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Article

Quantification of Air Change Rate by Selected Methods in a Typical Apartment Building

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Abstract: An important parameter that affects indoor climate of buildings and also ventilation heat losses and gains is the speed of air change between the outdoor environment and the interior of buildings. Indoor air quality is therefore significantly associated with ventilation. Quantification of air change rate is complicated, because it is impacted by many parameters, the most variable of which is air flow. This study focuses on the determination and comparison of air change rate values in two methods by quantification of the aerodynamic coefficient $C_p = C_{pe} - C_{pi}$, so-called "aerodynamic quantification of the building" and the methodology based on "experimental measurements of carbon dioxide". The study describes and takes into account the effect of wind, building parameters and air permeability for the building using "aerodynamic quantification of the building". The paper compares these calculated results with the values obtained from experimental measurements method of carbon dioxide in a selected reference room in apartment building and evaluates the accuracy of the prediction of the air exchange rate obtained by these methods. At higher wind speeds the values of air change rate with considering the effect of openings are closer to the values obtained based on experimental measurements of carbon dioxide and the difference between the values without considering the effect of openings increases significantly.

Keywords: apartment building; aerodynamic coefficient; wind speed; air change rate; concentration of carbon dioxide; experimental measurement

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1. Introduction

Buildings are currently built and modified to minimize energy losses and maximize efficiency of heating. Efforts to reduce the ventilation heat loss reduce the air change rate. Many studies on ventilation and health have concluded that lower air change rates can have a negative effect on people's health and low ventilation may result in an increase in allergic diseases [1–3]. Nowadays people spend up to 90% of their life indoors. The windows enable natural ventilation and energy savings are ensured, are they obtained not only by increasing the thermal technical properties of the perimeter walls but also by the design and implementation of quality and tight windows. However, this often leads to a conflict between energy requirements and hygiene criteria. The air change rate is undersized and causes changes in humidity conditions up to the limit of hygienic requirements with possible subsequent adverse hygienic errors and the formation of mold. Therefore, it is necessary to ensure an increase in the air exchange through regular and intensive ventilation by apartment users or by means of micro-ventilation.

People spend more time at apartments, in living spaces more than anywhere else, it is about 70%. Air change rate has a significant impact on energy consumptions and indoor quality. Proper use of natural ventilation can improve the indoor environment and reduce energy consumption.

Thus, the quality of indoor air has received an increased attention in recent years. In study [4], the authors try to establish the number of European residences that do not meet ventilation standards. They conclude that up to 40% of European residences can be considered under ventilated. This number varies too by the age of the building stock. The Slovak standard also considers this number [5].

Air change rate—*n*—represents the amount of filtered air through leakage openings structures (gaps, connections, etc.) with natural ventilation due to the action of total differential pressure of air. Air change rate, *n*, is a measure of the air volume added to or removed from the space in one hour, divided by the volume of the space and can be expressed as formula (1) (according to [6]):

$$n = 3600\frac{V_{inf}}{V_m} = 3600\frac{\sum(i_{l,v}.l)\Delta {p_c}^n}{V_m} \tag{1}$$

where:

V_{inf}—volume of infiltrated air in the room with natural airflow (m^3),
V_m—room volume (m^3),
$i_{l,v}$—gap permeability coefficient ($m^3/(m{\cdot}s{\cdot}Pa^{0.67})$),
l—length of the gap (m),
Δp_c—total air pressure difference (Pa).

The value of air change rate for living rooms in residential buildings as set by the Slovak national standard STN [5] $n_N \geq 0.5$ (1/h) does not correspond with real values of air change rate. In reality, the air change rate is very variable because it is affected by a number of parameters and depends mainly on the total air pressure difference Δp_c—the most difficult measurable value. More accurate analysis and calculations can be done using simulation methods, quantifying the total aerodynamic coefficient $C_p = C_{pe} - C_{pi}$—the so-called "aerodynamic quantification of building"—where it is necessary to know the pressure distribution in interior and therefore requires aerodynamic quantification expressed by the total aerodynamic coefficient $C_p = C_{pe} - C_{pi}$ (-), or by methodology based on experimental measurements of carbon dioxide where the measured data of CO_2 concentration makes it possible to calculate the air change rate in the room.

The air change rate values given in this article were determined and compared using two methods:

- by quantification of total aerodynamic coefficient $C_p = C_{pe} - C_{pi}$—"aerodynamic quantification of building", which accepts the variability of climatic parameters, takes into account the wind influence with building parameters and the air permeability of the building;
- based on experimental measurements of carbon dioxide in the selected reference room in an apartment building.

1.1. Aerodynamic Quantification of Building

1.1.1. Quantification of Total Aerodynamic Coefficient C_p

Ventilation is the air change that ensures the supply of fresh outdoor air to ventilated/air-conditioned spaces and the removal of degraded air from ventilated spaces [7,8]. Depending on how the ventilation of buildings is ensured, we distinguish natural ventilation, forced ventilation and combined ventilation [9,10]. In our climatic conditions, natural ventilation is still one of the most common methods of ventilation. Especially in residential buildings it is mostly a natural air change-natural ventilation, which arises due to leaks in window and door openings, windowsills, various transitions, etc.—infiltration, or as a result of the homeowner behavior—by opening windows. Natural ventilation is a type of ventilation in which the movement and air change is induced by natural motor forces. These forces are the temperature difference and the wind. The basic precondition for natural ventilation is thus the total air pressure difference Δp_c (Pa) [11,12] determined as the sum of the air pressure difference from different temperatures Δp_θ (Pa) and air pressure difference from wind effect Δp_w (Pa) wherein the two components act on the building envelope in parallel in overtime [10]. For total air pressure difference can be applied (2) [6]:

$$\Delta p_c = \Delta p_\theta + \Delta p_w = h_0 g(\rho_{ae} - \rho_{ai}) + C_p\left(v^2 \rho_{ae} \frac{\rho_{ae}}{2}\right) \tag{2}$$

where:

h_0—height from the neutral pressure plane NPP (m),
ρ_{ae}, ρ_{ai}—outdoor and indoor air density (kg/m^3),
C_p—total aerodynamic coefficient (-),
v—wind speed (m/s).

The value of the total pressure difference Δp_c is strongly influenced primarily by wind effects Δp_w. It varies during the day and depends primarily on wind direction, air flow speed above the ground and many other factors. Different investigators found a dependence on the square of the wind speed. In formula (2), the determination of total pressure aerodynamic coefficient C_p is very important [13,14].

For prediction of air change rate by simulation methods it is necessary to obtain knowledge of pressure distribution on buildings' facades. Therefore, it is necessary that aerodynamic quantification be expressed by total aerodynamic coefficient C_p (-), which takes into account the variable wind effects with the parameters of the building. Knowledge of external and internal aerodynamic coefficients C_{pe} and C_{pi} is a basic prerequisite for aerodynamic quantification of buildings [15–17].

$$C_p = C_{pe} - C_{pi} \tag{3}$$

where:

C_p—total aerodynamic coefficient (-),
C_{pe}—coefficient of external pressure (-),
C_{pi}—coefficient of internal pressure (-).

1.1.2. External Aerodynamic Coefficient

The aerodynamic coefficient of external pressure is a dimensionless, highly variable quantity, which is influenced by large number of parameters—building geometry, details and position on the facade, wind speed and wind direction [18,19]. When determining the external aerodynamic coefficient not all parameters need to be taken.

Aerodynamic coefficients of external pressure can be expressed by calculations according to national standards [20], experimental measurements in–situ [21,22], experimental measurements in the aerodynamic tunnel [23–26], simulations using CFD calculation software. Amin and Ahuja (2013) [26] performed a series of measurements on high-rise building models with a rectangular floor plan, in which they investigated the effect of the aspect ratio on the values of the external aerodynamic coefficients. Similar measurements were performed by Amin and Ahuja (2011) [23] on buildings with L and T-shaped floor plans. Between 2003 and 2007 a series of experimental measurements were performed at Tokyo Polytechnic University on 116 models of low-rise buildings and 22 high-rise buildings models with rectangular floor plans and different ratios of width, length and height. The results were summarized in aerodynamic databases (TPU Aerodynamic Database).

