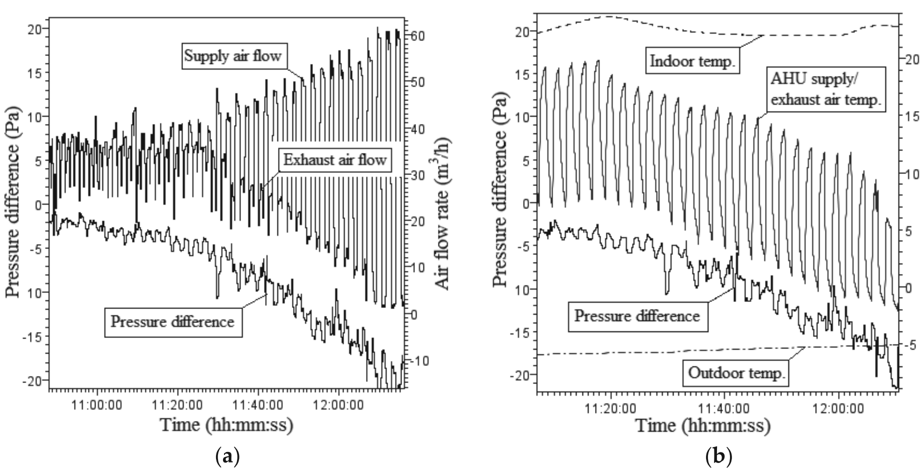


Figure 9. The results of the laboratory measurements of performance of the room unit with regenerative HEX at 75% fan power: (**a**) Pressure difference and air flows; (**b**) pressure difference and supply/exhaust air temperature.

The fan performance curves were constructed for the fan speed levels of 25%, 50%, 75%, and 100% (see Figure 10a). The fan performance curves show how the supply and extract airflows of the ventilation units are related to the in-and outdoor pressure difference. It is also possible to present how the pressure difference is related to the temperature efficiency of studied ventilation units (see Figure 10b). The results indicate that if the pressure difference rises then the temperature efficiency decreases. The same trend appears for all tested fan speeds. For example, in case the 50% speed level, the temperature efficiency is over 0.5 if the pressure difference is smaller than 4 Pa.

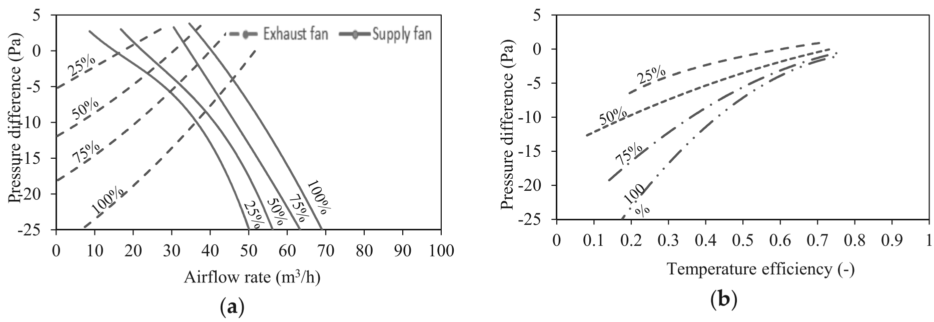


Figure 10. (**a**) Measurement based fan performance curves of room-based ventilation units with ceramic regenerative HEX; (**b**) measurement based temperature efficiencies of room-based ventilation units with ceramic regenerative HEX.

The fan performance curves and temperature efficiency graphs were also constructed for the ventilation units with recuperative HEX (see Figure 11a,b). The fan performance curves were constructed for the fan speed levels 25%, 50%, 75%, and 100%. Compared to the ventilation units with regenerative HEX, the units with recuperative can perform effectively in case of higher pressure differences between indoor and outdoor air. At the same time, if the pressure difference is −20 Pa at fan speed level 50%, the supply airflow is about 15% higher than exhaust airflow. The temperature efficiency of ventilation units with recuperative HEX is presented in Figure 11b. Compared to units with regenerative HEX, the temperature efficiency of studied ventilation units is significantly better at higher pressure difference conditions. The pressure difference influences the temperature efficiency the most in lower fan speed levels.

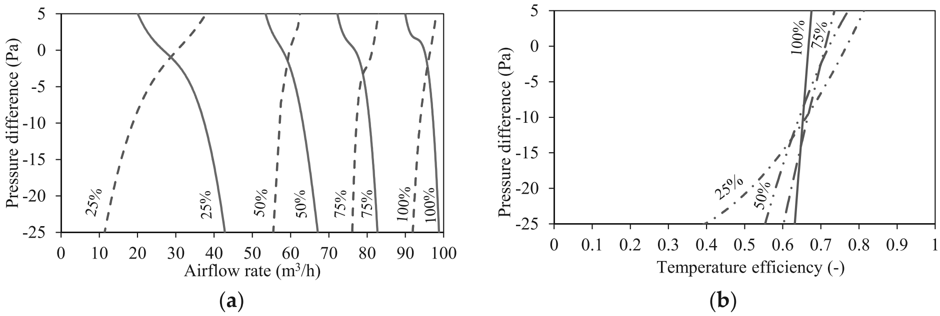


Figure 11. (**a**) Measurement based fan performance curves of room-based ventilation units with recuperative cross-flow plate HEX; (**b**) Measurement based temperature efficiencies of room-based ventilation units with recuperative cross-flow plate HEX.

3.3. Simulation Results

The simulation results achieved in the validation process are in good concordance with the field measurements (see Figure 12a), considering the fact that approximate wind pressure coefficients, performance of natural exhaust ventilation and wind data from an off-site weather station was used. The whole-year simulation results are presented in Figure 12b. The results show that the whole building is under negative pressure for 63% of the year (5521 h per year). In the first-floor apartments, the pressure difference is below −10 Pa for 22% (1927 h per year) and lower than −20 Pa for 2% of the year (180 h per year). The pressure difference across the exterior wall during the heating season in the 5-story building can be as high as −30 Pa on the first floor, −20 Pa on the third floor and −15 Pa on the fifth floor. Although the performed whole-year simulations has been done according to only one building and some simplifications have been done during the simulation process, the results confirm the fact that room based ventilation systems in 5-story buildings have to cope with the pressure difference which is more than −20 Pa.

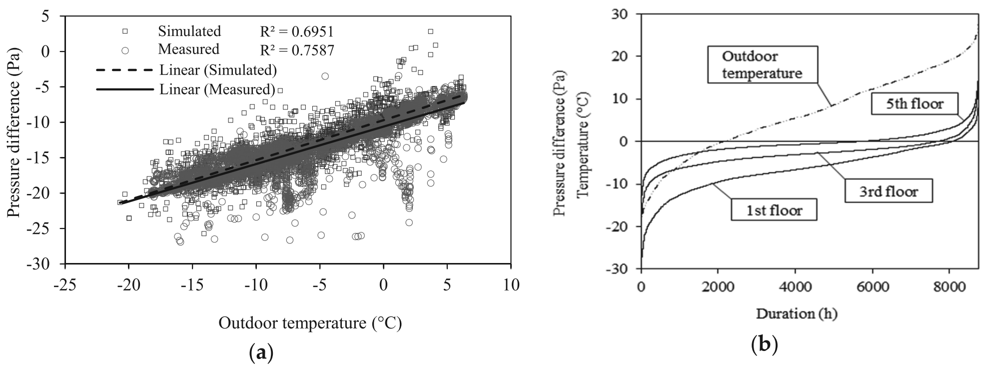


Figure 12. (**a**) Dependence between measured and simulated indoor and outdoor pressure differences on the indoor–outdoor temperature difference in the first-floor apartment. (**b**) The outdoor temperature and simulated whole-year pressure difference in the top, middle and bottom floor apartments of the 5-story apartment building.

The simulations of the single room ventilation units with the regenerative ceramic HEX were made using the same calibrated model of 5-story apartment building which was used in whole-year pressure difference simulations. The performance data of the fans and HEX has been taken from the results of laboratory tests that are described in pt. 3.2. As the studied ventilation units have to ensure the low noise level in living room and bedroom, the unit can only work in 30–50% speed level. An example of supply temperature and airflow rates simulation results of the ventilation unit with ceramic HEX, located in first floor, are shown as duration curves in Figure 13. During heating season, supply air temperature is relatively close to the outdoor temperature (Figure 13a) and that supply airflow rate is much higher than exhaust airflow rate (Figure 13b).

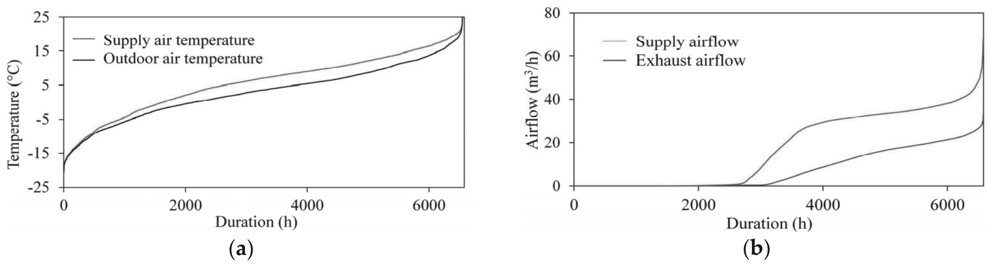


Figure 13. (**a**) Simulated supply air temperature and (**b**) airflow rates duration curves for ventilation unit with regenerative HEX during heating period in 1st floor apartment (September–May).

4. Discussion

The field measurements show that the pressure difference between the indoor and outdoor air in the bottom floor apartment depends heavily on the outdoor temperature, indicating the influence of the stack effect, whereas on the top floor, due to the smaller height of the exhaust ventilation shaft, the dependence is weak. Similar results have been also shown in other studies [50,51]. Kiviste and Vinha [50] have studied different Finish buildings and found that in some cases there can be large underpressure conditions (<-15 Pa) between in-and outdoor environments. Kalamees et al. [28] showed that in most critical cases, the air pressure across the building envelope may rise up to 30 Pa and the main reason for that is airtight building envelope with unbalanced ventilation. This study confirms that in renovated 5-stories apartment buildings with natural exhaust ventilation, the pressure difference across the building envelope can rise up to 20–30 Pa. Analyzing the fan performance of room-based ventilation units with regenerative HEX, it can be concluded that the pressure differences over the envelope were caused by the natural ventilation and density differences between the indoor and outdoor air. The room-based ventilation units itself did not play a significant role to increase the pressure drop across the building envelope.

During the analysis of the pressure difference measurement results and calibrating the model, the occasional peaks toward zero-pressure difference (see Figure 8a). These peaks are most likely caused by opening the windows or external doors to the balcony or staircase, the peaks and periods toward greater difference indicate the wind-induced effect. As the kitchen hoods and exhaust fans were installed in some apartments of studied building, the peaks can also be caused by these components of mechanical ventilation. Pressure difference caused by wind can be dominant also for longer periods. Although the wind-induced component varies in a wide range and depends on multiple variables, its contribution to the pressure conditions can be considerable, and thus special attention needs to be paid to buildings in wind exposed locations. Kalamees et al. [28] found that wind primarily influence the peak air pressure values and comparing the average values, the influence of wind is small. Despite the wind effect and other uncertainties during the pressure measuring and model compilation, we can see that dependence between measured and simulated indoor and outdoor pressure differences is quite strong (see Figure 12a). In the first floor the value of linear correlation coefficient of simulated data is 0.6951 and the correlation coefficient of measured data is 0.7587. The values of correlation coefficients, together with the similarity in results of simulation and measurement indicates that the calibration of the model was successful.

The laboratory measurement results of the studied room-based ventilation units show that supply and extract airflows are equal only at very low pressure differences. The greater the gap, the more the airflows differ. It can be seen, that the unit with plate HEX is performing considerably better, mainly due to centrifugal fans, but also because of the constant airflows. In case of the unit with regenerative HEX, the pressure difference is causing low-pressure axial fan to perform poorly: smaller volumes of exhaust air to flow through the unit during exhaust cycle, lowering the heat quantity accumulated in the HEX and leaving the outdoor air heating insufficient. The effect escalates with lower outdoor temperatures and higher pressure differences, in which case the heat transfer in the unit degrades and larger volumes of cold air are entering the ventilated space. It means that the pressure difference across the building envelope is closely related to the temperature efficiency of studied ventilation systems.

