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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 (Бaránková *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.

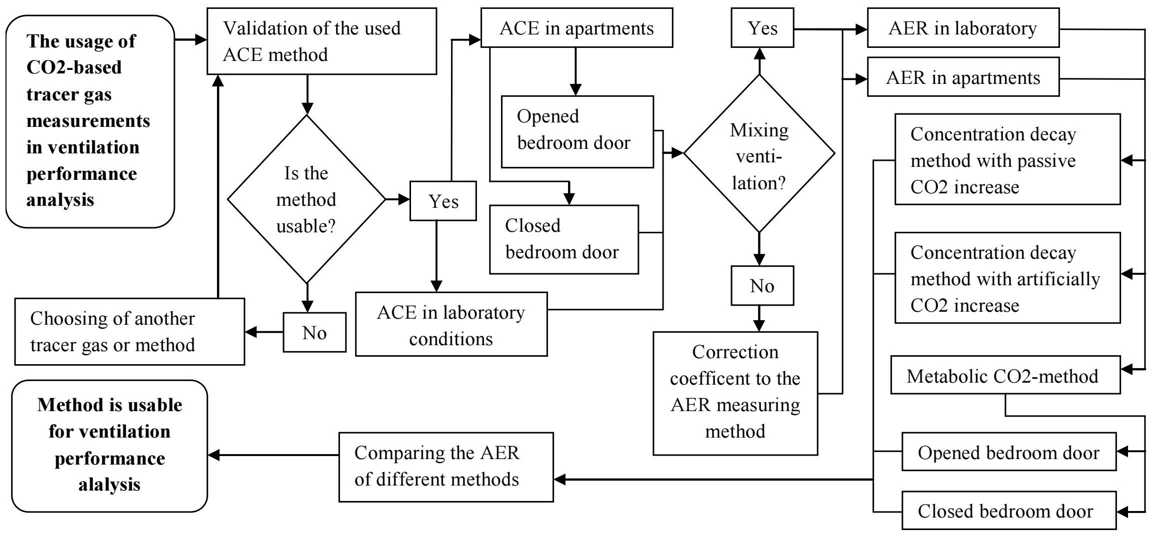

Fig. 1. The flow chart of the performed studies

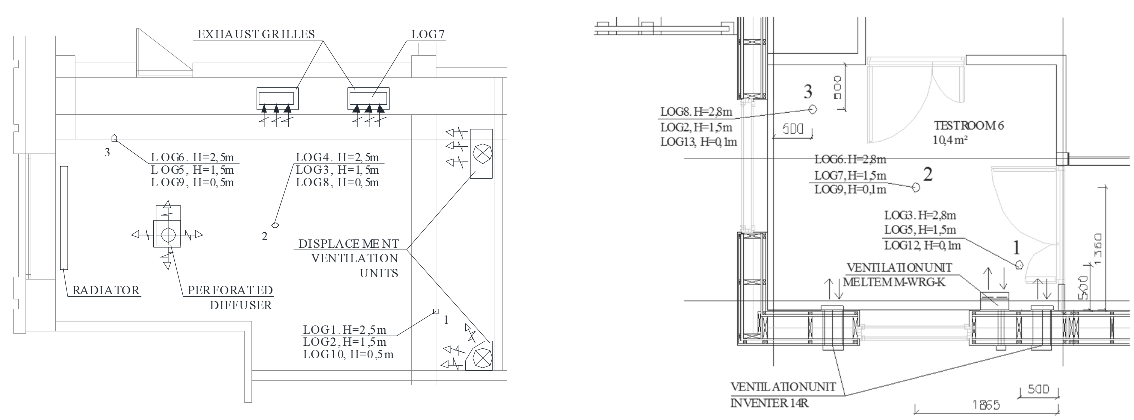

Fig. 2. The position of measuring devices and air diffusers in Mektory laboratory (2a) and Nearly zero energy test building (2b)

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:

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

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:

$$\varepsilon_p^a = \frac{\tau_n}{\tau_p} \cdot 100 , \quad (2)$$

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.

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