Since the building modifies the air flow mainly by its shape, it is necessary to define the buildings under consideration geometrically. The spatial geometric classification is at present defined only for rectangular buildings (square and rectangular shape) and for buildings with a circular floor plan. Based of building height are divided the buildings according to [11] into three groups: low buildings (up to 15 m high), medium-sized buildings (15 m to 50 m high) and tall buildings (with height over 50 m).

For simple buildings, with a rectangular ground plan, with the height to width ratio of *h:b* = 3 and the height to length ratio of *h:l* = 2, a typical value is C_{pe} = +0.7 to +0.8 on the windward side and C_{pe} = −0.1 to −0.5 on the leeward and side walls [20,27]. The aerodynamic coefficients in the standards are the values that respect only strong winds and represent the maximum value for the façade. If the external aerodynamic coefficient is uneven, the extreme value is significantly different from the average value, and at windward side there may be a difference of up to 50%.

1.1.3. Internal Aerodynamic Coefficient

In addition to very variable external climatic factors, pressure difference is affected by the air permeability of the peripheral structures. The facade shows a certain degree of air permeability, which causes the changes of external and internal pressure. The wind load on the building envelope always depends on the pressure difference between two surfaces of this structural surface and therefore external and internal pressures need to be known. Research on the determination of internal pressures has received much less attention, despite the fact that the load of buildings with internal pressure contributes significantly to the overall load of the building envelope.

Aynsley et al. investigated the effect of wall porosity on internal pressures and found that the internal pressure is uniform, and its value does not depend on where it is measured. Ginger and Ginger et Letchford [15,28] studied external and internal pressures and their interrelationships along with the effect of a dominant opening on a low-rise building on a real scale. They concluded that the pressure inside the building depends on the distribution of external pressures and the location and size of the openings in the facade. The measured values of the internal pressure coefficients agreed with the values obtained by theoretical analysis of the steady flow through the opening.

Chen et al. [16] performed measurements on an acrylic model of a low-rise building with openings located in all four walls and the roof. They found that the angle of the acting wind is an important factor and hypothesized that by multiple openings the internal pressure value is affected by the opening located on the windward side and that the porosity of the building is not a major factor in internal pressure changing.

It is very important for the engineering practice to know the value of internal aerodynamic coefficient, because infiltration can cause a change in the value of aerodynamic coefficients of positive total pressure (pressure) to negative (suction) value [27,29].

Knowledge of external and internal aerodynamic coefficients is a basic prerequisite for aerodynamic quantification of buildings using the total aerodynamic coefficient [11,27]. The approximate influence of the facade air permeability on the pressure and suction distribution on windward and leeward side for a tall building with a rectangular ground plan is shown in Figure 1.

In the calculation of the internal aerodynamic coefficient C_{pi} it is necessary to know the modification of the building that affects changes of internal and external pressures. Due to the fact that at present there are no legislative requirements for quantification of air permeability of all dividing structures of buildings (partitions, door panels, etc.) it is possible to fully deal only with aerodynamic coefficients of internal pressure in buildings without inner dividing by partitions [11,30].

The internal aerodynamic coefficient is a function of the dimensionless parameter a (-) and therefore, the value has to be quantified only proportionally [30] according to Equation (4):

$$C_{pi} = f(a) = f\left[\frac{(A(+)}{A(-)}\right] \tag{4}$$

where:

C_{pi}—the aerodynamic coefficient of internal pressure (-),
$A(+)$—the real equivalent area of openings on the windward side of the building (m^2),
$A(-)$—the real equivalent area of openings on the other sides of the building (m^2).

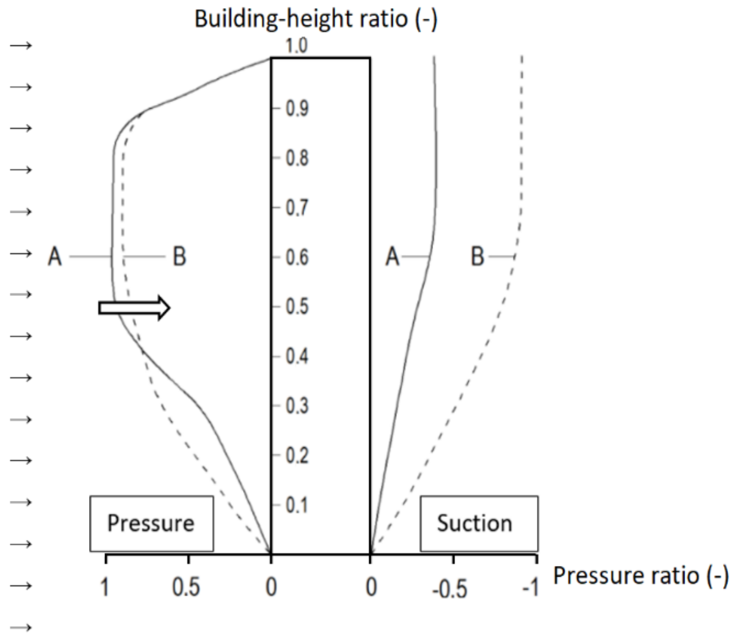


Figure 1. The approximate influence of the facade air permeability on the pressure and suction distribution on windward and leeward side for tall building with rectangular ground plan, A—zero air permeability building, B—air permeability building, (source authors, processed according to [11]).

To determine the parameter a (-) there are several assumptions by which the air permeability can be applied [11,27,30]. To determine the parameter a (-) for selected reference building it was assumed that it is possible for the façade air permeability to be applied only with filler windows with different dimensions and with the same gap permeability coefficient i_{LV} ($m^2/(s \cdot Pa^n)$).

Then applies Formula (5):

$$a = \frac{L(+)}{L(-)} \tag{5}$$

where:

$L(+)$—the sum of the lengths of the openings' gaps on the windward side of a building (m),
$L(-)$—the sum of the lengths of the openings gaps on the leeward and lateral sides of a building (m).

1.2. Measurement of Carbon Dioxide Concentration Values

In order to evaluate actual air change rate, gas tracing dilution methods have been developed and standardized EN ISO 12,569 [31]. Standard [31] describes among other method to the tracer gas concentration decay method which were used in this paper. According to [32–36], the tracer gas method may be used for determination of air change rate. The CO_2 is used as a tracer gas in our case.

The method was used by Weining et al. [37] in a study to determine the dependence of ventilation intensity by infiltration on wind speed. The research team Cui et al. [38] performed several experimental measurements in the laboratory in order to determine the error of measuring the air change rate in the building during cross-ventilation using the tracer gas decay method.

It can be determined the concentration of CO_2 by experimental measurements. In our case measurements were carried out predominantly during winter in one selected room. We conducted 24 measurements. From the measured data of CO_2 concentration, it was possible to calculate the air change rate in room.

In the room was produced CO_2 only by people. The continuing increase of CO_2 concentration was caused from the presence of people. Throughout the time of stay in the room air exchange was caused by infiltration. If no person is present in the room, we assume a zero production of CO_2. The tracer gas (CO_2) concentration is monitored over time and the air change rate is determined from the rate of concentration decay. Therefore, the air change rate caused by the infiltration can be calculated from the function of decrease of CO_2 concentration depending on time [34], where the influence of the CO_2 concentration of the outdoor air C_{SUP} is considered by Laussmann and Helm [39]. The issue of airtightness of buildings is addressed also in paper [40]. The air change rate n caused by infiltration can be expressed as:

$$n = \frac{1}{t} ln \frac{C_{IDA,S} - C_{SUP}}{C_{IDA,E} - C_{SUP}} \tag{6}$$

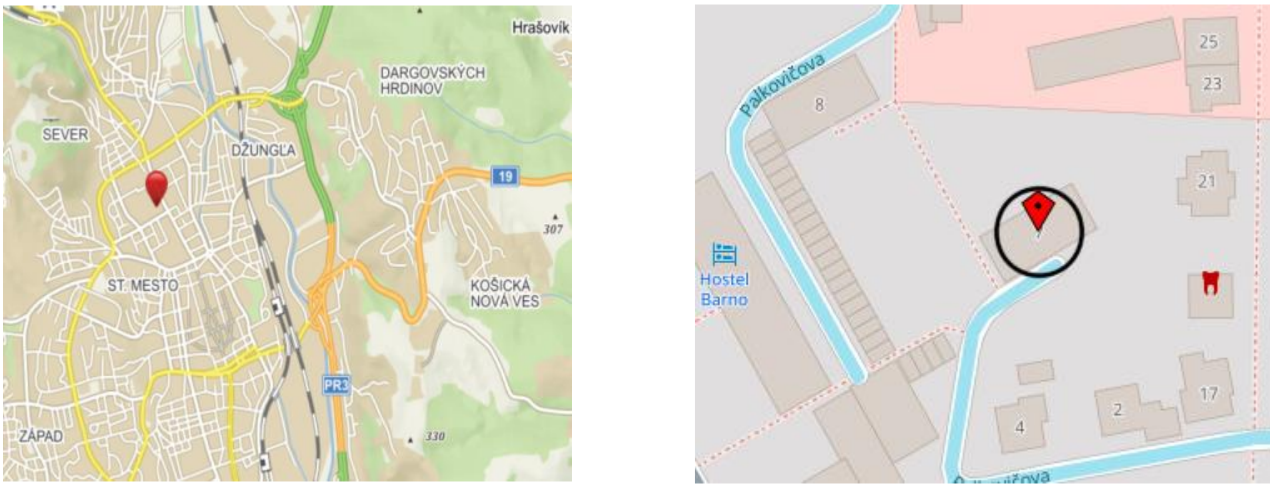
where:

n—air change rate (1/s),
$C_{IDA,S}$—CO_2 concentration in the room at the start of the decrease of concentration (mg/m^3);
$C_{IDA,E}$—CO_2 concentration in the room at the end of the decrease of concentration (mg/m^3);
C_{SUP}—CO_2 concentration in the outdoor air at time t; t (s) is duration of the decrease of CO_2 concentration (mg/m^3).

Several contributions have been devoted to this issue, focused on natural air exchange, in the recent period [41–44]. In paper [45], the focus is on air exchange in the summer when considering energy savings. Posts [46–49] are devoted to the issue of air exchange in various types of buildings, the increase in CO_2 and its impact on users.

2. Materials and Methods

The subject of the paper is a living room-bedroom located in a flat on the third floor in reference apartment building. This reference apartment building is located in the northern part of town Kosice (see Figure 2a,b). Košice is the second largest city in the eastern part of Slovakia.



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

Figure 2. (**a**,**b**) The situation of a case study (according to https://mapa.zoznam.sk/, accessed on 21 January 2021).

Views of the building from the exterior side can be seen in Figure 3, as well as floorplan of the reference apartment and selected room.

Figure 3. External view of selected apartment building, (source authors).

2.1. Description of the Reference Building

The reference building is situated (located) in the center of the city Kosice–North. It is a high-rise apartment building with 12 + 1 floors (total height 36.4 m), shaft type of building—a building with a vertical elevator shaft—position of the neutral pressure plane is determined in the range of 1/2–2/3 a height of the building—24 m. The reference building has rectangular ground plan with dimensions: length l = 25.2 m, width b = 12.3 m, height h = 36.4 m and 2 gable walls—see Figure 3. The reference building can be classified according to [11,30] as:

- the medium height building with a height 15 m < h = 36.4 m < 50 m → buildings to 15 floors
- the geometry is of the ground plan l/b = 25.2/12.3 ≈ 2—the plate type building with spatial proportionality: $1.5 \leq h/b = 36.4/12.3 = 2.9 \leq 6.0$ and with area proportionality: $1.5 \leq l/b = 25.2/12.3 = 2.04 \leq 4.0$

The building is insulated with a contact thermal insulation system and all apartments have the same types of windows.

2.2. Reference Room in Selected Apartment Building

The reference room is situated on the third floor, at a height above ground of approximately 8.4 m, oriented 315° NW, on windward wall. The reference room–bedroom is with internal dimensions 4 m × 3.55 m × 2.6 m. Volume of the room is 36.92 m^3. The window system consists of a plastic frame, with insulating double glazing and a length of gaps l = 12.1 m. Floorplan of the reference apartment and selected reference room can be seen in Figure 4.

2.3. Research Flowchart

The aim is to determine and compare the values of air change rate in two methods-using quantifying of total aerodynamic coefficient $C_p = C_{pe} - C_{pi}$—taking into account the variable influence of the wind with the parameters of the building and accepting the air permeability of the façade and by the methodology based on experimental measurements of carbon dioxide in the selected reference building.

The methodology is focused on in situ measurements, calculations, confrontation of measured and calculated values and determination of the effects of selected parameters.

As already mentioned, in this article, the following methodology is applied:

- Calculation of air change rate without considering of openings
- Calculation of air change rate with considering of openings
- Calculation of air change rate on the basis of measured concentrations of carbon dioxide

- Comparison and verification of individual two methods

The subject, goal and methodology of the research can be seen in flowchart in Figure 5.

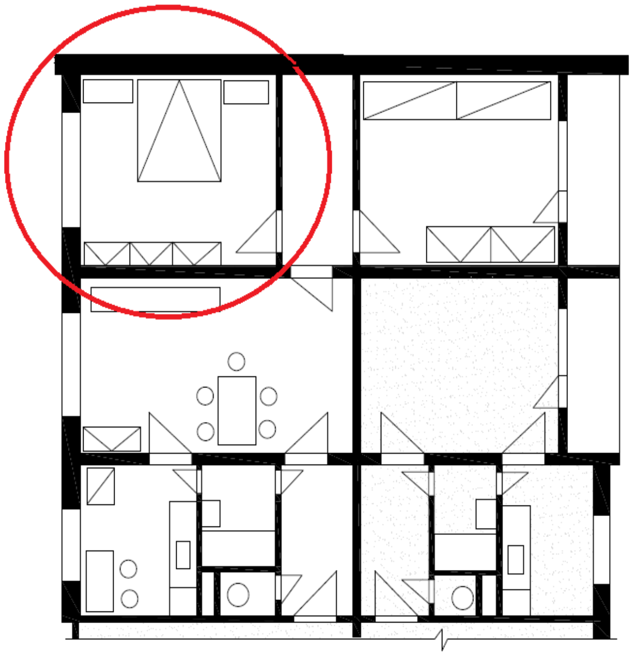


Figure 4. Ground plan: floorplan of the reference apartment.

Figure 5. The subject, goal and methodology of the research: flowchart of research.

3. Measurement and Calculation Analysis

3.1. Measurement and Description of the External Climatic and Internal Parameters

External climatic parameters influencing the pressure difference Δp_c are outdoor air temperature θe, wind speed w and wind direction. On selected days the wind speed measured was at hydro-meteorological station of 10 m above the open ground, but data on wind speed measured at hydro-meteorological stations are not always identical to the actual speed characteristic of a particular site of urban form. Because the reference building is located in the center of city, values of wind speed measured in open terrain were reduced by [27]:

$$v_z = k \cdot v_{10,met} \tag{7}$$

where:

$v_{10,met}$—wind speed measured at hydro-meteorological stations at 10 m height (m/s),
k—coefficient-indicating the impact of terrain categories and the height above the ground (-).

Coefficient indicating the impact of terrain for reference building in the center of cities 10 m above the ground is k = 0.65.

We measured indoor parameters: indoor air temperature, internal air flow speed, internal air pressure and relative air humidity using equipment *Testo 435-4* (SE & CO KGaA, Lenzkirch, Germany). For this purpose, a *Testo 435-4* measuring instrument with a *Testo 0632* sensor was used. Based on experimental measurements were assessed CO_2 concentration of the indoor air. Measurements were carried out predominantly during winter. The range of CO_2 concentration measurement of the instrument is from 0 to 10,000 ppm, while the sensitivity is 1 ppm, and the accuracy is ±3%. The range of temperature measurement is from 0 °C to +50 °C, with a sensitivity of 0.1 °C and accuracy of ±0.3 °C. The range of relative humidity is from 0 to +100% RH, the instrument sensitivity is 0.1% RH and the accuracy is ±1.8% RH

To enable a mathematical description of the variation of CO_2 concentration according to the measured data, it was important to ensure stable conditions during the measurements-room windows and doors were kept closed. A total of 24 experimental measurements were performed, recording the CO_2 concentration, indoor air temperature, relative humidity and air pressure in the room. The devices were placed close at a height of 1.0 m. During the measurement, a person was at least one meter or more away from the device, to prevent local influences on measurements.