The performance of room-based ventilation units have also been monitored in previous studies. Smith et al. have developed the ventilation units with plastic rotary HEX [25,44]. They have made airflow measurements of the tested units using the tracer gas method. The main conclusion of this study was that the temperature efficiency of studied unit on equal supply and exhaust airflows is about 0.83–0.84 [25]. As these tests were not performed in different indoor and outdoor pressure conditions, it is not possible to make the conclusion, how these units would perform in apartment buildings in cold climate region.

Based on the simulation results, the pressure difference across the exterior wall during the heating season in a five-story building can be as high as −30 Pa on the first floor, −20 Pa on the third floor, and −15 Pa on the fifth floor. Comparing the simulated pressure conditions and the measured characteristics of the ventilation unit, poor performance of the unit can be expected. The simulation results of room-based units with regenerative HEX show that during heating season, supply air temperature is relatively close to the outdoor temperature and that supply airflow rate is much higher than exhaust airflow rate. At the same time the unit with recuperative HEX can ensure the temperature efficiency of the unit over 0.5 even under negative pressure as high as −25 Pa, making it possible to use the device in first floor apartments.

Several studies have shown that room-based ventilation units in Estonian apartment buildings are not ensuring the necessary air change rate [3,7,18]. Mikola et al. [3] point out that as these room units generate high sound power level, people switched ventilation units to the 30% of the maximum airflow. If tested room units with regenerative HEX work at 30% speed level and the pressure difference across the building envelope is −8 Pa then the supply airflow is 2 times higher than the exhaust airflow from the room. Mikola et al. [3] also measured the air change rate in apartments with regenerative room-based units. According to the measurements results, the average air exchange rate was 0.18 h^{-1} and the average airflow per surface area of an apartment was 0.12 L/(s*m^2). According to the indoor climate category III, the general ventilation airflow in old apartments should be at least 0.35 L/(s*m^2) or 0.5 h^{-1} and airflow in living rooms and bedrooms should be at least 0.6 L/(s*m^2) or 4 L/(s*person). The indoor climate category III requirements for the air change rate were also a minimum requirement to apply for the renovation grant. The air exchange rate met the requirements of III class in 6% of the apartments with room-based ventilation units [3]. In rest of the apartments, the minimum requirement of renovation grant scheme, was not ensured. It can be concluded, that the measured room-based ventilation renovation solution in apartment buildings does not ensure the necessary air change rate.

In case of both studied room-based ventilation units, the only possible to protect the HEX from freezing in cold climate is to reduce the supply airflow. As proven in this study, the exhaust airflow can be very small if the air pressure difference across the building envelope is high. That is the reason why there is high risk of ice formation in HEX, which complicates using these units in rooms with high humidity. The freezing process of HEXs of room-based units is not analyzed in detail during this study, so it would be worth to study this in future.

Based on previous studies [1,8,40] in Estonian climate, the following ventilation renovation solutions have performed better than room ventilation units:

- Apartment based supply and exhaust ventilation system with heat recovery, with unit located in apartment, in corridor or staircase.
- Centralized supply and exhaust ventilation system with heat recovery, with unit located on roof, pipes located in external wall or in apartment.
- Centralized exhaust ventilation system with fresh air radiators and heat pump heat recovery.

5. Conclusions

In this study, field measurements of pressure difference across the building envelope were carried out during a three-month period of the heating season in a fully renovated five-story apartment building. The results were used to validate the IDA-ICE whole building simulation model allowing to simulate hourly whole-year pressure conditions and airflows. Considering the measured and simulated pressure conditions, the performance of two different single room ventilation units was studied: one of the units was a device with a recuperative cross-flow plate HEX and two centrifugal fans and another with a regenerative ceramic HEX and an axial fan. The units were tested in TalTech technological facility, where supply and exhaust temperatures and airflow rates were measured under changing pressure conditions and different fan speeds. Fan and heat recovery efficiency curves were created and modelled in IDA-ICE for whole-year performance assessment.

In both cases of the studied ventilation units, pressure differences generated large differences in the supply and exhaust air flow rates. Because of the higher pressure rise, the airflow balance difference was much smaller in case of the unit with centrifugal fans compared to the unit with axial fan. This resulted in the smaller change in heat recovery efficiency of the recuperative HEX, compared to the regenerative HEX case which practically lost its heat recovery because of dominating stack effect pressure.

The simulation results show, that in cold periods, apartments in the first floor can be under negative pressure as high as −20 Pa for longer periods of time. In ventilation system planning, values of −10 Pa in fifth floor, −15 Pa in third floor and −20 Pa in first floor apartments can be recommended to be used as design values for ventilation units. The simulation results of single room units with regenerative HEX show that during heating season, supply air temperature was close to the outdoor temperature and that supply airflow rate was much higher than exhaust airflow rate, showing that the unit operated as air intake. Due to the differences in supply and exhaust airflows, there is a risk for freezing the heat exchanger, which excludes using studied ventilation units in rooms with high humidity.

The laboratory measurement results confirmed, that the axial fan used in the ventilation unit was not capable to work in typical pressure conditions occurring in multi-story building in cold periods, in order to achieve sufficient air change rate, heat recovery and supply air temperature, with noise levels under acceptable limits. In the case of the unit with recuperative HEX, under the same circumstances, the temperature efficiency of the unit remained higher than 0.5 even under negative pressure as high as−25 Pa, making it possible to use the device in first floor apartments.

Author Contributions: The laboratory and field measurements were performed by A.M. and R.S. Analyses of the measured data was carried out by A.M. and R.S. The simulation model was calibrated by R.S. The research principles and methods of the study were developed by A.M., R.S. and J.K.

Funding: This research was supported by the Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts, ZEBE, grant 2014-2020.4.01.15-0016 funded by the European Regional Development Fund.

Acknowledgments: Authors would also like to thank Fund Kredex for cooperation of our research work.

Conflicts of Interest: The authors declare no conflict of interest.

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Publication V

A. Mikola, A. Hamburg, K. Kuusk, T. Kalamees, H. Voll, and J. Kurnitski, “The impact of the technical requirements of the renovation grant on the ventilation and indoor air quality in apartment buildings,” Build. Environ., vol. 210, p. 108698, Feb. 2022. https://doi.org/10.1016/j.buildenv.2021.108698.

Building and Environment 210 (2022) 108698

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

The impact of the technical requirements of the renovation grant on the ventilation and indoor air quality in apartment buildings

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ARTICLE INFO

Keywords:
Ventilation renovation
Performance of ventilation
Indoor air quality
CO_2 concentration
Air change rate
Exhaust air heat pump

ABSTRACT

In this study, the impact of ventilation requirements set in the conditions of a renovation grant was analysed with field measurements. Effects of renovation measures applied in two grant periods on the air change rate (ACR) and indoor air quality (IAQ) of apartments were examined. CO_2 levels and airflow rates were measured in 21 buildings during the first renovation grant period and in 15 buildings in the second grant period. During the first grant period, the average ACR studied apartments was as low as 0.17 h^{-1}, and in the second grant period ACR had improved to 0.57 h^{-1}, complying with requirements. Room-based ventilation requirements as well as heat recovery and preheating of intake air, mandatory airflow rate and sound pressure level measurement protocols, and third party inspection of design documentation assured adequate ventilation and IAQ in the second grant period. Centralized mechanical supply and exhaust ventilation with heat recovery resulted in best performance but an alternative system with exhaust heat pump and ventilation radiators may also be recommended. We concluded, that the installation of proper ventilation system is a key issue in renovation. The results of the study are a valuable input in designing technical conditions of the renovation grant.

1. Introduction

In many European countries, there is increasing awareness of the need for building renovation. As the buildings account for 40% of the total energy consumption in the European Union (EU), it is the leading source of carbon dioxide (CO_2) emissions [1]. According to the Energy Performance of Buildings Directive (EPBD) [1] countries in the EU need to reduce energy consumption and produce energy from renewable sources in the building sector. Moreover, the new recast of the EPBD suggests that the renovation of existing buildings into nearly zero-energy buildings needs to occur place [2]. Current renovation practices show that deep renovation in the EU is at a 0.2–0.3% renovation rate, and a similar situation has been reported in Estonian commercial buildings [3,4]. To change this situation, EU member states have prepared long term renovation strategies (LTRS) to renovate about 75% of existing building stock to nearly zero energy buildings (NZEB) until 2050. The Estonian LTRS states that all buildings built before 2000 must undergo major renovation [5]. Estonia is implementing one of the very few and validated deep renovation support schemes – the KredEx renovation grant scheme for apartment buildings. This practice shows that large-scale deep renovation with good energy and indoor climate performance is possible and that subsidies can be budget neutral [6]. These experiences and practices can be valuable in other EU countries to reduce CO_2 emissions. The EPBD directive [1,2] also emphasises that during renovation, the quality of healthy indoor air in buildings must be ensured. Indoor air quality (IAQ) in apartment buildings often depends strongly on heating and ventilation systems [7]. Heating, ventilation and air conditioning (as shortened to HVAC) systems in old buildings are often technologically obsolete; thus, using integrated renovation packages, including measures to improve IAQ, is inevitable [8].

Measurements during large-scale field campaigns on the performance of ventilation in old apartment buildings revealed that the air change rate (ACR) in Estonian apartment buildings is often insufficient because old natural ventilation (NV) systems are in poor condition and needs to be renovated [9–12]. Additionally, the renovation of ventilation systems in apartment buildings is one of the biggest obstacles to achieving the objectives [9,13]. If the existing NV system is not renovated during renovation, the airtightness of the building envelope increases, and the ACR is reduced [14,15].

Many studies have been investigated buildings in which the IAQ has worsened after building renovation [14–17]. Földváry et al. [14] measured indoor air CO_2 concentration before and after apartment building renovation and found that the median night-time level of CO_2

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https://doi.org/10.1016/j.buildenv.2021.108698
Received 17 June 2021; Received in revised form 23 November 2021; Accepted 18 December 2021
Available online 21 December 2021
0360-1323/

Nomenclature

Abbreviations

ACR	Air change rate
IAQ	Indoor air quality
EU	European Union
EPBD	Energy Performance of Buildings Directive
LTRS	Long term renovation strategy
NZEB	Nearly zero energy building
HVAC	Heating, ventilation and air conditioning
NV	Natural ventilation
HR	Heat recovery
HRV	Centralised balanced ventilation with ventilation heat recovery
EAHP	Exhaust air heat pump heat recovery
ME	Mechanical exhaust ventilation without heat recovery
SRVU	Single room ventilation unit with heat recovery
HEX	Plate heat exchanger
ICC	Indoor climate category
VR	Ventilation radiator
AHU	Air handling unit
PE	Primary energy
SCOP	Seasonal coefficient of performance

was higher than that before the renovation. In addition to the CO_2 measurement results, concentrations of other pollutants should also be investigated, for example, the concentration of fine particles in indoor and outdoor air in Estonian old apartment buildings [18]. The main conclusion of their study was that, in general, in Nordic countries, the indoor/outdoor ratios of fine particles are approximately 1, which means that a higher ACR does not affect the IAQ level [18,19] because there is no significant outdoor air filtration in old buildings. Studies have shown that the IAQ and the human health are strongly related [20,21] and that low air changes can cause health problems [22,23] and loss of productivity [24,25]. Because insufficient ventilation of buildings is related to adverse health effects, ensuring an adequate ACR should be prioritised over other renovation measures [8,26].

