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Quality of life control by selected methods of air exchange in a typical apartment building

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Abstract: Air change rate is an important parameter for quantification of ventilation heat losses and also affects the indoor climate of buildings. Indoor air quality is significantly associated with ventilation. If air change isn't sufficient, trapped allergens, pollutants and irritants can degrade the indoor air quality and affect the well-being of a building's occupants. 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. Quantification of air change rate is complicated, since it is affected by a number of parameters, of which the one of the most variable is the air-wind flow. This study aims to determination and comparison of values of the air change rate in two methods - by quantifying of 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 in the selected reference room in apartment building.

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. Efforts to reduce of 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, 2, 3]. Nowadays people spend up to 90% of their life indoors. Thus the quality of indoor air has received an increased attention in recent years. In a 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 on the age of the building stock.

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

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

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.s.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. In reality is the air change rate very variable, because 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, using quantifying of total aerodynamic coefficient $Cp = Cpe - Cpi$ – 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 is possible to calculate the air change rate in room. by specifying and quantifying the coefficient by calculation using the refined coefficient C_p by calculation using the specifying coefficient C_p

2. Methods of air change rate prediction

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

- using quantifying 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 influence of wind and building parameters and the air permeability of the building
- based on experimental measurements of carbon dioxide in the selected reference room in apartment building.

2.1 Quantification of total aerodynamic coefficient C_p

Ventilation is the air change that is, it ensures the supply of fresh outdoor air to ventilated / air-conditioned spaces and the removal of degraded air from ventilated spaces [9,10,12]. Depending on how the ventilation of buildings is ensured, we distinguish: natural ventilation, forced ventilation and combined ventilation [9,10,12]. In our climatic conditions, natural ventilation is still one of the most common methods of ventilation. When ventilating buildings of building construction- especially in residential buildings it is mostly a natural air change - natural ventilation, which arises due to leaks in window and door openings, window sills, various transitions, etc. – infiltration, or as a result of the homeowner behaviour - by opening windows. Natural ventilation is a type of ventilation in which the movement and air change is induced by natural motor forces [7, 8, 9,10]. These forces are the temperature difference and the wind. The basic precondition for natural ventilation is thus the total air pressure difference Δpc [Pa] [9,11,12] determined as the sum of the air pressure difference from different temperatures $\Delta p\theta$ [Pa] and air pressure difference from wind effect Δpw [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]:

$$\Delta pc = \Delta p\theta + \Delta pw = h_0 . g . (\rho ae - \rho ai) + Cp . (w^2 . \rho ae . \frac{\rho ae}{2}) \qquad (2)$$

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 [-]

w - wind speed [m/s].

The value of the total pressure difference Δp_c is strongly influenced mainly primarily by the effects of the wind Δp_w, which is very variable during the day and depends primarily on: the direction of the applied wind, the wind speed of the air flow above the ground and many other factors. Different investigators found a dependence on the square of the wind speed. A necessary input to formula (2) is the determination of the aerodynamic coefficient of total pressure C_p, which is currently the only problem in the field of physical quantification of natural ventilation of buildings [11,13,14].

For assessing of natural ventilation and for calculation of air change rate by using of simulation methods is it necessary the knowledge of distribution of pressure on the buildings facades and therefore is necessary aerodynamic quantification expressed by total aerodynamic coefficient C_p *(-)* takes into account the effects of variable wind with the parameters of the building. Knowledge of aerodynamic coefficients of external pressure C_{pe} and internal pressure C_{pi} is a basic prerequisite for aerodynamic quantification of buildings [11,13,15,16,17].

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

where

C_p - total aerodynamic coefficient [-],

C_{pe} - coefficient of external pressure [-],

C_{pi} - coefficient of internal pressure [-].

2. 1. 1 External aerodynamic coefficient

The aerodynamic coefficient of external pressure is a dimensionless, highly variable quantity, which is influenced by a number of parameters - building geometry, details on the facade, position on the facade, degree of exposure, or. coverage, wind speed and wind direction [18, 19]. Due to the number of parameters, it is not possible to take into account all parameters that affect it when determining the aerodynamic coefficient of external pressure.

Aerodynamic coefficients of external pressure can be expressed by: calculations according to national standards [20], experimental measurements in–situ [15, 21,22]~~,~~ experimental measurements in the aerodynamic tunnel [23,24,25,26], simulations using CFD calculation software. Amin and Ahuja (2013) [26] performed a series of measurements on models of high-rise buildings with a rectangular floor plan in order to investigate the influence of the aspect ratio on the values of aerodynamic coefficients of external pressure. Similar measurements were performed by Amin and Ahuja (2011) [23] also 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 models with rectangular floor plans and different ratios of width, length and height of the building and the results were summarized in aerodynamic databases (TPU Aerodynamic Database).

The aerodynamic coefficient of external pressure can be affected by a large number of parameters. Since the building modifies the air flow mainly by its shape, it is necessary to define the buildings under consideration geometrically in order to determine the aerodynamic coefficients of external pressure. At present, the spatial geometric classification is defined only for rectangular buildings of square and rectangular shape and for buildings with a circular floor plan. According to [11] we can divide buildings on the basis of height into three groups, namely 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, the ratio height to width h: b = 3 and the height to length h: l = 2 – is a typical value of Cpe = 0.7 to 0.8 on the windward side and C_{pe} = - 0.1 to - 0.5 on the leeward and side walls [20,29]. The aerodynamic coefficients in the standards are the values applied in respect only strong winds and represent the maximum value for the façade. However, if the external aerodynamic coefficient unevenly, extreme value is significantly different from the average and at windward may be a difference of up to 50%.