The individual access of occupants was not allowed, entering or exiting was done simultaneously by the in the given time. In addition to the measured indoor parameters, hourly outdoor data of air temperature and wind speed were also recorded, since these have an impact on the air exchange rate caused by infiltration. External and internal parameters in selected days and hours are in Table 1.

During all experimental measurements we recorded the CO_2 concentration, indoor air temperature, relative humidity and air pressure in the room. The course of one experimental measurement from 3 February 2019–No 15 in the reference room is shown in Figure 6.

In Figure 6 the course of indoor air parameters is documented. The red arrow shows the selected section of decreased CO_2 concentration. During this period, the room was closed and without any people. The CO_2 concentration decreased only due to a leak in the building structure. From the record it is possible to observe that the air pressure was constant, temperature difference was minimal and the relative humidity copied the course of the CO_2 concentration. The detail of the course of CO_2 concentration for the selected time period is documented in Figure 7.

Table 1. External and internal parameters in selected days and hours.

Number of Measurement	Date and Hours of Measurement		CO_2 Concentration			Air Temperature		Reduced Wind Speed v
			Starting $C_{IDA,S}$	Ending $C_{IDA,E}$	The Time of Decrease t	Indoor	Outdoor	
(-)	(d. m. y)	(h:m)	(ppm)	(ppm)	(min)	(°C)	(°C)	(m/s)
1	5 March 2018	8:40	1151	1064	69	23.1	−5.0	3.9
2	5 March 2018	10:30	1076	1019	69	23.1	−6.0	3.9
3	17 March 2018	18:00	1133	891	52	25.5	−12.3	9.4
4	17 March 2018	21:00	1440	1170	31	26.4	−14.1	10.3
5	1 December 2018	21:00	945	874	42	23.0	−4.0	2.7
6	2 December 2018	9:00	1326	1215	28	24.4	−3.0	1.6
7	2 December 2018	14:00	964	896	38	23.2	−3.0	1.6
8	25 January 2019	20:10	1200	1024	59	22.9	−4.0	6.7
9	26 January 2019	9:10	1346	1206	29	24.4	−5.0	3.4
10	26 January 2019	20:00	1353	1230	42	23.0	−6.0	1.1
11	27 January 2019	15:10	841	771	57	23.0	−2.0	1.6
12	2 February 2019	9:30	2052	1907	45	24.2	4.0	2.3
13	2 February 2019	13:30	1778	1698	32	23.6	5.0	2.7
14	2 February 2019	20:30	1400	1279	61	23.1	4.0	0.7
15	3 February 2019	9:30	1654	1525	60	24.0	7.0	2.0
16	4 February 2019	19:00	1375	1214	60	24.0	2.0	3.6
17	5 February 2019	10:00	1307	1180	60	24.1	2.0	2.0
18	25 March 2019	20:30	1740	1686	25	25.0	8.0	4.4
19	1 April 2019	20:30	1322	1276	15	25.1	8.3	6.3
20	8 April 2019	19:10	1751	1682	45	24.6	19.0	5.4
21	10 April 2019	20:10	1310	1210	30	24.5	10.0	8.3
22	11 April 2019	20:00	1121	0991	50	23.9	6.0	9.4
23	17 April 2019	20:20	1918	1789	45	24.1	11.0	4.7
24	6 May 2019	18:40	1251	1077	60	24.0	6.0	6.6

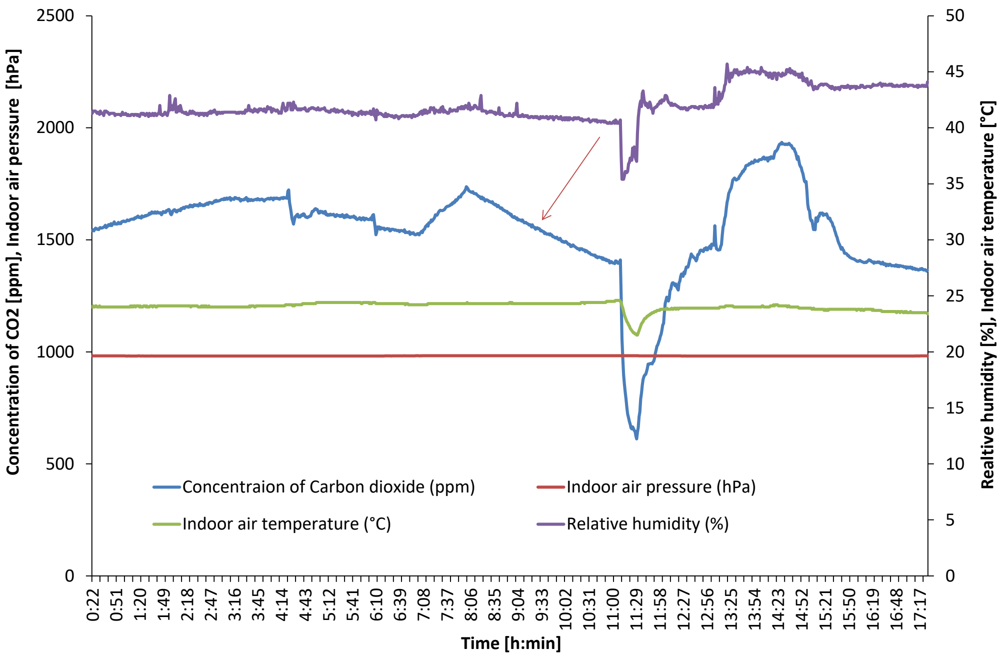


Figure 6. Recording of indoor air quality courses from experimental measurements No 15 (3 February 2019).

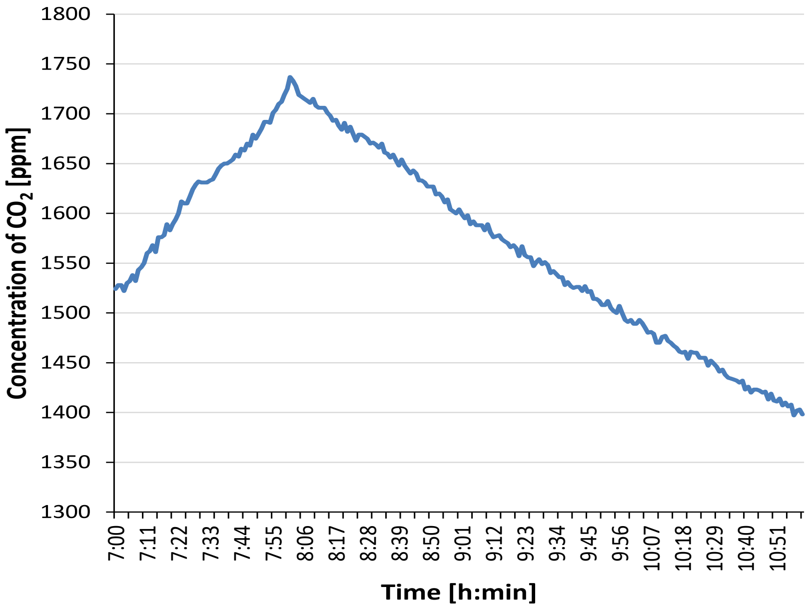


Figure 7. Recording of concentration of CO_2 for selected day 3 February 2019 No 15.