The renovation of old ventilation systems is a natural part of the renovation process and using exhaust air heat recovery (HR) in cold climate regions is the only solution to reach the energy saving targets of the EU [27]. Leech et al. [28] showed that in energy-efficient houses with mechanical supply and exhaust ventilation with HR, the health of occupants improved over one year period. Additionally, the energy consumption of ensuring sufficient ACR is between 30 and 60% of the total energy demand of an apartment building [6,29–31]. If a high-efficiency exhaust HR system is used, the consumption of supply air heating falls below 10% of the total heating energy consumption [32]. The behaviour of occupants can also influence the practical performance of apartment ventilation systems [10,33,34]. Park et al. [33] conducted a questionnaire survey of the residents of 139 apartments with mechanical ventilation; they found that 68% of the residents did not turn on the ventilation units and that 58% of residents who did not use mechanical ventilation said that the primary reason was the cost of heating energy. Based on the referenced studies [32,33], the mechanical ventilation without HR can cause the ventilation systems to be turned off, which means very low ACRs and extra energy costs because of the opening of the windows. Moreover, the renovation of old NV systems can increase electricity consumption [35], which is inevitable because the initial ACR does not fulfil these requirements.

Olsson et al. [36] interviewed six Swedish property owner organisations and concluded that increasing the sustainability of the built environment would require government subsidies. Pikas et al. [37] calculated that 17 jobs per EUR 1 million of investment were generated in the renovation of old Estonian apartment buildings and that the tax revenue from renovation construction projects was over 32%. The same study also pointed out that it is most beneficial to invest in integrated renovation, which includes both measures to improve IAQ and increase energy efficiency [37]. Kurnitski et al. [6] developed the Estonian energy roadmap and pointed out that support schemes for apartment buildings are necessary if the renovation cost is higher than 200 €/m^2. Additionally, because the integrated renovation process generates 32% of tax revenue, the invested money is partially or totally returned to the state budget. Thus, we conclude that renovating schemes can revive the economy, increase the energy efficiency of apartment buildings, and improve IAQ.

The most common ventilation renovation measures used in cold climates are centralised balanced ventilation with ventilation heat recovery (HRV), mechanical exhaust ventilation with exhaust air heat pump heat recovery (EAHP), and mechanical exhaust ventilation without heat recovery (ME) [38–40]. Some alternative ventilation renovation measures, such as single room ventilation units with HR (SRVU) [41–43] or renovation of the old NV system, have also been used [16,17]. Even if ventilation systems are renovated using viable ventilation renovation measures, the correct design, construction, operation, and maintenance of all parts of the system must be implemented [44]. Discomfort to the occupants may be caused if mistakes have been made in a renovation phase [14,15,17,45], for example, the wrong position of the supply air valves [17] or an incorrect solution to frost protection of the plate heat exchanger (HEX) [46,47]. Studies of Estonia [9,10,48] have shown that some ventilation renovation measures and technical solutions are not suitable for renovating apartment ventilation systems.

In this study, the impact of technical conditions on ventilation renovation measures in renovation support grants was analysed based on long-term measurements in buildings renovated with grants provided by two different renovation grant schemes. Both renovation grant schemes aimed to achieve deep, integrated renovation. Different ventilation renovation solutions were used.

2. Methods

The ventilation performance was studied using field measurements. A detailed flowchart of the study methods is presented in Fig. 1. The ACR in existing Estonian apartment buildings before renovation grants is the starting point for ventilation renovation measures. The activities in steps 1 and 2 outlined in the flowchart have been performed in previous studies [9,13]. Because the ACR during the old renovation measures did not fulfil the requirements, new technical requirements for indoor climate and ventilation were introduced for renovating apartment buildings using state financial support. In Fig. 1, the first renovation grant scheme is outlined in Step 3, and the second scheme is outlined in Step 4. The main focus of this paper is to determine how the technical requirements of the first and second renovation grants improved IAQ and the ACR.

In response to the first and second support grants, 21 buildings and 15 buildings were analysed, respectively. All renovated buildings had NV systems before renovation. The studied buildings were built between 1953 and 1986. The net heated area for buildings varied between 550 m^2 and 5030 m^2, and the number of apartments varied between 12 and 72. The average number of apartments in one building was 27, and the average heated area was 1757 m^2. In four buildings, the performance of NV was improved by cleaning the old NV shafts, and in six buildings, the performance of NV was increased by adding fresh air intakes. In 10 buildings, HRV systems were installed; in eight buildings, EAHP systems were installed; in three buildings, ME without HR was installed; and in five buildings, SRVUs were installed.

Ventilation renovation measures in the first grant scheme did not perform effectively, and the requirements of the grant scheme were not fulfilled. This failure initiated the development of new requirements to improve the situation. Because some ventilation renovation measures in

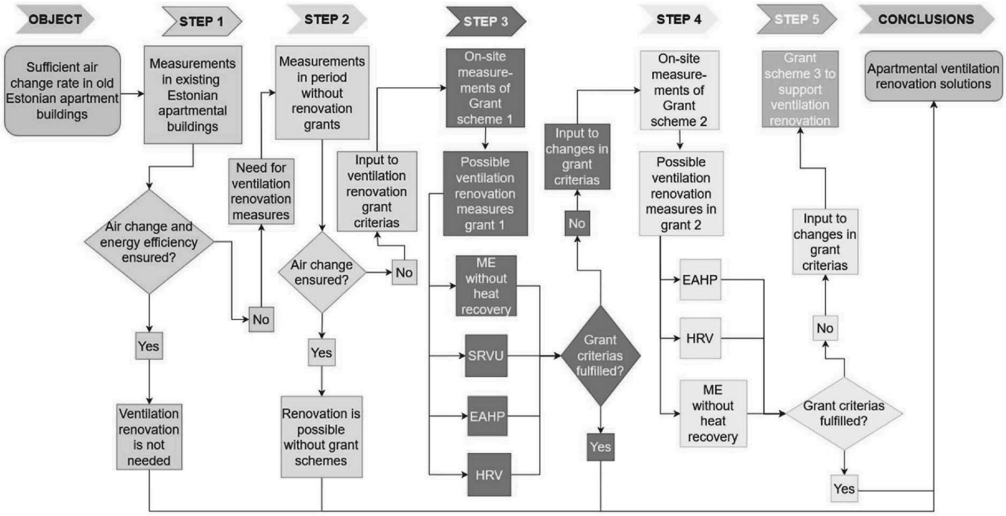

Fig. 1. General flowchart of the methods of the study.

the first grant scheme did not ensure adequate indoor climate parameters, these solutions were excluded from the second grant scheme. New recommendations to improve the technical conditions of the ventilation renovation measures were made according to the airflow and supply air temperature measurement results of the second grant scheme. The new inputs to the grant scheme developed in this study are shown in flowchart Step 5. In the conclusion, suitable ventilation renovation measures and the main technical principles of these measures are discussed.

2.1. General requirements for the ventilation design in Estonian apartment buildings

The ventilation systems of Estonian apartment buildings built before 1990 were designed using NV. At first, the designed air change level in living rooms was 1 h^{-1}, and later, it changed to 0.8 $l/(s*m^2)$ [44]. Extract air was removed from the toilets (WC), bathrooms, and kitchens. Normative extract airflow from the kitchen was 20 l/s; from the bathroom, 7 l/s; and from the WC, 7 l/s. Intake air was designed to enter the cracks of the leaky windows and external walls.

According to EVS-EN 15251:2007 [50] and EVS-EN 16798–1:2019 [49], the air velocity in living spaces, volume of the room per person, and content of harmful substances in indoor air must not exceed permitted values. Indoor air CO_2 concentration is the standard of indoor environmental input parameters and design criteria CR 1752 [9] and the energy performance standard of buildings in EVS-EN 16798–1:2019 [49]. Ventilation performance was assessed based on target values from the standard in EVS-EN 15251:2007 (2007–2018) and EVS-EN 16798–1:2019 (since 2019). The II indoor climate category (ICC), representing the normal level of expectation for new buildings and major renovations, was used for comparison. The general ventilation airflow in new apartments (ICC II) should be at least 0.42 $l/(s*m^2)$ or 0.6 h^{-1}, and airflows in living rooms and bedrooms should be at least 1.0 $l/(s*m^2)$ or 7 l/(s*person). According to the II ICC, extract airflow from the kitchen should be 20 l/s (25 l/s); from the bathroom, 15 l/s; and from the WC, 10 l/s.

2.2. Requirements for the renovation in apartment buildings according to the Estonian grant schemes

There were three renovation grant support levels for construction work (15%, 25%, and 35%) for the first grant scheme and two basic levels (25% and 40%) for the second grant scheme (Table 1). These levels are based on the designed energy performance level achieved after renovation work has been completed. In Estonia, energy performance levels in buildings are expressed using primary energy (PE). The PE requirement accounts for the energy used for space heating, ventilation, domestic hot water, appliances, and lighting, with the national primary energy factors of energy carriers.

No specific requirements were for ventilation and indoor climate in the first support grant (Table 1). After the renovation, the indoor climate had to fulfil the EN-15251 ICC II requirements (this standard has been updated with minor changes to EN 16798–1:2019). The heating system has two requirements: the system must be hydraulically balanced, and radiators must be equipped with thermostats to allow room-based indoor temperature control. Typical ventilation renovation measures were fresh air intakes for NV, SRVU, ME without HR, EAHP, and HRV.

According to the ACR measurement results in the buildings renovated during the first grant scheme, specific requirements were added to the renovation grant requirements. These requirements included room-based airflow rates, mandatory airflow measurement report, third party

Table 1
Overview of the financial support and requirements on energy performance of renovating Estonian apartment buildings using the state support.

Period	Financial support	Requirements for energy performance
2010–2014 first grant	Support at 15%, 25% or 35% depending on the renovation solution	15% support: heating energy reduction ≥20% (<2000 m^2) and ≥30% (>2000 m^2), PE ≤ 250 (kWh/m^2)/year; 25% support: heating energy reduction ≥40%, PE ≤ 200 (kWh/m^2)/year; 35% support: heating energy reduction ≥50%, PE ≤ 150 (kWh/m^2)/year.
2014–2018 second grant	Support at 25% or 40% depending on the renovation solution	25% support: PE ≤ 180 (kWh/m^2)/year; 40% support: PE[1] ≤ 150 (kWh/m^2)/year.

[1] Estonian PE values include appliances and lighting which contribution is 59 kWh/m^2/year, therefore PE requirement for EPBD uses is 91 kWh/m^2/year.

inspection for design documentation preheating the intake air and specific airflow calculation rules (Table 2 and Table 3). Typical ventilation renovation measures were ventilation radiators (VR) with EAHP, HRV with ductwork installation on the façade, and ME without HR (only for the 25% grant level).

2.3. Description of ventilation renovation solutions used in studied buildings

Five types of ventilation systems have been installed during the renovation of Estonian apartment buildings:

- centralized balanced ventilation with ventilation heat recovery (HRV);
- mechanical exhaust ventilation with heat pump heat recovery (EAHP);
- mechanical exhaust ventilation without HR (ME);
- renovating the old natural ventilation systems (without heat recovery) (NV); and
- single room ventilation units with ventilation heat recovery (SRVU); used in 2010–2014.

The most widely used ventilation renovation solution for old apartment buildings is HRV with ductwork installation on the façade (60% in the second grant period). The ventilation unit of this system was installed on the roof or in the attic (Fig. 2 and Fig. 3). Flat-or round-shaped supply ducts are installed inside the additional insulation of the external walls and roof (Figs. 3a and 13). Old ventilation shafts are used to extract air from apartments. Because the air tightness of old ventilation shafts is often low, new ventilation ducts should always be installed inside old shafts. Occasionally, an air ductwork is installed on the façade in a similar fashion to that of the supply air ductwork. The supply air is ducted to the living rooms, and the bedrooms and extracts are in toilets, bathrooms, and kitchens. Installing ventilation ducts inside the additional insulation layer helps avoid visible ducts inside the apartments. The supply air diffusers were installed on the external wall of the living room and bedroom, and the extract air valves were placed on the wall near ventilation shafts. The volume of ventilation work inside the apartment is minimal and does not disturb individuals much. Ventilation ducts on the roof should be installed inside the insulation layer of the roof or covered with a separate insulation layer. In ensuring high HR efficiency and avoid the spread of odours, the counter-flow plate HEX is commonly used. According to the EVS-EN 16798–3:2019 [49], the supply side of the unit should be equipped with the ePM1 60% (F7) and exhaust side with ePM10 60% (M5) filters. According to requirements of the support grant, a water-based heating coil should be used to reheat the supply air. The detailed working principle of the HRV with ductwork installation on the façade is shown in Figs. 2, Figs. 3 and 4.