2. 1. 2. Internal aerodynamic coefficient

In addition to external climatic factors, which are highly variable, pressure difference is affected by the air permeability of the peripheral structures. Façade shows a certain degree of the 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 the two surfaces of this structural surface and therefore both external and internal pressures need to be known. Research to estimate the internal pressures caused by wind has received much less attention than the measurement of external pressures, despite the fact that the internal pressure load of buildings contributes significantly to the overall load of the building envelope. Aynsley et al. [7] investigated the effect of wall porosity on internal pressures and found that the internal pressure is uniform and its value does not depend on the measurement site. Ginger [15] and Ginger et Letchford [27] 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 coat. 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 in the case of 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 changing internal pressure.

For engineering practice is very important to knowledge of the value of the internal aerodynamic coefficient, because it can cause result in increased values at leeward and lateral sides, because infiltration may cause alteration of aerodynamic coefficients of positive total pressure (pressure) to negative (suction) value [8]. Knowledge of aerodynamic coefficients of external pressure and internal pressure is a basic prerequisite for aerodynamic quantification of buildings using the aerodynamic coefficient of total pressure [11,28,15,16,17]. The approximate influence of the air permeability of the perimeter walls of a tall building of rectangular plan shape on the basic distribution of pressures and suction on its windward and leeward side is shown in Fig. 1 [11].

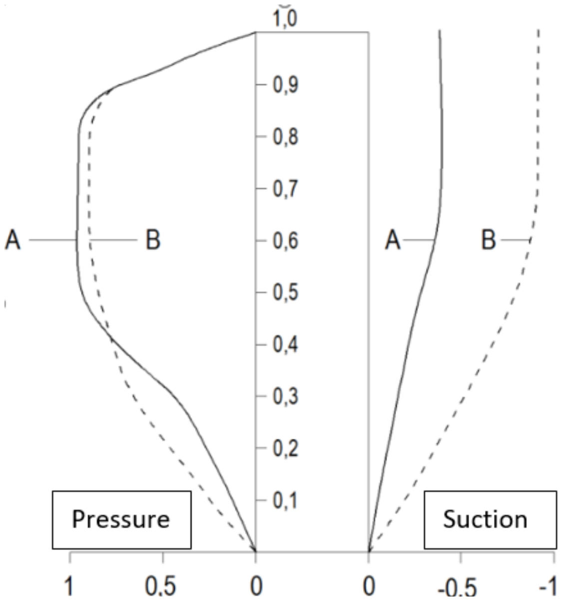


Figure 1 The approximate influence of air permeability of the perimeter walls of a high building with a rectangular floor plan on the basic distribution of pressures and suction on its windward and leeward side according [11] A - building with zero air permeability B - building with air permeability

In the calculation of the internal aerodynamic coefficient *Cpi* it is necessary to know the modification of the building which affects changes of internal and external pressures [11]. Given that, in the current period there are no legislative requirements for quantification of air permeability of all dividing structures of buildings (partitions, doors, etc.), is it possible to deal with aerodynamic coefficients of internal pressure only for buildings without inner dividing by partitions [11].

The aerodynamic coefficient of internal pressure is a function of the parameter a [-], the value of which, since it is a dimensionless parameter, does not have to be quantified absolutely, but 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].

To determine the parameter a [-], there are several assumptions by which the air permeability can be applied [11]. For its solution on the selected reference building, we assume that the air permeability of the perimeter walls is applied only by infill window constructions with different dimensions and with the same joint air permeability coefficient i_{LV} [m^2/(s.Pa^n)]. Then applies the formula (5) [11]

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

$L_{(+)}$ - the sum of the lengths of the joints of openings on the windward side of a building [m],

$L_{(-)}$ - the sum of the lengths of the joints of openings on the leeward and lateral sides of a building [m].

2. 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 12569 [31]. Standard [31] describes among other method to the tracer gas concentration decay method which were used in this paper. According to [32,33,34,35,36], 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.

We can determine 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 *Csup* 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 [41,42,43,44]. In paper [45], the focus is on air exchange in the summer when considering energy savings. Posts [46,47,48,49] are devoted to the issue of air exchange in various types of buildings, the increase in CO_2 and its impact on users.

3. Materials and methods

The subject of the paper is a living room - bedroom located in a flat in reference apartment building. The reference apartment building is located in the northern part of town Kosice, in eastern part of Slovakia (see Fig.3). The subject, goal and methodology of the research can be seen in Fig. 2.