It can be seen from Figure 7 that the maximum achieved CO_2 concentration in the room was 1728 ppm at 8:03. After the person leaves from the room and closes the door to the room, the CO_2 concentration began to decrease. The starting decline was intense, but later, at 8:30, it stabilized. The initial sharper decrease of CO_2 concentration was caused by leaks in building structures and at the same time by the opening and closing of the door, which was caused by the person leaving the room. From the record it is possible to see that from 8:30, when the CO_2 concentration was $C_{IDA,S}$ = 1671 ppm, the decrease in CO_2 concentration was regular. It can be assumed that from 8:30, the air change rate was caused only by the leaks in building structures. The CO_2 concentration range in the outdoor air was from 392 to 428 ppm.

A total of 24 experimental measurements were carried out. On some days, three measurements were performed and on some days only one measurement. All measurements were carried out during the normal use of the apartment so that the inhabitants were not limited. The only limitation was a time period when the person had to close the door to the room after leaving the room and was not allowed to re-enter for about one hour.

3.2. Prediction of Air Change Rate Using Quantifying of Total Aerodynamic Coefficient C_p

Calculations of air change rate in the reference room were processed for selected days and hours with wind direction N, NNE-360°, 22,5° (accurate to 22.5°). Because the reference room is oriented NW, the values of external aerodynamic coefficient for different wind direction are $C_{pe,N}$ = +0.35 and $C_{pe,NNE}$ = +0.525, internal aerodynamic coefficient C_{pi} were determined for building with two gable walls graphically according [27,30]. External and internal pressure act at the same time. The values of air change rate were calculated for building without considering the influence of openings $C_p = C_{pe}$ and when considering the effect of openings $C_p = C_{pe} - C_{pi}$.

The values of air change rate for reference building with two gable walls for higher and lower wind speed are in Figures 8 and 9.

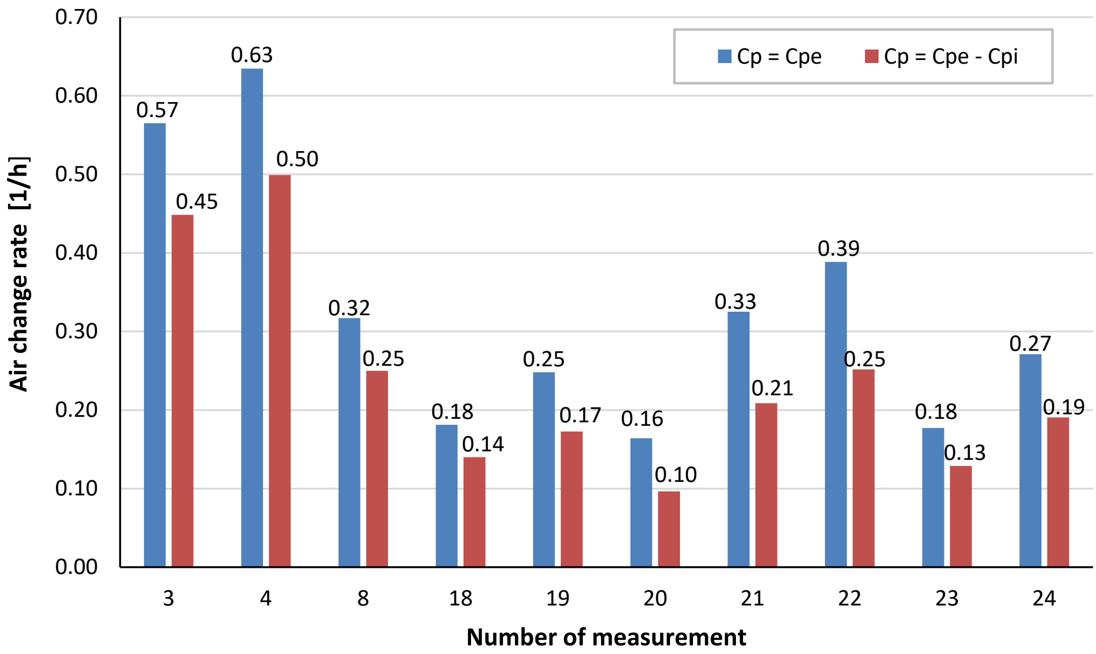


Figure 8. The values of air change rate without considering the influence of the openings $C_p = C_{pe}$ and when considering the effect of the openings $C_p = C_{pe} - C_{pi}$ for higher wind speed v = 4.4–10.3 m/s.

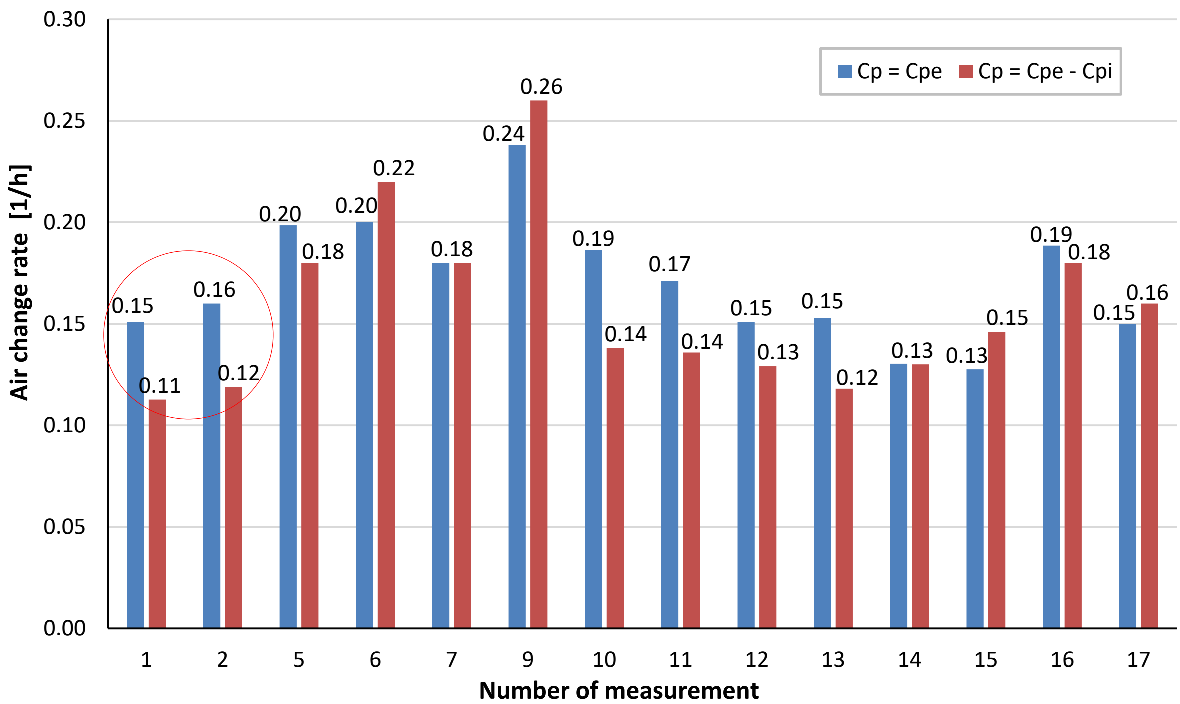


Figure 9. The values of air change rate without considering the influence of openings–$C_p = C_{pe}$ and when considering the influence of openings $C_p = C_{pe} - C_{pi}$ for lower wind speed v = 1.1–4.1 m/s.

At higher wind speeds can see from Figure 8 a significant effect of the openings, which causes a decrease in the values of the air change rate n. The difference between the values is in the range 0.05–0.137 1/h, i.e., by 20.6–41.2%, which is on average 25.1%. At the same time can be stated from Figure 9 that the influence of the openings at lower wind speeds does not play a significant role–the difference of air change rate n = 0.00–0.048, i.e., 0.00–29.4%, on average 8.3%, except two measurements—on 5 March 2018 at 8:30 a.m. (No 1) and 9:30 a.m. (No 2) where the difference was up to 35%.

3.3. Determination of Air Change Rate on the Basis of Measured Values of Carbon Dioxide Concentration

CO_2 was produced only by people in the room. The increase of CO_2 concentration was caused by the continued presence of people. Throughout the time of their stay in the room, air change was caused by infiltration.