Table 2
Overview of the requirements for indoor climate and ventilation when renovating apartment buildings using state financial support.

Period	Requirements for indoor climate and ventilation
2010–2014 first grant	No specific requirements, but in accordance with the indoor climate requirements according to EN-15251 (2007) ICC II
2014–2018 second grant	All grant levels: • Continuous ACR for apartment at least 0.5 h^{-1} + see Table 3 • Sound pressure levels in bedrooms and living rooms 25 dB(A) • Third party inspection of design documentation • Mandatory airflow measurement report • Indoor climate according to the EN-15251 (2007) ICC II requirements or following ventilation requirements specified in the grant scheme 40% grant level (most popular, 80% of buildings): in addition to aforementioned: • Heat recovery ventilation system serving all rooms in an apartment • Preheating the intake air with VRs in EAHP system • Ventilation units should be without electric preheating coils

EAHP system with VRs have also been actively used (35% in second grant period) in renovation of apartment buildings. During the first grant period, the fresh air inlets were used for supply air, but due to many complaints about the cold draught, the requirement to preheat the supply air was added in the conditions of the second grant. To preheat the air, VRs are used. The outdoor air enters through VRs where it is filtered (typically ePM1 60% (F7) filters) and heated. Extract air moves through ventilation shafts to air to water HEX of ventilation unit where the heat is transferred through a brine loop to water-water heat pump. The heat pump provides heat to the domestic hot water and the space heating system. The seasonal coefficient of performance (SCOP) is 3.0–3.5 [32,45,51]. The main problem of this renovation solution is using old NV shafts without inserting new ducts inside the old shafts. The airtightness of old shafts is too low and therefore, the ventilation systems are often unbalanced and very noisy. That, in turn, means that the air flow rates are reduced. The main principle of EAHP system is described in Fig. 5.

The EAHP system with VRs has also been actively used (35% in second grant period) in apartment building renovation. During the first grant period, fresh air inlets were used to supply air, but due to many negative reports on cold draughts, the requirement to preheat the supply air was added under the conditions of the second grant. VRs are used to preheat air. Outdoor air enters through the VRs, where it is filtered (typically ePM1 60% (F7) filters) and heated. Exhaust air moves through ventilation shafts to the air to water HEX of the ventilation unit, where the heat is transferred through a brine loop to a water–water heat pump. The heat pump provides heat to the domestic hot water and space heating system. The seasonal coefficient of performance is 3.0–3.5 [32, 45,51]. The main problem of this renovation solution is using old NV shafts without inserting new ducts inside old shafts. The airtightness of old shafts is too low; therefore, ventilation systems are often unbalanced and noisy. This thus implies that airflow rates are reduced. The main principle of the EAHP system is illustrated in Fig. 5.

SRVU with HR (Fig. 6a) has also been used for ventilation renovation during the first grant period (40% in the first grant period), mainly SRVUs with regenerative ceramic HEXs. Single-fan-based units work in cycles, switching between the supply and exhaust modes every 60–70 s. During the exhaust cycle, the heat from the warm exhaust air accumulates in the ceramic comb-like HEX and is then used to heat the cold outdoor air during the supply cycle. These units were equipped typically with G3 type of coarse filters. Field measurements have shown that this system does not ensure sufficient ACR and efficient HR [48,52–54]. The main problem is related to the large negative pressure due to the stack effect in the lower-floor apartments. Fans used in SRVUs are not capable of working under typical pressure conditions in multi-story buildings in cold periods [17,48]. Because the results of using SRVUs as a ventilation renovation measure were unsatisfactory, this solution was not accepted for use in implementing the second grant scheme which detailed technical conditions made it impossible to use this system.

Apartment-based HRV has also been used (Fig. 6b). The ventilation unit of this system is installed in staircases, corridors, or sanitary rooms, under the ceiling or on the wall. A plate or rotary HEX was used for HR. These units have adequate filters, ePM1 60% (F7) on the supply side and ePM10 60% (M5) filters in extract air following the requirements of the EVS-EN 16798–3:2019 [49]. Air is extracted from kitchen hoods, toilets and bathrooms. Supply air devices are installed in living rooms and bedrooms. Since installing this system to an apartment requires space and construction work in the apartment, it was used very rarely (~1%).

2.4. Evaluation of the performance of ventilation renovation measures

In the case of the first grant scheme, the indoor air CO2 levels and airflow were measured in 21 renovated apartment buildings. Four apartments were studied in each building, and the measurement period

Table 3
Ventilation airflow rate calculation for model apartments according to the II grant requirements, 2014–2018.

Apart-ment type	Floor area,	Extract airflow rate, l/s				Supply airflow rate, l/s					ACR
	m^2	WC	Bath-room	Kitc-hen	To-tal	Li-ving	Bed1	Bed2	Bed3	To-tal	h^{-1}
Single room	35	–	10	6	16	10+6[1]	–	–	–	16	0.63
1 bed-room	55	–	15	8	23	10+2[1]	10+1[1]	–	–	23	0.58
2 bed-rooms	70	10	15	8	33	10+2[1]	10+1[1]	10	–	33	0.65
3 bed-rooms	80	10+2[1]	15+1[1]	8+2[1]	40	10	10	10	10	40	0.69

[1]values marked with "+" indicate the requirement to balance airflows.

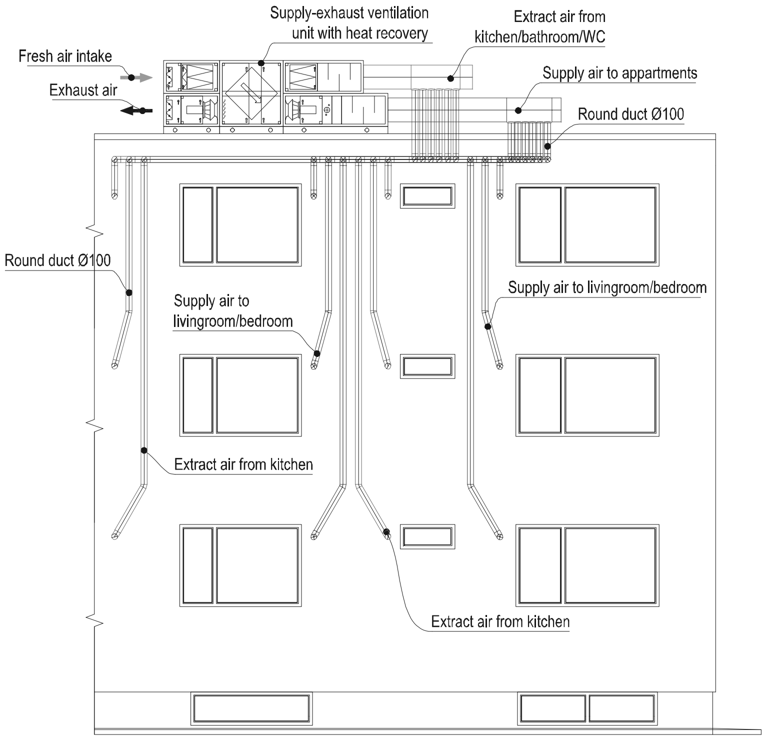

Fig. 2. Section of ventilation ducts inside the building façade.

was one year. During the second grant scheme, 15 renovated apartment buildings were selected. In each building to 2–4 apartments were studied, and the measurement period was four months. The same measurement methodology was used in both grant schemes. The indoor air temperature, relative humidity of indoor air, and the level of CO_2 were measured using an Evikon E6226 measurement unit (temperature −10–+50 °C; relative humidity 0–100%; CO_2 level 0–10,000 ppm). All measurement units were located in the bedrooms. To measure the airflow, we used a multifunction IAQ metre Testo 435–4 with a hood Testo 410 (airspeed 0–20 m/s and accuracy ±0.03 + 5%; differential pressure 0–250 Pa and accuracy ±1 Pa). Airflow in the supply and extract valves was calculated according to the differential pressure measurements in the valves. Airflow was measured twice during the installation and removal of the sensors. In the case of SRVU and NV, the ventilation airflows were measured using the measuring hood Testo 410. All airflow measurements in apartments were collected in the mode of operation of the ventilation system that was used daily in the building.

For assessment of CO_2 levels, the ICC II (1200 ppm) of standard EVS-EN 16798–1:2019 [49] was used. The measurement results of the CO_2 level are reported for occupancy time only. The allowed exceeding time of the CO_2 level according to the standard in CEN/TR 16798–2:2019 [55] is 6% of the measuring time. Because the occupancy time was not measured directly, a special algorithm was developed to select only the period when residents were at home and windows were not opened. The algorithm included ACR and apartment volume information, and it identified the moments when the CO_2 level decreased faster than it would be normal if there was one sleeping person in an apartment. For calculating the normal decrease in the CO_2 level, the instantaneous CO_2 value was compared with the average CO_2 value of the last 50 min. In addition, CO_2 measurements close to ambient air levels were excluded from the occupancy period. Mikola et al. [9] use the same method to determine the occupancy period in old unrenovated apartment buildings.

ACR in apartments was assessed using the requirements of the second support grant. Thus, the continuous ACR in apartments must be at least 0.5 h^{-1}, and the supply and extract airflows must be calculated according to the requirements listed in Table 3. One of the requirements for applying the support grant during the second grant scheme was the mandatory airflow measurement report according to the methodology of the standard in EVS-EN 12599:2012 [56]. The airflow measurement

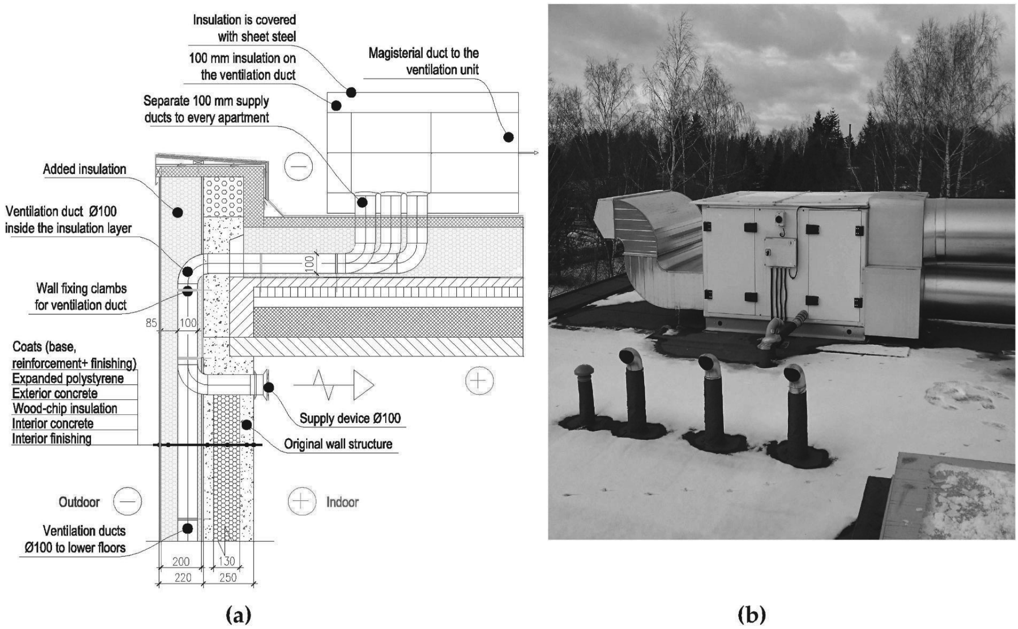

Fig. 3. (a) Ventilation ducts on the wall and (b) HRV ventilation unit on the roof.

report was available for all the studied buildings, and during the study, the reports were examined. According to the measurement reports, airflow in the measured valves conformed to the designed values. During the apartment visits, the positions of the valves were recorded and compared with the values in the airflow measurement reports.

To study the influence of frost formation inside the plate HEX of air handling units (AHUs), the supply air temperature, extract air temperature, outdoor temperature, and temperature after the HEX on the supply side were measured. For measuring the temperatures, Onset Hobo UX100-014 M, U12-006, and U12-013 data loggers together with K-type thermocouple probes (air temperature 0–1250 °C, accuracy ±0.75%) were used. The supply air temperature was measured only during the second grant scheme.