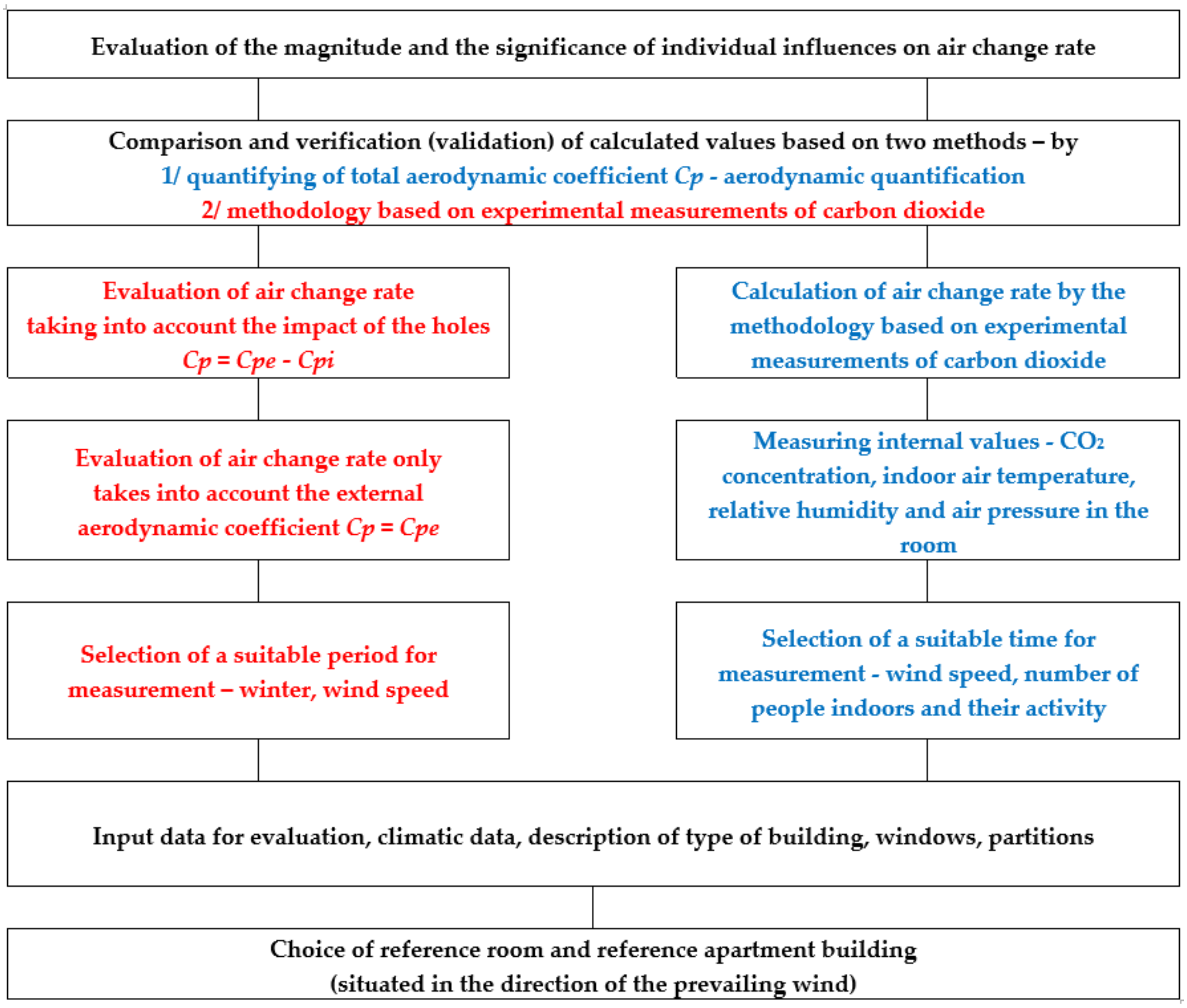


Figure 2 The subject, goal and methodology of the research

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.

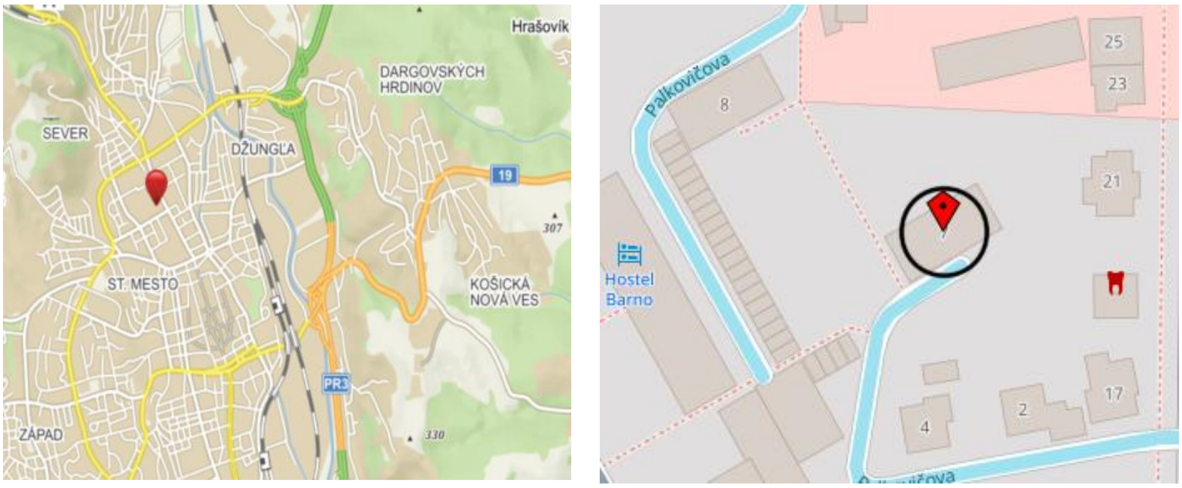
The methodology is focused on in situ measurements, calculations, confrontation of measured and calculated values and determination of the effects of selected parameters.