For each experiment, CO_2 concentration measurements were made at time intervals of 1 min. In order to calculate of air change rate, the duration of CO_2 concentration decrease was considered as a multiple of several 1 min time intervals. As an example, for measurements carried out on 3 February 2019, the first interval was 1 min and the last (31st time interval) was 31 min, resulting in 31 calculated CO_2 air change rates (Figure 10).

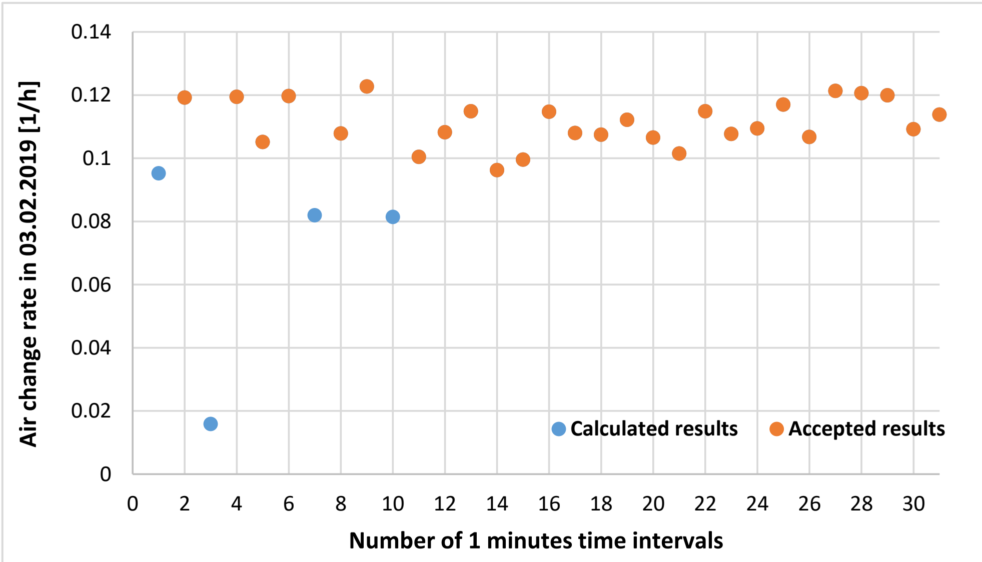


Figure 10. The screening of the calculated values of air change rate for 3 February 2019 (No 15).

From these results, the extreme values were excluded (the first four), and from the remainder of 27 values, the air change rate for that experiment was calculated as the arithmetic mean. A final value 0.11 (1/h) was obtained.

Calculated differences and margin of error of the air change rate established by calculations according to measurements of CO_2 are given in the Table 2.

Table 2. Calculated differences and margin of error of the air change rate established by calculations according to measurements of CO_2.

No. (-)	n (1/h)	U (%)	No. (-)	n (1/h)	U (%)	No. (-)	n (1/h)	U (%)	No. (-)	n (1/h)	U (%)
1	0.10	4.10	**7**	0.19	3.79	**13**	0.11	2.07	**19**	0.19	1.55
2	0.08	4.47	**8**	0.28	1.89	**14**	0.13	2.74	**20**	0.08	4.03
3	0.46	1.02	**9**	0.30	2.50	**15**	0.11	4.70	**21**	0.24	2.42
4	0.59	2.12	**10**	0.20	2.50	**16**	0.18	3.96	**22**	0.23	5.24
5	0.18	5.85	**11**	0.19	1.76	**17**	0.16	4.74	**23**	0.11	0.88
6	0.26	1.93	**12**	0.11	1.94	**18**	0.09	8.63	**24**	0.23	1.62

No.—measurement number; n—the air change rate (1/h); U—the uncertainty (%).

Based on the calculated differences listed in Table 2 it can be concluded that the average margin of error is approximately 3.23%.

4. Results and Discussion

This case study examines the effect of the wind direction and size and position of windows on the facade on interior air pressure. It points out the redistribution of these pressures and confronts the calculated results with experimentally measured values of carbon dioxide. It is used to find solutions in order to specify the air change rate, which significantly affects the thermal regime and comfort of the indoor environment. To determine the values of the air change rate, we used the calculation by aerodynamic quantification of buildings to account for the influence of the wind with the parameters of the building and accepting the air permeability of the facade, and the actual measurements by means of the instrument, on the basis of which the experimental measurements of carbon dioxide was used. The results were evaluated and compared with each other. The values of the air change rate can be seen in Figures 11 and 12 where they are shown and compared values of air change rate for higher and lower wind speed.

At higher wind speeds v = 4.4–10.3 m/s (see Figure 11) is the effect of openings much more pronounced. At higher wind speeds v = 4.4–10.3 m/s the values of air change rate with considering the effect of openings ($C_p = C_{pe} - C_{pi}$) are closer to the values obtained based on experimental measurements of carbon dioxide and the difference between the values without considering the effect of openings ($C_p = C_{pe}$) increases significantly. The difference between the values of air change rate taking into account the influence of openings ($C_p = C_{pe} - C_{pi}$) and the values based on experimental measurements of carbon dioxide was in the range 0.00–0.09 (1/h), which is from 0.00% to 20.2% (Table 3, Figure 13). The big difference 34.6% was only during one measurement No 18 on 25 March 2019 (Figure 11). Calculations of air change rate values without considering the effect of openings ($C_p = C_{pe}$) differed significantly from the values obtained based on experimental measurements of carbon dioxide in range 0.04–0.16 (1/h), i.e., in the range 7.0–53.3% (Table 4).

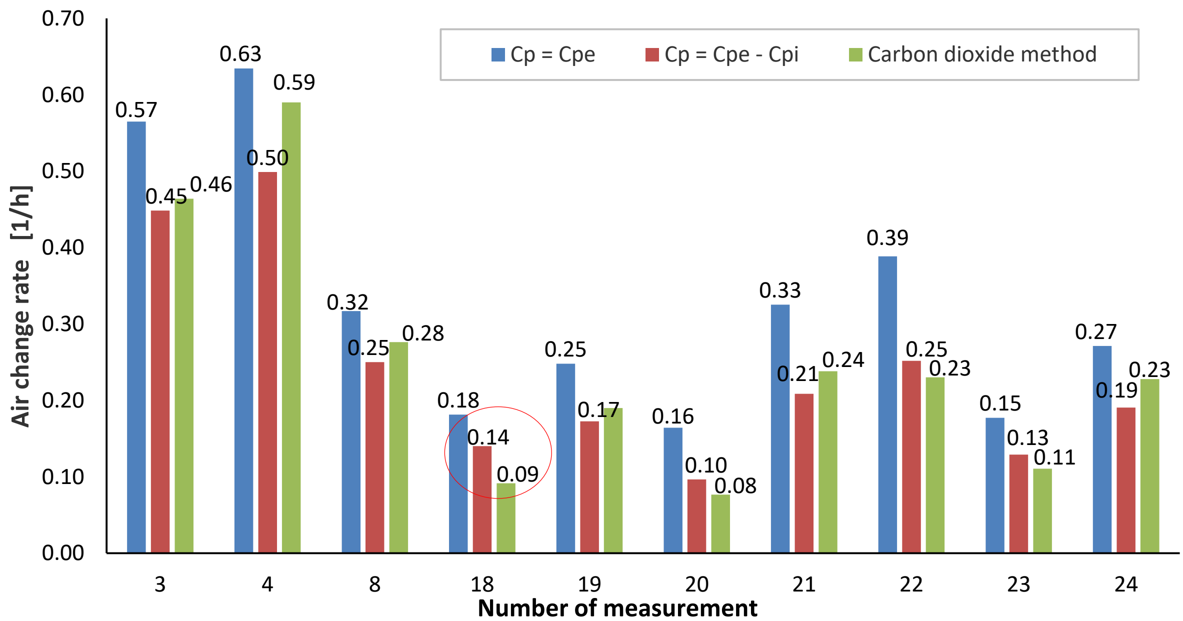


Figure 11. Comparison of the values of air change rate without considering the influence of openings $C_p = C_{pe}$, with considering the effect of openings $C_p = C_{pe} - C_{pi}$ and calculation based on experimental measurements of carbon dioxide for higher wind speed v = 4.4–10.3 m/s.