3. Results

3.1. Development of ventilation requirements in the first and second grant scheme

In the following, the airflow rate and CO2 measurement results are compared for ventilation systems used in the renovation. In principle, the same EN-15251 ICC II requirement applied for both grant schemes, but in grant II the requirements were wrote out and supervision was strengthened (Table 2). Writing out and complementing the requirements in II grant scheme affected the selection of ventilation systems, however, EAHP and HRV were used in both grants enabling the performance comparison of the same system under different conditions. Grant II requirements specified room-based airflow rates, airflow measurement report was made mandatory, and third party inspection for design documentation was conducted before the funding decision. Also, requirements to preheat the intake air, general ventilation principle that the ventilation system should serve all rooms in an apartment (outdoor air to bedrooms and living rooms, and extract from wet rooms and kitchen), and continuous ACR in apartments at least 0.5 h^{-1} were added. Ventilation airflow rate design according to the grant II requirements for typical apartments is shown in Table 3.

Technical conditions of second grant made it impossible to continue the use of NV systems. Similarly, the requirement that the heat recovery ventilation should serve all rooms in an apartment together with 25 dB (A) sound requirement blocked the use of SRVUs. These systems have therefore not been used in the period of second grant period.

3.2. Indoor CO_2 levels in renovated apartment buildings

Indoor air CO_2 concentration in the studied apartment buildings varied during the first grant scheme from 346 to 6714 ppm and during the second grant scheme from 401 to 3645 ppm. The average CO_2 concentration of all apartments during the occupancy period was 970 ppm during the first scheme and 837 ppm during the second scheme. The average human presence in the apartments during the heating period was 61% and 63%, respectively. The average, minimum, and 95% percentile levels of the CO_2 measurements of renovated apartments during the occupancy period are shown in Fig. 7. According to the standard in CEN/TR 16798–2:2019, the CO_2 level of indoor air may exceed the specified limit values by 6% (II ICC) of the annual use of the building daily, weekly, monthly, or yearly. CO_2 concentration in the bedrooms fulfilled the requirements of the II ICC in 41% and 58% of the measured grant and second grant apartments, respectively. In different ventilation systems, CO2 concentration in first grant scheme corresponded to the values in EVS-EN 16798 II ICC during the following percentage of the occupancy time:

- 44% of apartments in the case of NV without fresh air valves;
- 35% of apartments in the case of NV with fresh air valves;
- 30% of apartments in the case of EAHP;
- 45% of apartments in the case of SRVU; and
- 100% of apartments in the case of HRV.

In second grant scheme CO_2 concentration corresponded to EVS-EN 16798 II ICC values:

- 43% of apartments in the case of ME ventilation without HR;

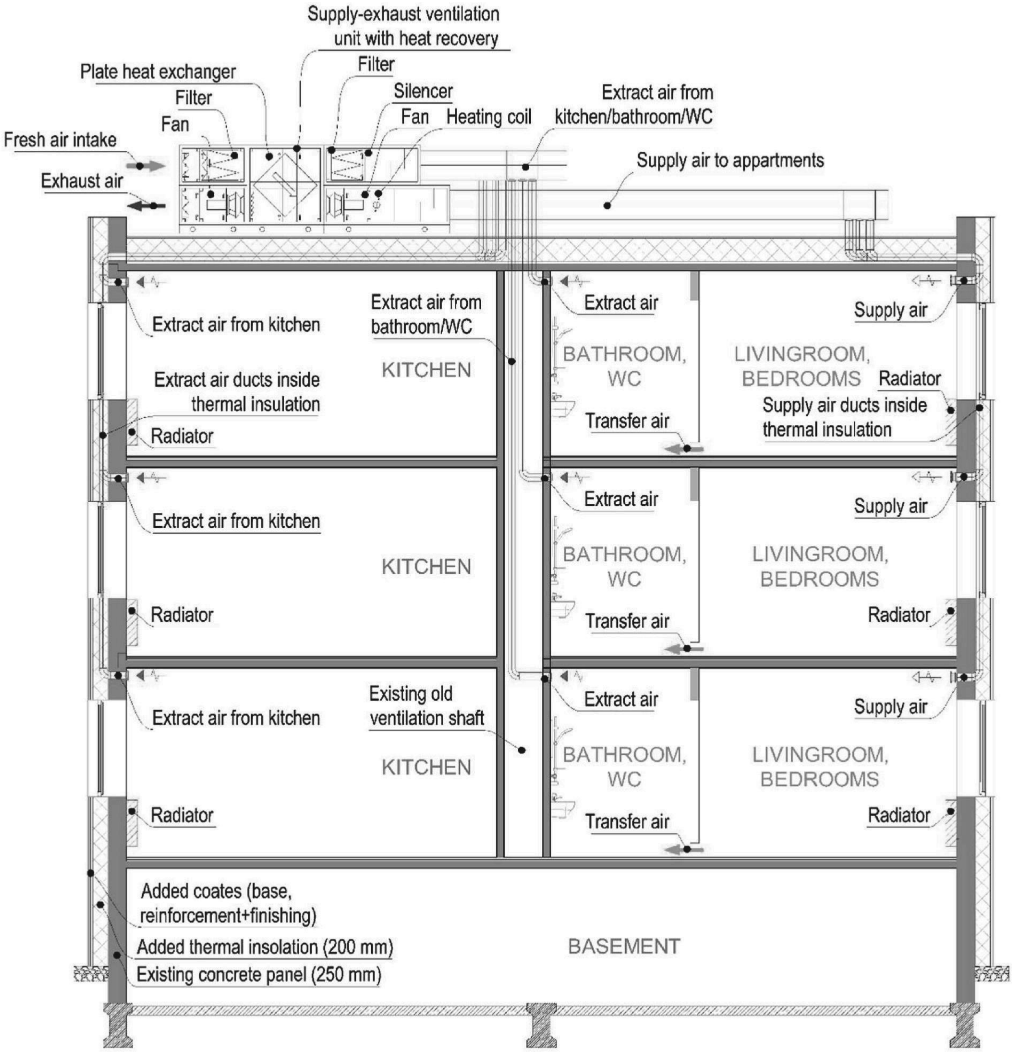

Fig. 4. Working principle of HRV renovation solution.

- 75% of apartments in the case of EAHP; and
- 62% of apartments in the case of HRV.

3.3. ACR and supply air temperatures in renovated apartment buildings

For evaluating the performance of ventilation renovation measures in the case of both grant periods, the ACRs in apartments were calculated from measured airflow rates and the volume of apartments. The average extract airflows in different ventilation systems and apartments are shown in Fig. 8 and Fig. 9. The ACR fulfils the requirements of the support grant (0.5 h-1) in 4.8% and 55% of the apartments in the first and second grant periods, respectively. The average ACR of all measured apartments was 0.17 h^{-1} and 0.57 h-1 in the first and second grant periods, respectively.

During the first grant period, the ACR was the lowest in apartments with NV without fresh air intake and in apartments with SRVUs. Measured ACRs and total measured extract airflows from the WC, kitchen, and bathroom are shown in Fig. 8. In apartments where the NV with or without fresh air intakes and SRVUs were installed, no apartments fulfilled the minimum requirement of support grants. The total average extract airflow from the WC, bathroom, and kitchen was 5.2 l/s. Extract airflows are extremely low in apartments with SRVUs. The main reason for this phenomenon was that the extract grilles were closed to improve the indoor and outdoor pressure conditions of the SRVUs. These results led to changes in the technical conditions for second grant period.

During the second grant period, the average ACR of HRV ventilation was 0.73 $h^{-1,}$ and the average ACR of ME without HR and EAHP systems was 0.32 h^{-1} (Fig. 9a). In the case of HRV ventilation in 88% of the apartments, ACR was ensured. ACR was not required in any of the studied apartments with EAHP or ME without an HR ventilation system. The measurement results of ACRs in apartments indicate that the HRV ventilation ensured approximately two times higher ACR than EAHP or ME without HR. Because the airflow of all studied systems fulfilled the requirements during the commissioning airflow measurement, airflows

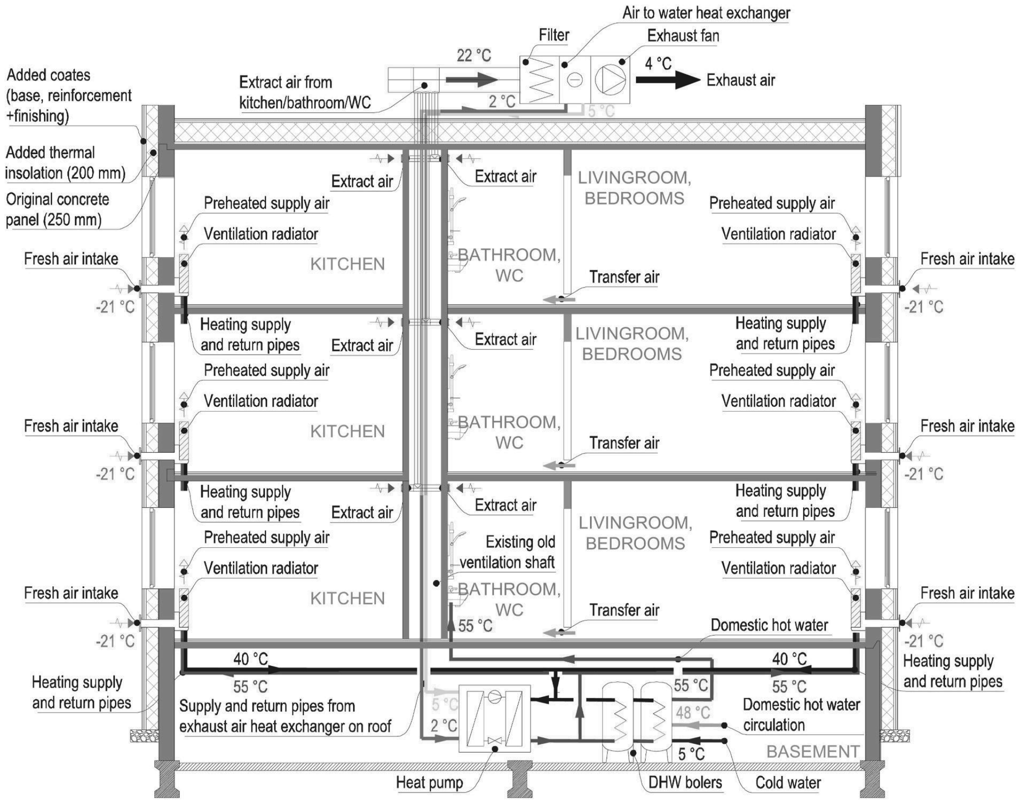

Fig. 5. Ventilation radiators with exhaust heat pump heat recovery.

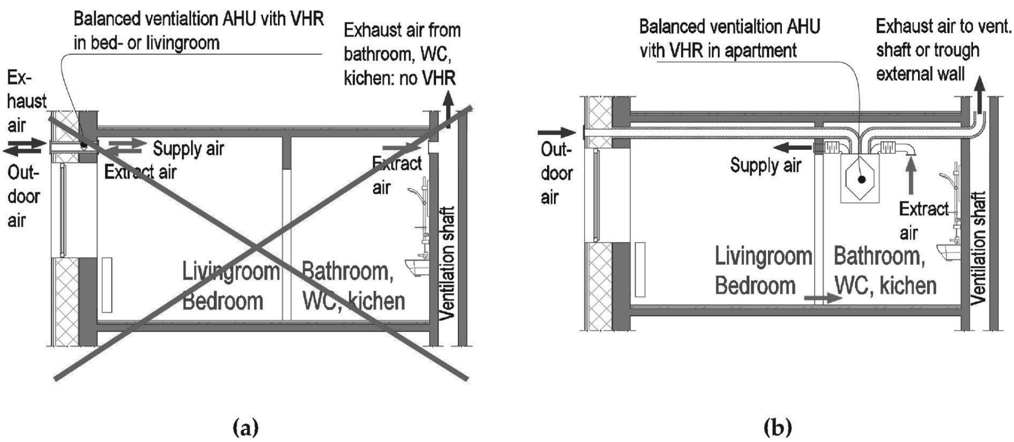

Fig. 6. (a) SRVU with HR (2010–2014) banned since 2015 and (b) apartment based balanced ventilation with HR.

of the EAHP and ME without HR ventilation systems decreased during operation.