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

4. Reference room in selected apartment building

The selected reference apartment building is located in the centre of city Kosice, north (see Fig. 3 a, b). Used reference room in the case study is located on the third floor of this selected building.



a) b)

Figure 3 a) **b**) The situation of a case study

Views of the building from the exterior side can be seen in Fig. 4, as well as floorplan of the reference apartment and selected room can be seen in Fig. 5.

4.1 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=24.6 m, width b =12.1 m, height h = 36,4 m and 2 gable walls - see Fig. 4. According to [11] the reference building can be classified 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 = ≈ 3 - the plate type building with spatial proportionality: 0,5 ≤ h/b = ≤ 1,5 and with surface area proportionality: 1,5 ≤ l/b = 2.3 ≤ 4,0

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

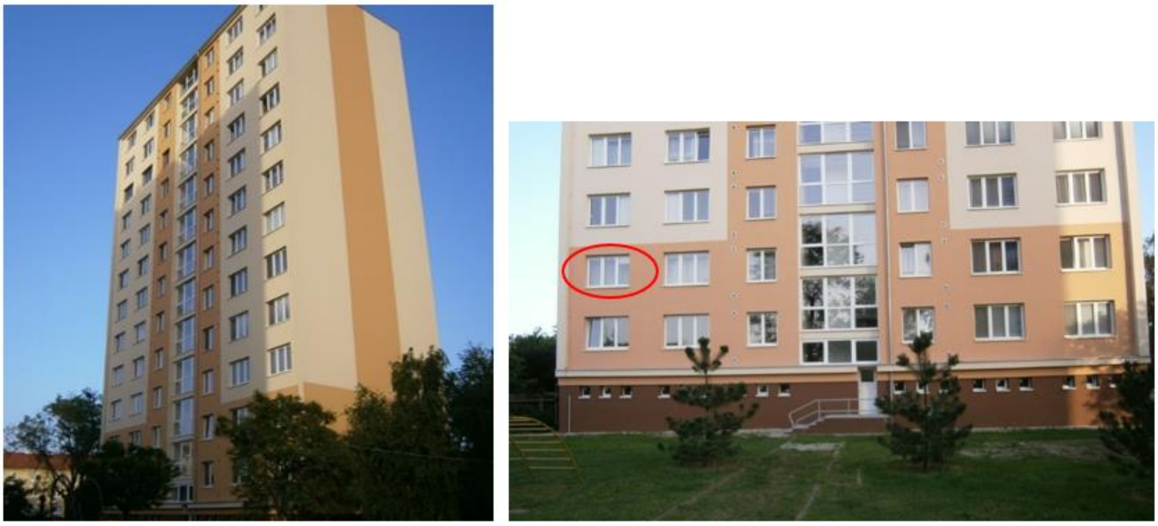


Figure 4 External view of selected apartment building

The reference room is situated on 3nd floor - at height above ground approximately 8.4 m, oriented NW – 315 ° – on windward wall. The reference room – bedroom is with internal dimensions 4 x 3.55 x 2.6 m and area of the room is 36.92 m². The window system consists of a plastic frame, with an isolation binocular and a length of gaps l =12.1 m.

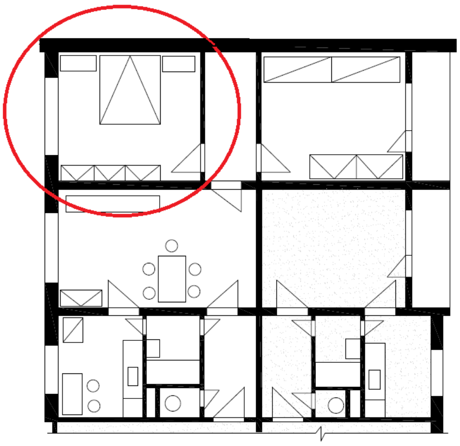


Figure 5 Ground plan – floorplan of the reference building

4.2 Measurement and description of the external climatic and internal parameters

External climatic parameters influencing the pressure difference Δpc are outdoor air temperature θe, wind speed w and wind direction. On selected days was the wind speed measured 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 is the reference building located in centre of city, values of wind speed measured in open terrain were reduced by [29]

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

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 centre of cities 10 m above the ground is k = 0,65.