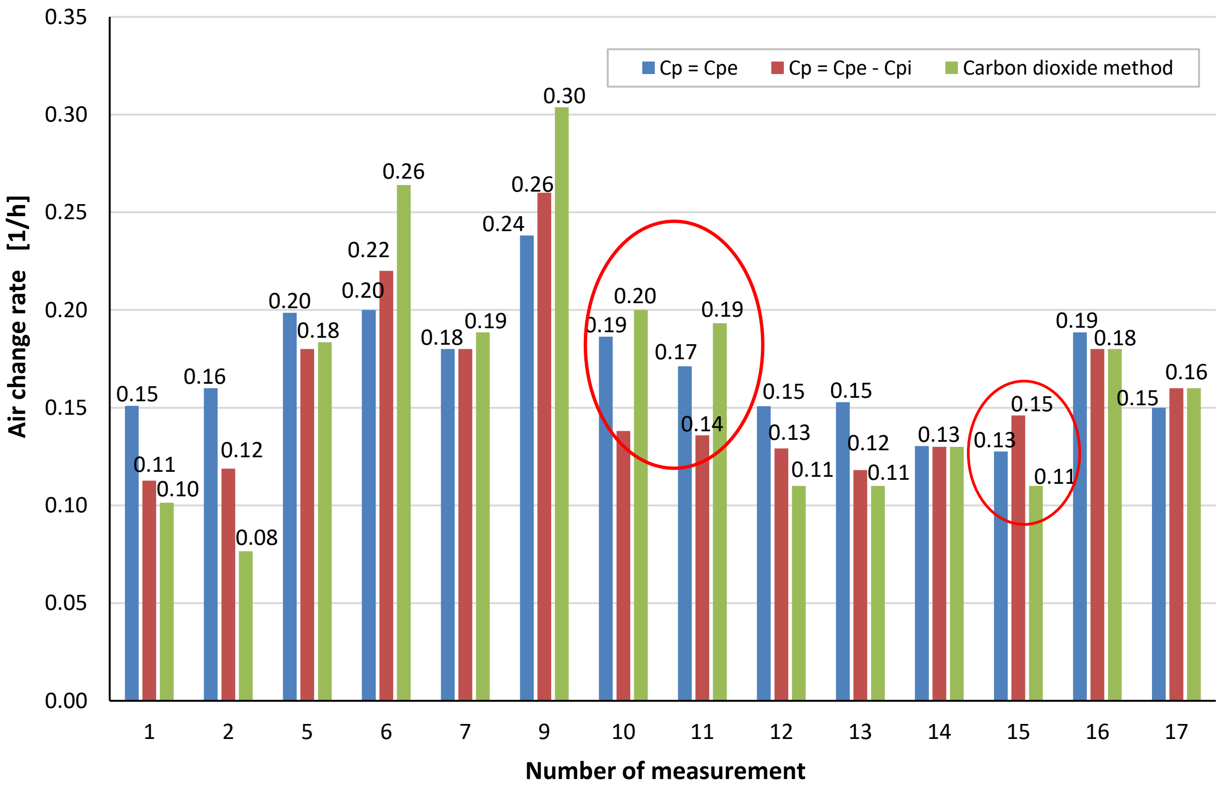


Figure 12. Comparison of air change rate values without considering the influence of openings $C_p = C_{pe}$ with considering the effect of openings $C_p = C_{pe} - C_{pi}$ and calculation based on experimental measurements of carbon dioxide for lower wind speed v = 1.1–4.1 m/s.

Table 3. Calculated differences and percentage differences in air exchange rate determined by different methods—higher wind speeds.

Number of Measurements	The Air Change Rate, n: $C_p = C_{pe}$	$C_p = C_{pe} - C_{pi}$	Carbon Dioxide Method	Difference between			
	A	B	C	B–C		A–C	
(-)	(1/h)	(1/h)	(1/h)	(1/h)	(%)	(1/h)	(%)
3	0.57	0.45	0.46	0.02	3.5	0.10	17.9
4	0.63	0.50	0.59	0.09	18.2	0.04	7.0
8	0.32	0.25	0.28	0.03	10.5	0.04	12.8
18	0.18	0.14	0.09	0.05	34.6	0.09	49.5
19	0.25	0.17	0.19	0.02	10.0	0.06	23.4
20	0.16	0.10	0.08	0.02	20.2	0.09	53.3
21	0.33	0.21	0.24	0.03	14.0	0.09	26.8
22	0.39	0.25	0.23	0.02	8.6	0.16	40.7
23	0.18	0.13	0.11	0.02	14.3	0.07	37.6
24	0.27	0.23	0.23	0.04	19.6	0.04	15.9

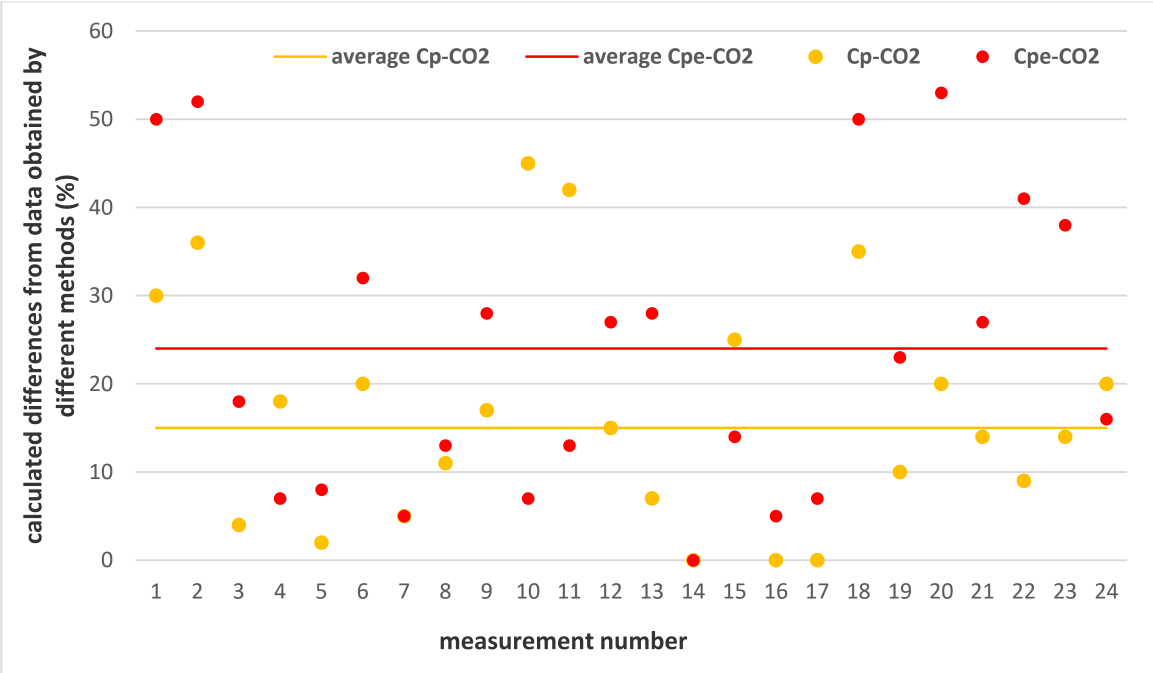


Figure 13. Calculated differences and percentage differences in air change rate determined by different methods.

Table 4. Calculated differences and percentage differences in air exchange rate determined by different methods for lower wind speeds.