Conditions of the second renovation grant established the requirements for the extract air airflows from bathrooms, toilets and kitchens. Therefore, the room extract airflows in apartments were also analysed (Fig. 9b). Total extract airflow from the bathroom, WC, and kitchen was 26 l/s in HRV, 10.8 l/s in EAHP and 11.3 l/s in ME without HR. In the case of HRV, the designed extract airflow was ensured in 21% of bathrooms, 78% of toilets and 88% of kitchens. In the case of EAHP, the designed extract airflow was ensured in 13% of bathrooms and in none of the toilets or kitchens. The extract airflow was not ensured in any of the rooms measured in the ME without HR.

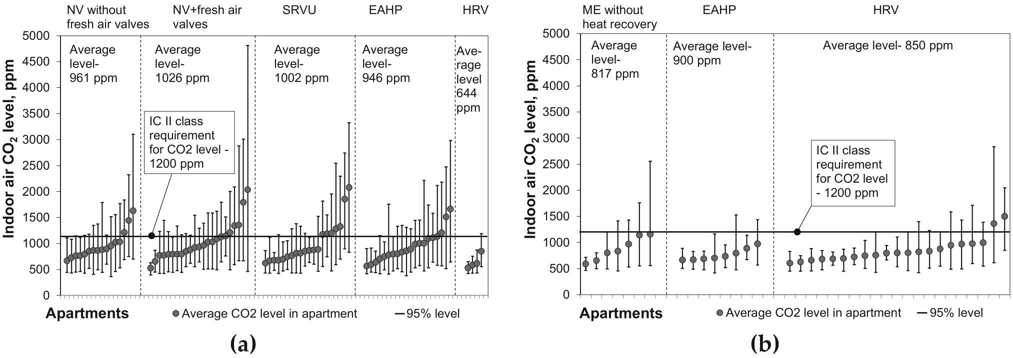

Fig. 7. (a) Occupancy period CO_2 concentration of studied ventilation renovation measures in the first and (b) second grant.

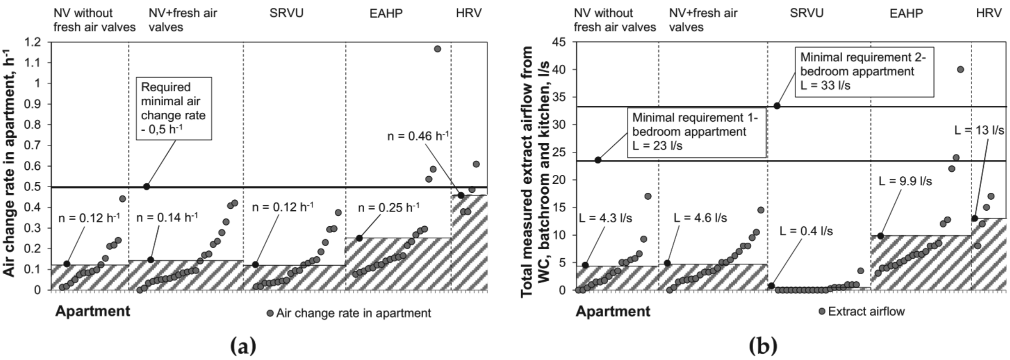

Fig. 8. (a) The ACR in apartments and (b) extract airflows of the studied apartments during 1. grant period.

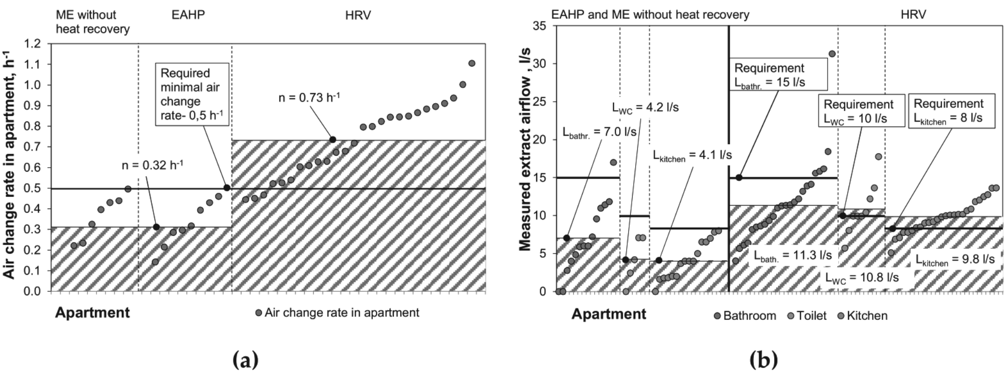

Fig. 9. (a) ACR in apartments and (b) extract airflows of the studied ventilation systems during the second grant period.

Supply airflows in living rooms and bedrooms were measured only in the case of the HRV ventilation system (Fig. 10a). According to the requirements of the renovation grant, the supply airflow in living rooms and bedrooms must be at least 10 l/s and 6 l/(s*person). The average supply airflow of the measured living rooms was 9.0 l/s and in the bedrooms 8.2 l/s. Considering the uncertainty of airflow measurement, 61% of the studied apartments fulfilled the requirements of the support grant. The average supply airflow was reduced in five apartments, where the supply valves were almost closed or sealed with tape.

Supply air temperatures were measured in every building with HRV during the second grant scheme measurements. The results of the supply air temperature measurements are shown in Fig. 10b. The lowest measured temperature in the supply air was 6.6 °C. This temperature was measured in a building in which the heating coil was not installed. The supply air temperature setpoints were between 15 and 20 °C. The measurement results in Fig. 10b show that the majority of the measured supply air temperatures fulfilled the setpoint values if the outdoor air temperature was over 2–4 °C. In the case of one ventilation unit,

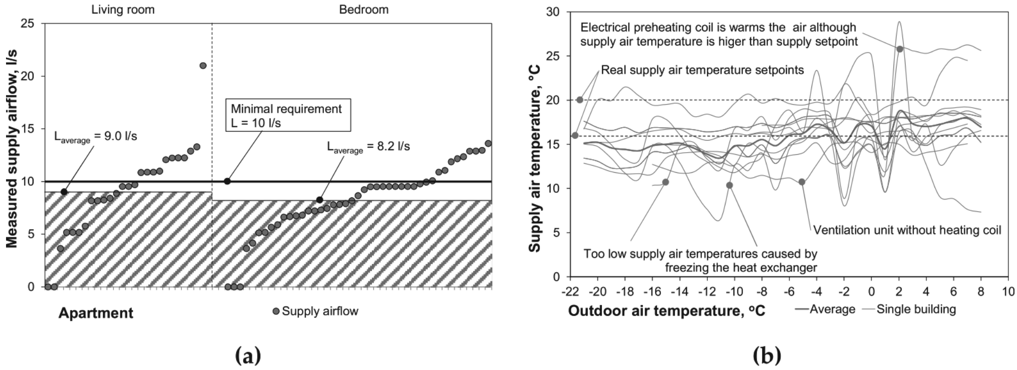

Fig. 10. (a) Supply airflows and (b) measured supply air temperatures of HRV in living- and bedrooms during second grant period.

electrical preheating coils were used. The measurement results show that control of the preheating coil was implemented incorrectly, which caused the supply air temperature to be high in the apartments.

4. Discussion

4.1. *Measured ACR and CO_2 levels in renovated apartment buildings*

The average indoor air CO_2 level in old Estonian concrete and brick buildings during the occupancy period was 1265 ppm [9]. This study shows that during the first grant period, the average CO_2 level was 970 ppm, and during the second period, 837 ppm. These values show the trend that IAQ during the second grant is considerably better than during the first grant. Leivo et al. stated that after the ventilation retrofit, the average CO_2 level during the measurement period was 715 ppm, which is much lower than that measured in this study for the second grant scheme [57]. Because the CO_2 levels in this study were calculated for the occupancy period, they could not be directly compared with those of other studies. The average CO_2 levels of the whole measuring period for the first and second grants were 886 ppm and 789 ppm, respectively. Because the average CO_2 level depends on the occupants' presence, the occupancy period values are more informative. However, it should be noted that the CO_2 measurement results are sensitive to a number of factors such as infiltration, variation in human CO_2 generation, window opening, apartment door positions, and ventilation schedule effects. In this study, none of measured apartments had gas stoves, so all CO_2 has human origin. Therefore, CO_2 measurements show the combined effect of ventilation, occupancy, and occupant behavior. For this reason, airflow rate measurements are straightforward in the ventilation system performance assessment.

The average ACR in old Estonian concrete and brick buildings had been measured and was 0.24 h^{-1} and in new buildings with ME ventilation without HR 0.42 h^{-1} [9]. During the first grant period, the average ACR of renovated apartments decreased to 0.17 h^{-1}. During the second grant period, the average ACR of all studied apartments was 0.57 h^{-1}. Leivo et al. analysed the influence of the renovation of ventilation systems in cold climates and pointed out that after renovation, the ACR was 0.48 h^{-1} [57]. Kamendere et al. also [40,58] measured the ACR in renovated apartments and observed that ACRs were 0.39 h^{-1}–0.52 h^{-1}. During the second grant scheme, ventilation airflows in the studied buildings were close to the designed values (minimal required ACR 0.5 h^{-1}), and similar results have been shown. Additionally, during the first grant scheme, the measured ACR in apartments was lower than the same value in old Estonian concrete and brick buildings. Some ventilation renovation measures used in the first grant scheme did not work for various reasons, which are discussed in Ch. 4.4.

4.2. *Impact of the technical requirements of the renovation grant on the ventilation renovation measures*

Comparing the performance of different ventilation renovation measures during both grant periods, we observe that ACRs of HRV systems significantly improved from 0.46 h^{-1} to 0.73 h^{-1}. The main reasons for the improved performance of these systems were stricter requirements for airflows and sound levels, third-party inspection of design documentation, and mandatory airflow measurement reports. These systems were designed more carefully which together with commissioning improved the quality. Airflow measurements and observations of the supply and extract valves showed that the airflow measurement reports were correct. In only five apartments, the positions of the valves were different from those in the measurement reports. These changes were made by occupants. One of the most positive aspects during the second grant period was the outstanding performance of the HRV ventilation system. ACR was ensured in 88% of apartments with HRV. This result is better than in new apartment buildings, according to the literature [9].

After the first grant period, when the average ACR of EAHP systems was only 0.25 h^{-1}, new technical conditions were added to the requirements of the support grant. In the second grant period, the average ACR increased to 0.32 h^{-1}. In the first grant scheme, there was only one building with an EAHP system and VRs. Additionally, the average ACR of that building was much higher (0.61 h^{-1}) than in other buildings with an EAHP system (0.16 h^{-1}). Thus, preheating the supply air had a significant impact on ACRs. In the case of the EAHP system, there could have been some influence of the requirement of third-party inspection for design documentation. The requirement for the mandatory airflow measurement report did not influence ACRs because, in the case of this system, the airflow measurement report was also performed in buildings studied during the first grant scheme.Using SRVUs to renovate old NV systems was unsuccessful because these units did not guarantee sufficient ACR (Fig. 8). The results were so poor that the SRVUs were banned in the second grant scheme. This was a result of the requirement that the heat recovery ventilation should serve all rooms of an apartment, and more importantly 25 dB(A) sound requirement and room based supply and extract airflow requirements which made it impossible to use SRVUs in the second grant period. Technical problems of SRVUs are discussed in Section 4.4.

ME ventilation systems without HR were used only for renovations with a 25% grant. During the first grant scheme, local extract fans were designed for the WC, kitchen, and bathrooms to ensure the correct extract airflows from these rooms. Because the airflows of these fans were not measured, the requirement for the mandatory airflow measurement report changed the technical solution of this system. Designers and builders realised that the extract fans were noisy and did not guarantee the required airflow rates. Thus, central extract fans mounted on roofs or between ducts were used during the second grant period. This is the main reason why the measured airflows of the ME system during the second grant scheme were at the same level for EAHP (0.32 h^{-1}).In the first grant period, NV was used in some buildings, and thus fresh air intakes were added, but the improvement in ACR from 0.12 h^{-1} to 0.14 h^{-1} was minimal. This was conducted together with cleaning and retrofitting old exhaust shafts. Neither of these measures increased the ACR of the NV. Another reason for the reduction is the infiltration reduced by the renovation of building envelopes and replacements of old windows with tighter ones. This study revealed that adding fresh air intake does not solve this problem.