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 w
			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	05.03.2018	8:40	1,151	1,064	69	23.1	-5.0	3.9
2	05.03.2018	10:30	1,076	1,019	69	23.1	-6.0	3.9
3	17.03.2018	18:00	1,133	891	52	25.5	-12.3	9.4
4	17.03.2018	21:00	1,440	1,170	31	26.4	-14.1	10.3
5	01.12.2018	21:00	945	874	42	23.0	-4.0	2.7
6	02.12.2018	9:00	1,326	1,215	28	24.4	-3.0	1.6
7	02.12.2018	14:00	964	896	38	23.2	-3.0	1.6
8	25.01.2019	20:10	1,200	1,024	59	22.9	-4.0	6.7
9	26.01.2019	9:10	1,346	1,206	29	24.4	-5.0	3.4
10	26.01.2019	20:00	1,353	1,230	42	23.0	-6.0	1.1
11	27.01.2019	15:10	841	771	57	23.0	-2.0	1.6
12	02.02.2019	9:30	2,052	1,907	45	24.2	4.0	2.3
13	02.02.2019	13:30	1,778	1,698	32	23.6	5.0	2.7
14	02.02.2019	20:30	1,400	1,279	61	23.1	4.0	0.7
15	03.02.2019	9:30	1,654	1,525	60	24.0	7.0	2.0
16	04.02.2019	19:00	1,375	1,214	60	24.0	2.0	3.6
17	05.02.2019	10:00	1,307	1,180	60	24.1	2.0	2.0
18	25.03.2019	20:30	1,740	1,686	25	25.0	8.0	4.4
19	01.04.2019	20:30	1,322	1,276	15	25.1	8.3	6.3
20	08.04.2019	19:10	1,751	1,682	45	24.6	19.0	5.4
21	10.04.2019	20:10	1,310	1,210	30	24.5	10.0	8.3
22	11.04.2019	20:00	1,121	0,991	50	23.9	6.0	9.4
23	17.04.2019	20:20	1,918	1,789	45	24.1	11.0	4.7
24	06.05.2019	18:40	1,251	1,077	60	24.0	6.0	6.6

Internal climate parameters - indoor air temperature, internal air flow speed, internal air pressure and relative air humidity was measured using equipment *TESTO 435 – 4*. 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 CO_2 concentration measurement range of the instrument is from 0 to 10,000 ppm, while the sensitivity is 1 ppm and the accuracy is ± 3%. The measurement range of temperature is from 0 °C to + 50 °C, with a sensitivity of 0.1 °C and accuracy of ± 0.3 °C. The relative humidity range 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, where they were recorded - 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 was person at least one metre and 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 2.

During all experimental measurements were recorded: CO_2 concentration, indoor air temperature, relative humidity and air pressure in the room. Course of one experimental measurement from 03.02.2019 No 15 in the apartment is shown in Fig. 6.

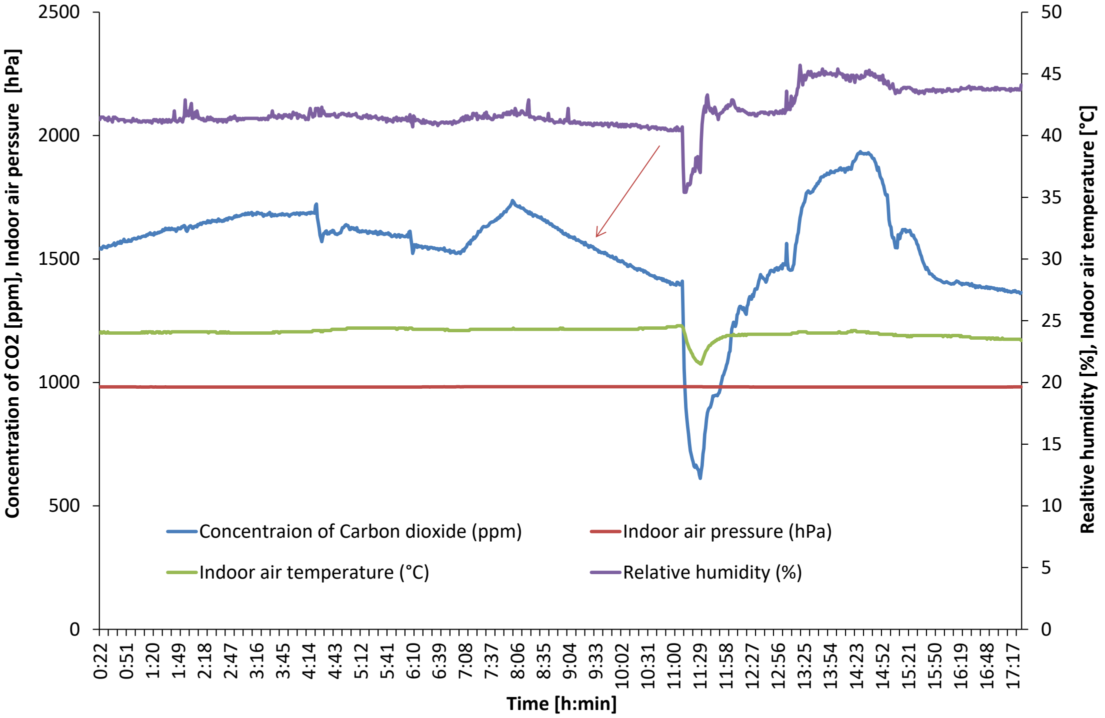


Figure 6 Recording of indoor air quality courses from experimental measurements No 15 (03.02.2019)

On the Figure 6 is documented the course of indoor air parameters. The red arrow shows the selected section of decrease CO_2 concentration of decrease. During this period, the room was closed and without persons. 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 a 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.