Number of Measurements	The Air Change Rate, n			Difference between			
	$C_p = C_{pe}$	$C_p = C_{pe} - C_{pi}$	Carbon Dioxide Method				
	A	B	C	B–C		A–C	
(-)	(1/h)	(1/h)	(1/h)	(1/h)	(%)	(1/h)	(%)
2	0.16	0.12	0.08	0.042	35.6	0.083	52.1
5	0.20	0.18	0.18	0.003	1.9	0.015	7.6
6	0.20	0.22	0.26	0.044	20.0	0.064	32.0
7	0.18	0.18	0.19	0.009	4.7	0.009	4.7
9	0.24	0.26	0.30	0.044	16.8	0.066	27.6
10	0.19	0.14	0.20	0.062	44.8	0.014	7.3
11	0.17	0.14	0.19	0.057	42.2	0.022	12.9
12	0.15	0.13	0.11	0.019	14.8	0.041	27.1
13	0.15	0.12	0.11	0.008	6.9	0.043	28.0
14	0.13	0.13	0.13	0.000	0.0	0.000	0.3
15	0.13	0.15	0.11	0.036	24.7	0.018	13.8
16	0.19	0.18	0.18	0.005	0.0	0.009	4.5
17	0.15	0.16	0.16	0.000	0.0	0.010	6.7

As can be seen from Figure 12 (values for lower wind speed), the values obtained using quantifying of total aerodynamic coefficient $C_p = C_{pe} - C_{pi}$ are comparable to the values obtained by calculation based on experimental measurements of carbon dioxide. At the same time can be stated, that at such low wind speeds, the effect of openings does not play a significant role. At lower wind speeds there was a smaller difference between the values obtained by quantifying of total aerodynamic coefficient C_p and the methodology based on experimental measurements of carbon dioxide (see Table 3 and Figure 12). In 11 measurements, closer to the values obtained by the carbon dioxide method, was the value of the air change rate calculated with considering the openings ($C_p = C_{pe} - C_{pi}$). The difference was in the range 0.01–0.043 (1/h) thus by 0.0–35.6%.

The calculations without considering the openings were more pronounced—up to 52.1%. In three measurements 26 January 2019 (No 10), 27 January 2019 (No 11) and 3 February 2019 (No 15) indicated in Figure 12 it was the value without considering the effect of openings $C_p = C_{pe}$ closer to the value based on experimental measurements of carbon dioxide.

The calculated differences and percentage differences in air change rate determined by different methods for each measurement day can be seen in Figure 13. This figure is illustrative only and shows the percentage differences according to Tables 3 and 4.

It can be seen also the interaction of wind effects and different temperatures. On 2 December 2018 (No 7) and 1 April 2019 (No 19) was calculated the same change rate $n = 0.19$ (1/h) at different wind speeds $v = 1.6$ m/s and 6.3 m/s, however, the outside air temperature was $\theta e = -3$ °C and $\theta e = +8.3$ °C.

The difference between the values of the air exchange rate taking into account the influence of the holes $C_p = C_{pe} - C_{pi}$ and the values based on experimental measurements of carbon dioxide for a higher wind speed v = 4.4–10.3 m/s is shown in Figure 14. In the figure, there are differences in the results obtained according to the individual methods only in those measurements where a high wind speed was recorded. There are ten measurements.

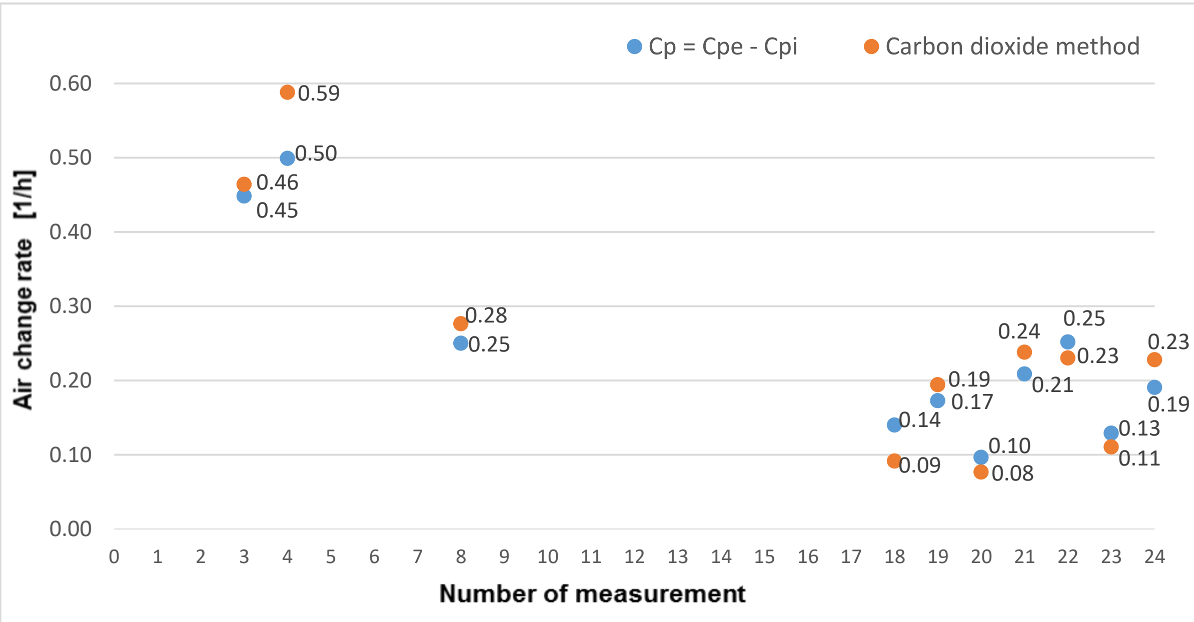


Figure 14. The difference between values of air change rate taking into account the influence of openings $C_p = C_{pe} - C_{pi}$ and the values based on experimental measurements of carbon dioxide for higher wind speed $v = 4.4$–10.3 m/s.

However, these results also indicate that the value of air change rate is at high wind speeds significantly lower than the value set by STN [5] $n = 0.5$ (1/h), except for one measurement on 17 March 2018 (No 3, No 4) at wind speed $v = 9.4$ m/s and 10.3 m/s and external temperature $\theta e = -12.3$ °C and $\theta e = -14.1$ °C.

5. Conclusions

The aim of the study was to evaluate the accuracy of the predictive value of determining the of air change rate by comparing two methods using quantifying of total aerodynamic coefficient C_p (aerodynamic quantification of buildings) and the method based on experimental measurements of carbon dioxide. Based on the calculations and measurements used in this study on different days (as shown in the tables and graphs), the results were compared and evaluated.

As already mentioned, the results obtained by specifying the aerodynamic coefficient $C_p = C_{pe} - C_{pi}$ when accepting the air permeability of the building facade and the values based on experimental measurements of carbon dioxide are comparable and can be accepted. This comparison can be generally applied for following conditions: living room with the exterior wall to the windward direction, no impact of interior restrictions to air movement, all leakage is due to window leakage, no air entering room from lower unit.

At present, when manufacturers are trying to produce windows with almost zero joint air permeability, it is not possible to ensure natural air exchange with the windows closed. This problem must be solved by acknowledging micro-ventilation joints in the window construction. The eternal problem is to maintain a balance between hygiene and energy requirements. Hygienists, doctors would like a natural exchange of fresh air several times an hour, not only twice but three to four times. This is unacceptable for creators of artificial material environments, building architects who want to save energy for heating. When designing, they consider very small values of n (natural air exchange number) to predict low energy consumption for heating or cooling.

The current situation in the world, where infectious diseases (such as COVID-19) are spreading, people in Slovakia have to spend most of their time at home because it is forbidden to leave home. Children learn at home using computers in conjunction with the teacher via the Internet. With very tight windows, there is an increase in the amount and multiplication of bacteria in the indoor air. Therefore, the natural exchange of air for human health is very much needed. The whole process of such evaluation is based on very unstable methods, into which a number of unknowns enter. The building design process today requires completely different approaches than in the past. Everything leads to a certain virtual reality, simulation methods, where it is necessary to consider reference values for the calculation. Therefore, the value of air change when considering simulation tools requires that it be determined and verified by measurement. This study points to the possibilities of verifying the air change rate.

The results of measurements and calculations show that the values of the air change rate at both lower and higher wind speeds are below the standard level. This means that they differ significantly from the value for living rooms in residential buildings specified by the standard, which is n = 0.5 (1/h). At higher wind speeds, the air permeability of the building facade plays an important role. The resulting values obtained taking into account the effect of openings (considered total aerodynamic coefficient $C_p = C_{pe} - C_{pi}$ are comparable with the values obtained based on experimental measurements of carbon dioxide.

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