4.3. Performance of studied ventilation renovation solutions

To compare the performance of the ventilation systems used during both grant periods, the occupancy period average CO_2 levels of all measured renovated apartment buildings are summarised in Fig. 11a. The occupancy period average CO_2 level for all measured buildings was 928 ppm, for HRV 818 ppm, ME without HR and EAHP systems 891 ppm, SRVUs 1002 ppm, and NV 1000 ppm. The statistical analysis (*t*-test) of measured CO_2 levels and calculated *p* values are shown in Fig. 11b. The calculated *p* values show a statistically significant difference between HRV and NV (*t*-test: $p = 0.0091 < 0.05$) and between HRV and SRVUs (*t*-test: $p = 0.049 < 0.05$). At the same time, there is not statistically significant difference between HRV and EAHP and ME without heat recovery (*t*-test: $p = 0.27 > 0.05$).

To compare the performance of the ventilation systems used during both grant periods, the average ACRs are summarised in Fig. 12a. HRV ventilation ensured the average ACR 0.70 h^{-1} as the average of both grant periods, ME without HR and EAHP systems 0.32 h^{-1}, SRVUs 0.12 h^{-1}, and NV 0.13 h^{-1}. The statistical analysis (*t*-test) of measured ACRs in the case of different renovation measures and calculated p values are shown in Fig. 12b. The calculated p values show a statistically significant difference between HRV and all other ventilation renovation measures (*t*-test: $p = 1.2 \cdot 10^{-11} < 0.05$).

Although the average ACR for the EAHP system was lower than the requirement, in some cases (mostly for tall buildings), this solution is the only possible technical solution to provide the extract air HR. This reason is the main reason why this solution can be recommended for buildings for which HRV cannot be technically used or is economically not viable. Khadra et al. [38] analysed the EAHP system with VRs in Swedish multifamily buildings and concluded that the EAHP renovation measure was the most cost-effective alternative to HRV. Kuusk et al. showed that EAHP had better energy performance than HRV in the central Europe climate, but in the cold Estonian climate, HRV showed better energy performance [59].

Using SRVUs to renovate old NV systems of apartment buildings was unsuccessful because these units did not guarantee sufficient ACR and did not ensure extract airflow from toilets and bathrooms.

We also find that adding fresh air intakes to renovate the old natural ventilation systems did not ensure sufficient ACR in apartments. The main reason for this failure was the dimensioning of NV systems in old apartment buildings in Estonia, in which the design outdoor air temperature was +5 °C. Therefore, passive stack ventilation cannot guarantee sufficient annual extract airflows from apartments, even in theory.

4.4. Main technical issues that influence the performance of ventilation in studied buildings

In the case of the SRVU, there was a problem with undersized fans. These units were designed to work at the highest possible airflow, but working at the highest speed level generated such high sound pressure levels that occupants switched these units to 30% of the maximum airflow [17,48]. Mikola et al. [48] and Vasileios et al. [60] have stated that the pressure differences across building envelopes due to wind and stack effects had a negative impact on the HR and supply air temperatures to SRVUs equipped with axial fans. Because of the negative pressure on the lower floors, extract airflow decreased, and the HR efficiency of the unit decreased to 30%; thus, the supply air temperature was too low to ensure thermal comfort [48,52,53]. This reason was also a reason why the speed of SRVUs was decreased.

In the case of the EAHP and ME ventilation systems, airflow was reduced by decreasing the fan speed. One reason why the fan speed was reduced was to save energy during operation. Additionally, it shows that users potentially misunderstand the operation principle of the EAHP system as the lower speed limits the heat source and heat recovery in this system. One common problem was related to old extract air grilles not being replaced with modern extract air valves, causing the ventilation system to be unbalanced between apartments. If the old NV shafts were used for the mechanical exhaust systems, the technical conditions of the exhaust shafts were not improved by the installation. According to onsite observations and airflow measurements of the EAHP and ME systems, old ventilation shafts cannot be used without installing new ventilation ducts inside the old channels. The best solution for ventilation ductwork is performing the installation inside the insulation layer on the façade (Fig. 13).

Renovated NV systems did not have transfer air grilles in the kitchens, toilets, and bathrooms, and the technical condition of the exhaust shafts remained poor. Deficiencies in the maintenance services of ventilation systems were also detected. For example, filters were not changed as often as necessary, the heat pump was not working to recover the heat from the extract air, or the systems were not monitored to find the critical errors. VR systems also had problems with cold floors

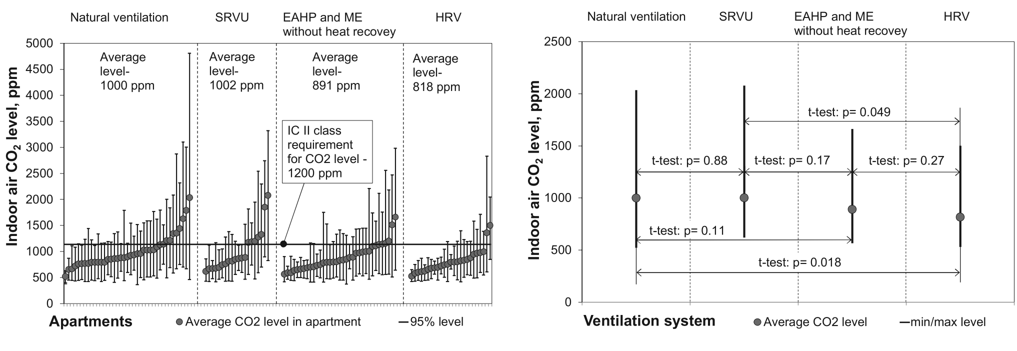

Fig. 11. (a) Occupancy period CO_2 concentration in different ventilation systems and (b) the statistical analyse (*t*-test) of average CO_2 levels of these systems.

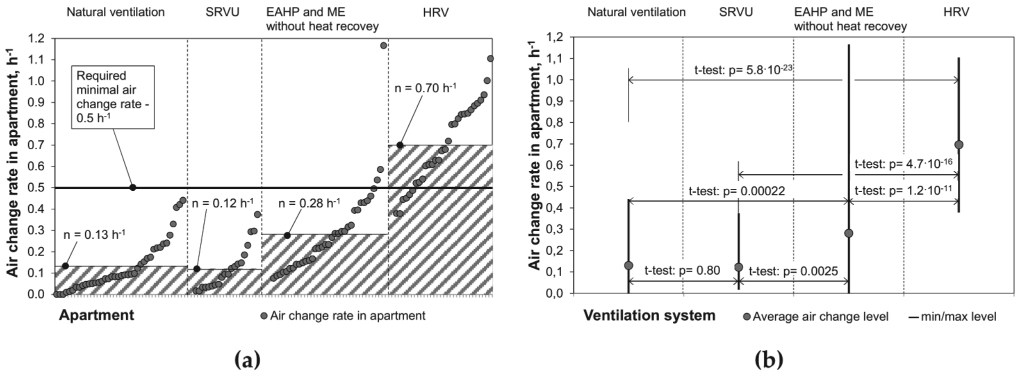

Fig. 12. (a) Air change rate of different ventilation systems and (b) the statistical analyse (*t*-test) to compare the performance of the systems.

Fig. 13. (a) Supply air valve installed without sector plate and flat ventilation duct inside the insulation layer and (b) ventilation ducts inside the insulation layer.

near the radiator, caused by the incorrect connection of the intake air duct.

Although the HRV system performed well, there were technical problems that required solutions. One of the most common problems was that the supply air valve had been installed without the sector plate, which caused the cold draught reported by the residents (Fig. 12). The same problem was pointed out by Thomsen et al. in renovated Danish apartment buildings [35]. One of the most notable limitations to the measurements was frost formation inside the plate HEXs of AHUs. Frost formation occurs if the surface temperature of the exhaust side of HEX is below the freezing point (<0 °C). Problems with frost formation in the case of plate HEXs in cold climate apartment ventilation were also reported by Alonso et al. [61]. The low supply air temperatures during the cold period (Fig. 10) result in several problems related to ineffective frost prevention or defrosting of ice. Defrost measures must be used to avoid the freezing of condensed water vapour. The main techniques of frost prevention (preheating and bypassing the outdoor airflow) have been analysed [46,47,62]. Jedlikowski and Anisimov [47] concluded that the fully open bypass technique for frost prevention does not provide complete frost protection under sub-zero outdoor air temperature operating conditions. According to the supply air temperature measurement results in this study, the heating coil of the AHU is necessary in cold climates. We can also infer that frost formation must be considered in the design phase and that this issue requires further research and product development to develop the most energy-efficient measures to manage the problem. Frost protection solutions such as sectional defrosting, cold-corner control, and exhaust air dew point control are worth analysing in practical operation.

According to the analysed technical issues of the second grant scheme, we propose new recommendations to improve technical conditions of ventilation renovation measures. First, the solution of frost formation inside the plate HEXs of the AHUs should always be used in the design stage. Second, the post-heating coil of the AHU with plate HEX is necessary. Third, supply air valves installed on the wall should always be designed for wall mounting. The last recommendation is to install new ventilation ducts in the old NV channels or install new ductwork inside the insulation layer on the façade.

5. Conclusions

A major obstacle to apartment building renovation is the ventilation system. This study shows that it is possible to renovate old NV systems by using proper technical solutions and supporting the process with governmental subsidies. Additionally, we conclude that the IAQ and ACR in renovated apartments depend strongly on the technical conditions of renovation grants. The first Estonian renovation grant period without specific ventilation requirements resulted in the average ACR of studied apartments as low as 0.17 h^{-1}. The second grant period with detailed ventilation requirements increased the average ACR to 0.57 h^{-1}. A higher ventilation rate remarkably reduced the maximum CO_2 concentration in the bedrooms.

The results will allow to draw the following conclusions on the ventilation systems performance:

- Comparing the performance of ventilation renovation measures during two grant periods, we observe that ACRs of the same HRV systems have significantly improved from 0.46 h^{-1} to 0.73 h^{-1}, and that this finding was due to the more detailed requirements for airflow rates and noise level design and the third-party inspection for design documentation.
- Average ACR of EAHP systems in the first period was 0.25 h^{-1} and in second grant period increased to 0.32 h^{-1} due to requirement of preheating intake air. EAHP achieved the required ventilation rates in measurement reports of commissioning, but the main problem of this system was related to the reduction in fan speed in the operation. The reduction in fan speed was performed to reduce energy in operation, which indicates the potential misunderstanding of the operation principle of EAHP as the lower fan speed will reduce the heat source and heat recovery.
- The best ventilation performance was achieved with centralized HRV with a ductwork installation on the façade. HRV ensured the necessary ACR in 88% of the measured renovated apartments. This system was the most widely used renovation measure for renovation up to 5-storey apartment buildings in Estonia. Although the average ACR operation of the EAHP system was lower than in the requirements, this system can also be recommended and is in some cases (mostly for tall buildings) the only feasible technical solution to provide the extract air HR.
- The renovation of old NV systems or using SRVUs did not guarantee sufficient ACR. Because of major problems, these ventilation renovation solutions were banned and were not used in second grant period.

The ACR and CO_2 measurements during the first grant period show that only the general requirement to ensure ICC II does not guarantee the compliance. Lesson learnt in the first grant period led to detailed ventilation requirements with room-based airflow rates and noise levels implemented in the II grant. The measurement results revealed that the most important technical conditions of the grant are mandatory airflow and sound pressure level measurement reports and third party inspection for design documentation. We conclude that there is a need to specify the required room-based outdoor and extract airflow rates and ventilation noise levels in the technical conditions of the grant to make the requirements and the design process transparent.

The main limitations to be solved are frost protection and defrosting operation of AHUs that designers and manufacturers should take seriously. Although the HRV system performed well, one of the most commonly observed problems was that the supply air valve was installed without a sector plate, which caused a cold draught and occupants to report their negative experiences with it. Another challenge is achieving the required ACR of EAHP systems in the operation phase.