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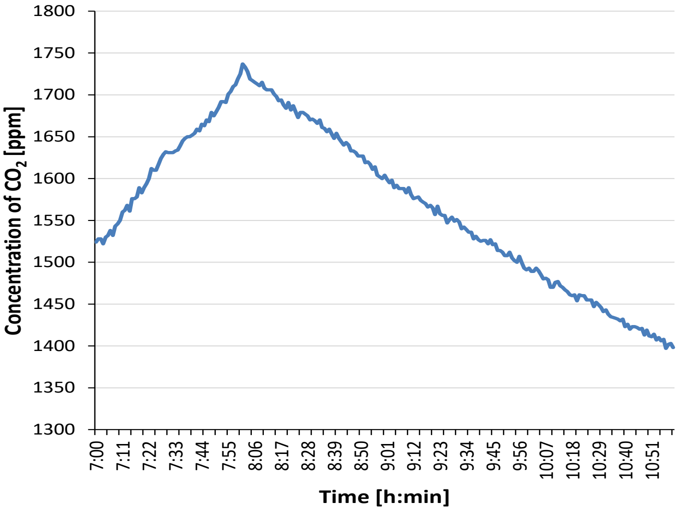

Figure 7 Recording of concentration of CO_2 for selected day 03.02.2019 No 15

It can be seen from Figure 7 that the maximum achieved CO_2 concentration in the room was 1,728 ppm at 8:03. After the person leaves from the room and closing the door to the room the CO_2 concentration began to decrease. The starting decline he was intense, but later at 8:30 was stabilized decline. The starting sharper decrease of CO_2 concentration was caused by leaks in building structures and at the same time opening and closing the door, which was caused by the person leaving from the room to the next room. From the record it is possible to see that from 8:30, when the CO_2 concentration was $C_{IDA,S}$ = 1,671 ppm, the decrease in CO_2 concentration is regular. It can be assumed that from 8:30, the air change rate is ensured only by 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. On some days were performed tree measurements 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 enter it for about one hour.

4.3 Prediction of air change rate using quantifying of total aerodynamic coefficient C_p

Calculation of air change rate in the reference room were processed for selected days and hours with wind direction N, NW, NE – 360 °, 315 °. The values of external aerodynamic coefficient for different wind direction are C_{pe} = +0.525 and C_{pe} = +0.35, internal aerodynamic coefficient C_{pi} was determined for building with two gable walls graphically according [28,29]. 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 with considering the effect of openings $C_p = C_{pe} - C_{pi}$.

The values of air change rate for reference building with 2 gable walls for higher and lower wind speed are in the Fig. 8 and 9.

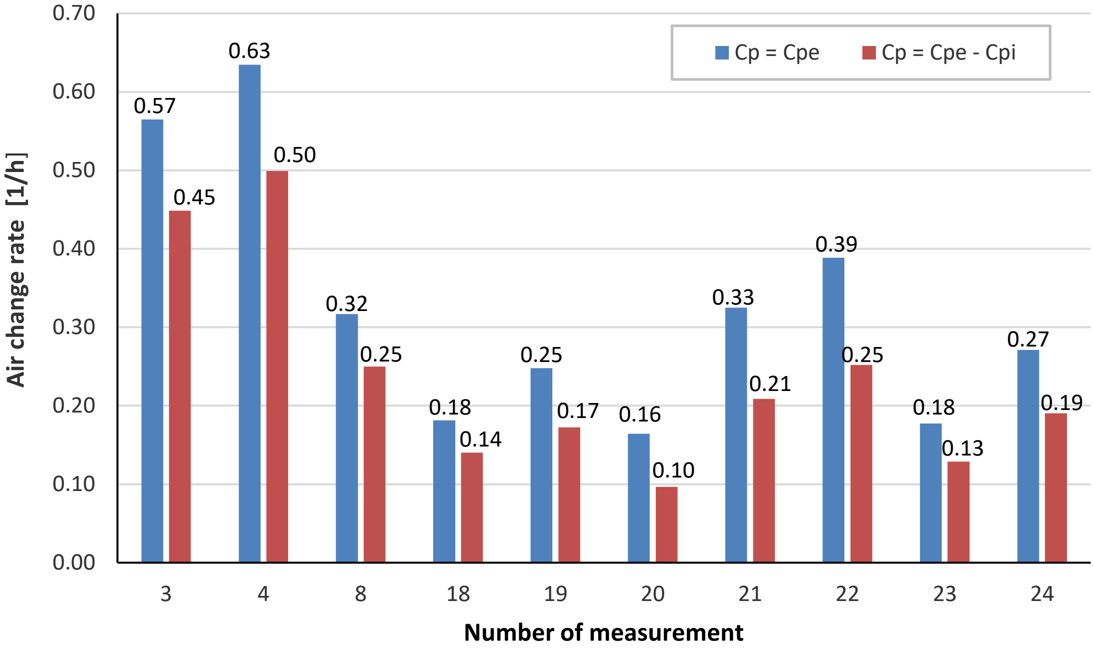

Figure 8 The values of air change rate without considering the influence of the openings $C_p = C_{pe}$ and with considering the effect of the openings $C_p = C_{pe} - C_{pi}$ for higher wind speed v = 4.4 m/s – 10.3 m/s

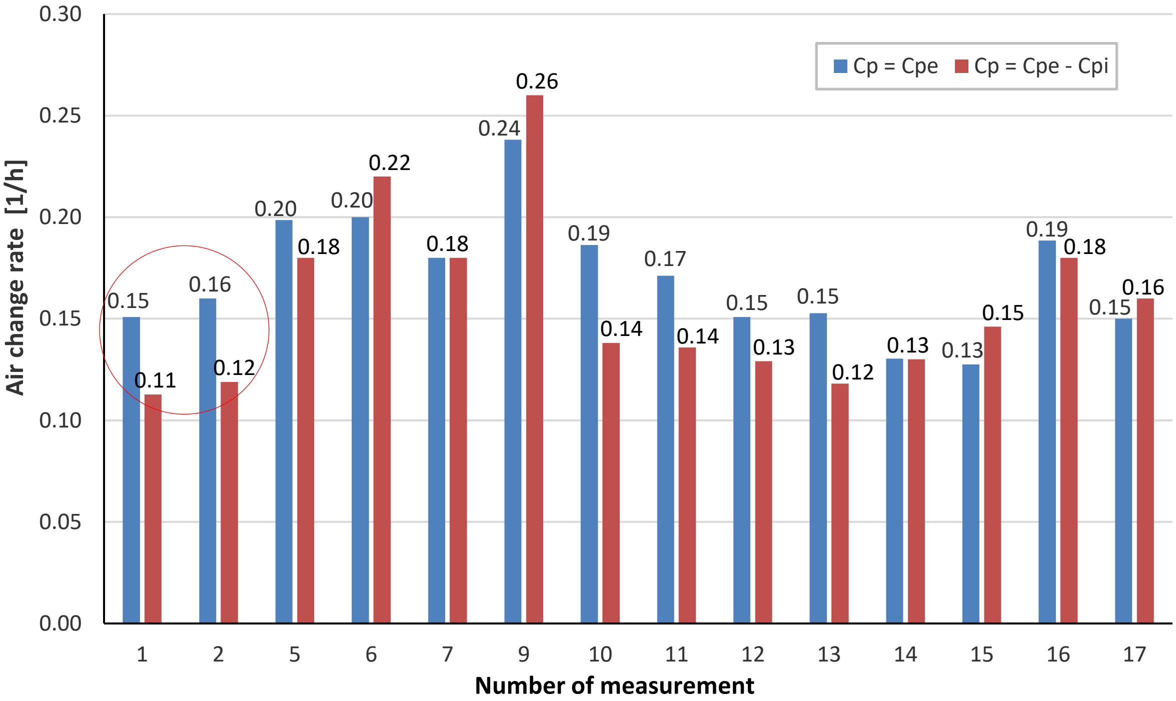

Figure 9 The values of air change rate without considering the influence of openings - $C_p = C_{pe}$ and with considering the effect of openings $C_p = C_{pe} - C_{pi}$ for lower wind speed v =1.1 m/s – 4.1 m/s

In Fig. 8 and 9 shows and compares the value of air change rate without considering the effect of openings $C_p = C_{pe}$ and with considering the effect of openings $C_p = C_{pe} - C_{pi}$ for higher wind speeds from 4.4 m/s – 10.3 m/s (Fig. 8) and for lower wind speed 1,1 m/s – 4.0 m/s (Fig.9). From Figure 8 and 9 can be seen that the effect of the openings on the air change rate is significantly influenced by the wind speed. At higher wind speeds is the effect of the openings significant, see Fig. 8. The values of the air change rate n whit considering the influence of openings $C_p = C_{pe} - C_{pi}$ are lower than without considering the openings $C_p = C_{pe}$, the difference between the values is in the range 0.05 - 0.137 [1/h] thus by 20.6% -

41.2%, which is on average 25.2%. At the same time, is it possible to state from Fig. 9, that at lower wind speeds the influence of openings does not play a significant role, the difference is from 0.00 to 0.048 [1/h], i.e. 0.00% - 29.4%, on average 8.3%. During two measurements, on March 5, 2018 at 8:30 (No 1) and 9:30 (No 2) is the difference 35% (Fig. 9).

4.4 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 continuing by the presence of people. Throughout the time of stay in the room air exchange was caused by infiltration.

For each experiment, CO_2 concentration measurements were made at time intervals of 1 minute. In order to calculate of air change rate, the duration of CO_2 concentration decrease was considered as a multiple of several 1minutes time intervals. As an example, for measurements carried out on 03.02.2019, the first time interval was 1 minute and the last (31st time interval) was 31 minutes, resulting 31 calculated CO_2 air change rates (Figure 10).

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.

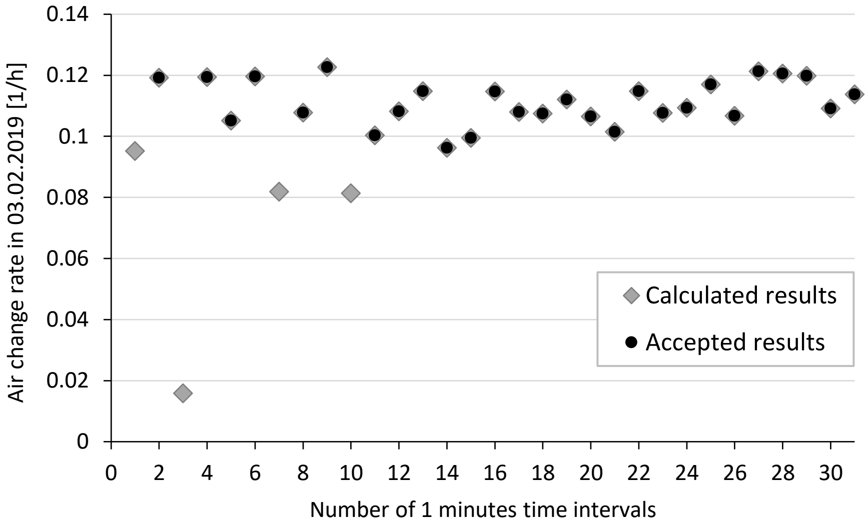

Figure 10 The screening of the calculated values of air change rate for 03.02.2019 (No 15)

The calculated air change rate values for individual experimental measurements are given in the table 2 A.