Author contributions

The field measurements were performed by A.M. and A.H. Analyses of the measured data was carried out by A.M. The research principles and methods of the study were developed by A.M., K.K., T.K., H.V. and J. K.

Funding

This research was supported by the Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts, ZEBE, grant 2014-2020.4.01.15-0016 funded by the European Regional Development Fund, by the Estonian Research Council, grant No. PRG483 and by the Academy of Finland, grant for DECARBON-HOME 335253.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgements

The authors also thank Fund KredEx for its cooperation with our research work.

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Curriculum vitae

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2001–2004	Saaremaa Co-Educational Gymnasium, High school

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10.2010–08.2015	OÜ AEK, Engineer
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Scientific publications

Mikola, A.; Hamburg, A.; Kuusk, K.; Kalamees, T.; Voll, H.; Kurnitski, J. (2022). The impact of the technical requirements of the renovation grant on the ventilation and indoor air quality in apartment buildings. Building and Environment, 210, #108698. DOI: 10.1016/j.buildenv.2021.108698.

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Scientific projects

PRG1487 "Engineering Tools of Stratified-Flow Processes in the Built Environment" (1.01.2022−31.12.2026); Principal Investigator: Janek Laanearu; Tallinn University of Technology, School of Engineering, Department of Civil Engineering and Architecture; Financier: Estonian Research Council; Financing: 183 250 EUR.

VFP19039 "Driving decarbonization of the EU building stock by enhancing a consumer centred and locally based circular renovation process" (1.10.2019−30.09.2024); Principal Investigator: Targo Kalamees; Tallinn University of Technology, School of Engineering, Department of Civil Engineering and Architecture (partner); Financier: Euroopa Liidu programmid; Financing: 211 250 EUR.

VA21004 “Citizens as agents of change in decarbonizing suburban and rural housing (DECARBON-HOME)” (1.01.2021−30.09.2023); Principal Investigator: Jarek Kurnitski; Tallinn University of Technology, School of Engineering, Department of Civil Engineering and Architecture; Financier: Suomen Akatemia; Financing: 121 586 EUR.

AR20013 “Smart City Center of Excellence” (1.01.2020−31.08.2023); Principal Investigator: Ralf-Martin Soe; Tallinn University of Technology, Smart City Center of Excellence, Tallinn University of Technology, School of Engineering, Department of Civil Engineering and Architecture (partner), Tallinn University of Technology, School of Engineering, Department of Mechanical and Industrial Engineering (partner), Tallinn University of Technology, School of Engineering, Department of Electrical Power Engineering and Mechatronics (partner), Tallinn University of Technology, School of Information Technologies, Department of Software Science (partner), Tallinn University of Technology, School of Information Technologies, Department of Computer Systems (partner); Financier: Euroopa Liidu Struktuurifond ‘ERDF’ 85%; Riiklik toetus 15%; Financing: 7 158 053 EUR.

LEAEE20107; LEEE20107; LIEEE20107; LITEE20107A; LITEE20107B; LIAEE2017 “Energy flexilibilty service pilot project - Stage 2” (30.09.2020−30.05.2023); Principal Investigator: Martin Thalfeldt; Tallinn University of Technology, School of Engineering, Department of Electrical Power Engineering and Mechatronics (partner), Tallinn University of Technology, School of Engineering, Department of Civil Engineering and Architecture, Tallinn University of Technology, School of Information Technologies, Thomas Johann Seebeck Department of Electronics (partner), Tallinn University of Technology, School of Information Technologies, Department of Software Science (partner), Tallinn University of Technology, School of Information Technologies, Department of Computer Systems (partner); Financier: Eesti Energia AS; Financing: 140 559 EUR.

SS21011 “Climate Neutral Green Campus” (1.01.2021−31.12.2022); Principal Investigator: Jarek Kurnitski; Tallinn University of Technology, School of Engineering, Department of Civil Engineering and Architecture; Financier: Tallinn University of Technology ; Financing: 96 000 EUR.

VNF21045 “Impacts of ambitious energy policy pathways” (1.01.2021−31.12.2022); Principal Investigator: Jarek Kurnitski; Tallinn University of Technology, School of Engineering, Department of Civil Engineering and Architecture (partner); Financier: Nordic Energy Research; Financing: 24 841 EUR.

COVSG38 “Development of ventilation solutions for reduction of respiratory infections and sizing principles for SARS-CoV-2 virus” (1.11.2020−31.12.2021); Principal Investigator: Jarek Kurnitski; Tallinn University of Technology, School of Engineering, Department of Civil Engineering and Architecture; Financier: Estonian Research Council; Financing: 100 000 EUR.

VNF20025 “Knowledge sharing on NZEB buildings in the Nordic-Baltic region” (1.01.2020−31.10.2021); Principal Investigator: Jarek Kurnitski; Tallinn University of Technology, School of Engineering, Department of Civil Engineering and Architecture; Financier: Nordic Energy Research; Financing: 59 333 EUR.

AR17141 “Young Engineer Programme” (3.04.2017−31.12.2020); Principal Investigator: Karin Käär, Riina Arvisto; Tallinn University of Technology, School of Engineering, Department of Civil Engineering and Architecture (partner), Tallinn University of

Technology, School of Engineering, Department of Electrical Power Engineering and Mechatronics (partner), Tallinn University of Technology, School of Engineering, Department of Energy Technology (partner), Tallinn University of Technology, School of Engineering, Department of Materials and Environmental Technology (partner), Tallinn University of Technology , School of Engineering, Department of Mechanical and Industrial Engineering (partner); Financier: Archimedes Foundation; Financing: 84 803 EUR.

LEAEE20039 “Artefact storage rooms indoor climate control solutions development for Estonian National Library building” (22.04.2020−31.10.2020); Principal Investigator: Jarek Kurnitski; Tallinn University of Technology, School of Engineering, Department of Civil Engineering and Architecture; Financier: SIRKEL & MALL OÜ; Financing: 20 000 EUR.

LEP19101 “Automated machine learning and rule-based methods for fault detection of air handling units to increase their efficiency” (16.12.2019−30.09.2020); Principal Investigator: Martin Thalfeldt; Tallinn University of Technology, School of Engineering, Department of Civil Engineering and Architecture; Financier: Ruut8 OÜ; Financing: 183 750 EUR.

LEP19093 “Technical expertise of the War of Independence Victory Column” (4.12.2019−20.02.2020); Principal Investigator: Argo Rosin; Tallinn University of Technology, School of Engineering, Department of Electrical Power Engineering and Mechatronics; Financier: State Real Estate Ltd; Financing: 33 600 EUR.

IUT1-15 “Nearly-zero energy solutions and their implementation on deep renovation of buildings” (1.01.2013−31.12.2018); Principal Investigator: Targo Kalamees; Tallinn University of Technology, Faculty of Civil Engineering, Department of Structural Design, Tallinn University of Technology, School of Engineering, Department of Civil Engineering and Architecture; Financier: Estonian Research Council; Financing: 1 074 000 EUR.

LEP17097 “Ventilation unit heat exchanger frost formation” (5.10.2017−18.11.2017); Principal Investigator: Jarek Kurnitski; Tallinn University of Technology, School of Engineering, Department of Civil Engineering and Architecture; Financier: Venteco Systems OÜ; Financing: 6 900 EUR.

Lep15116 “Sanatoorium Tervis AS hoonekompleksi energiatõhususe analüüs ja meetmete väljatöötamine energiaefektiivsuse suurendamiseks” (30.11.2015−29.02.2016); Principal Investigator: Alo Mikola; Tallinn University of Technology, Tallinn University of Technology, Faculty of Civil Engineering, Department of Environmental Engineering, Chair of Heating and Ventilation; Financier: Sanatoorium Tervis AS ; Financing: 23 850 EUR.

Lep14034 “Indoor Climate mesurements and analyzis at Metro Plaza office building” (20.02.2014−10.06.2014); Principal Investigator: Hendrik Voll; Tallinn University of Technology (partner), Tallinn University of Technology, Faculty of Civil Engineering, Department of Environmental Engineering, Chair of Heating and Ventilation (partner); Financier: Trigon Capital AS; Financing: 7 120 EUR.

Lep13065 “Reconstruction successive research of apartment in Sõpruse pst 244, Tallinn” (19.04.2013−31.03.2014); Principal Investigator: Targo Kalamees; Tallinn University of Technology (partner), Tallinn University of Technology, Faculty of Civil Engineering, Department of Structural Design, Chair of Building Physics and Energy Efficiency (partner); Financier: Foundation Kredex; Financing: 15 000 EUR.

AR12045 “Development of efficient technologies for airexchange and ventilation necessary for the increase of energy efficiency of buildings” (1.04.2012−31.03.2014); Principal Investigator: Teet-Andrus Kõiv; Tallinn University of Technology (partner), Tallinn University of Technology, Faculty of Civil Engineering, Department of Environmental Engineering, Chair of Heating and Ventilation (partner); Financier: Archimedes Foundation; Financing: 130 000 EUR.

VIR488 “Central Baltic Cooperation in Energy Efficiency and Feasability in Urban Planning (ENEF)” (1.01.2011−31.12.2013); Principal Investigator: Teet-Andrus Kõiv; Tallinn University of Technology (partner), Tallinn University of Technology, Faculty of Civil Engineering, Department of Environmental Engineering , Chair of Environmental Protection (partner); Financier: Euroopa Regionaalarengu Fond ; Financing: 258 247 EUR.

Lep12040 “Decreasing the consumption of heating energy by awareness rising and performance of consumers based on measurements of individual heating costs” (17.02.2012−30.09.2012); Principal Investigator: Teet-Andrus Kõiv; Tallinn University of Technology (partner), Tallinn University of Technology, Faculty of Civil Engineering, Department of Environmental Engineering, Chair of Heating and Ventilation (partner); Financier: Foundation Kredex; Financing: 29 150 EUR.

Lep11049 “Analysis of energy audits carried out estonian apartment buildings in 2008-2011” (20.06.2011−31.10.2011); Principal Investigator: Teet-Andrus Kõiv; Tallinn University of Technology (partner), Tallinn University of Technology, Faculty of Civil Engineering, Department of Environmental Engineering, Chair of Heating and Ventilation (partner); Financier: Foundation Kredex; Financing: 1 250 EUR.

Elulookirjeldus

Isikuandmed

Nimi:	Alo Mikola
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Sünnikoht:	Kuressaare, Eesti
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Hariduskäik

2010–2022	Tallinna Tehnikaülikool, Ehitus ja keskkonnatehnika, PhD
2006–2010	Tallinna Tehnika Ülikool, keskkonnatehnika, MSc
2001–2004	Saaremaa Ühisgümnaasium, keskharidus
1996–2001	Kuressaare Põhikool, põhiharidus

Keelteoskus

Eesti keel	emakeel
Inglise keel	kõrgtase
Vene keel	algtase
Saksa keel	algtase

Teenistuskäik

09.2016–...	Tallinna Tehnikaülikool, Inseneriteaduskond, Ehituse ja arhitektuuri instituut, nooremteadur
01.2016–08.2016	Tallinna Tehnikaülikool, Ehitusteaduskond, Keskkonnatehnika instituut, Kütte ja ventilatsiooni õppetool, insener
01.2015–12.2015	Tallinna Tehnikaülikool, Ehitusteaduskond, Keskkonnatehnika instituut, Kütte ja ventilatsiooni õppetool, assistent
01.2013–01.2014	Tallinna Tehnikaülikool, Ehitusteaduskond, Keskkonnatehnika instituut, Kütte ja ventilatsiooni õppetool, nooremteadur
02.2011–12.2012	Tallinna Tehnikaülikool, Ehitusteaduskond, Keskkonnatehnika instituut, Kütte ja ventilatsiooni õppetool, teadur
10.2010–08.2015	OÜ AEK, insener
10.2008–12.2009	Fläkt OÜ, müügi-insener
07.2008–08.2008	Merko Ehitus Eesti AS, KVVKJ praktikant
07.2007–08.2007	Arco Ehitus OÜ, väliskommunikatsioonide ehituse praktikant