Table 2 A The calculated values of air change rate basis of measured values of carbon dioxide concentration for all measurements

Number (-)	The air change rate n (1/h)	Number (-)	The air change rate n (1/h)	Number (-)	The air change rate n (1/h)	Number (-)	The air change rate n (1/h)
1	0.10	7	0.19	13	0.11	19	0.19
2	0.08	8	0.28	14	0.13	20	0.08
3	0.46	9	0.30	15	0.11	21	0.24
4	0.59	10	0.20	16	0.18	22	0.23
5	0.18	11	0.19	17	0.16	23	0.11
6	0.26	12	0.11	18	0.09	24	0.23

Table 2 B Margin of error of the air change rate established by calculations according to measurements of CO2

Number (-)	**The uncertainty (%)**	**Number (-)**	**The uncertainty (%)**	**Number (-)**	**The uncertainty (%)**	**Number (-)**	**The uncertainty (%)**
1	4.10	7	3.79	13	2.07	19	1.55
2	4.47	8	1.89	14	2.74	20	4.03
3	1.02	9	2.50	15	4.70	21	2.42
4	2.12	10	2.50	16	3.96	22	5.24
5	5.85	11	1.76	17	4.74	23	0.88
6	1.93	12	1.94	18	8.63	24	1.62

Based on the calculated differences listed in table 2A, 2B we conclude that the average margin of error is approximately 3.23%.

5. Discussion

This case study examines the effect of the wind direction and size and position of windows on the facade to 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 intensity of air change, which significantly affects the thermal regime and comfort of the indoor environment. To determine the values of the of air change rate the calculation was used by aerodynamic quantification of buildings - account the influence of the wind with the parameters of the building and accepting the air permeability of the façade - 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 Fig. 11, 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 m/s – 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% (Tab.3, Fig.13). The big difference 34.6% was only during one measurement No 18 on March 25, 2019 (Fig.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% (Tab. 4).

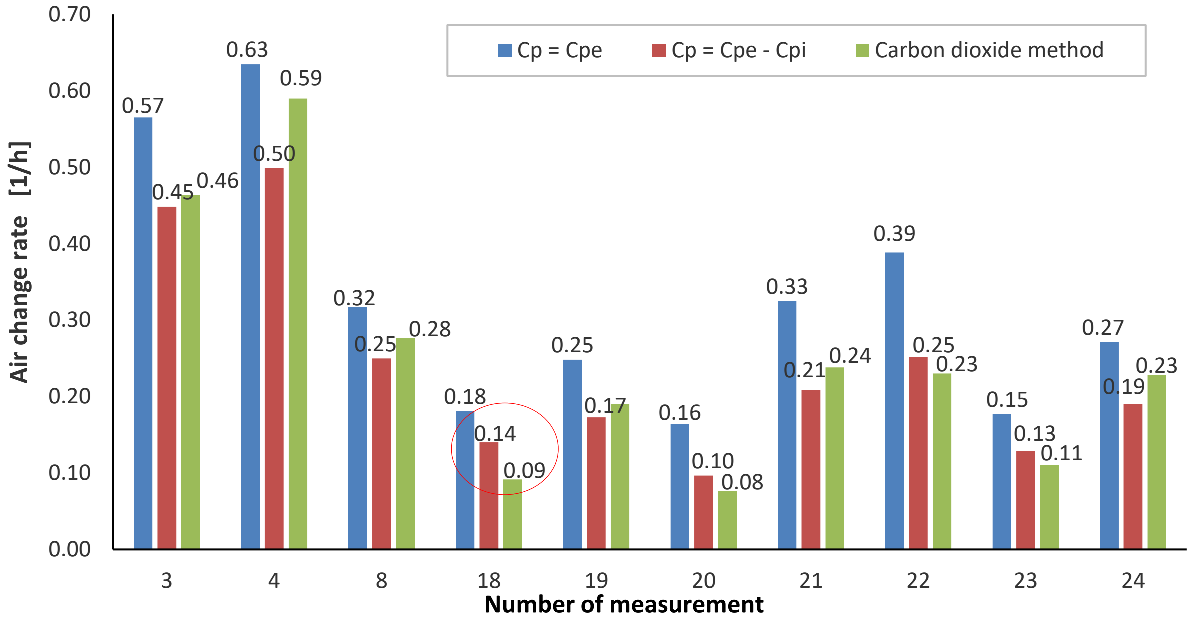

Figure 11 Comparison of the values of air change rate without considering the influence of openings $C_p = C_{pe}$, with considering the effect of openings $C_p = C_{pe} - C_{pi}$ and calculation based on experimental measurements of carbon dioxide - for higher wind speed v = 4.4 m/s – 10.3 m/s

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 Tab.3 and Fig.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 3 measurements 26.1. 2019 (No 10), 27.1. 2019 (No 11) and 3.2.2019 (No 15) indicated in Fig. 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.

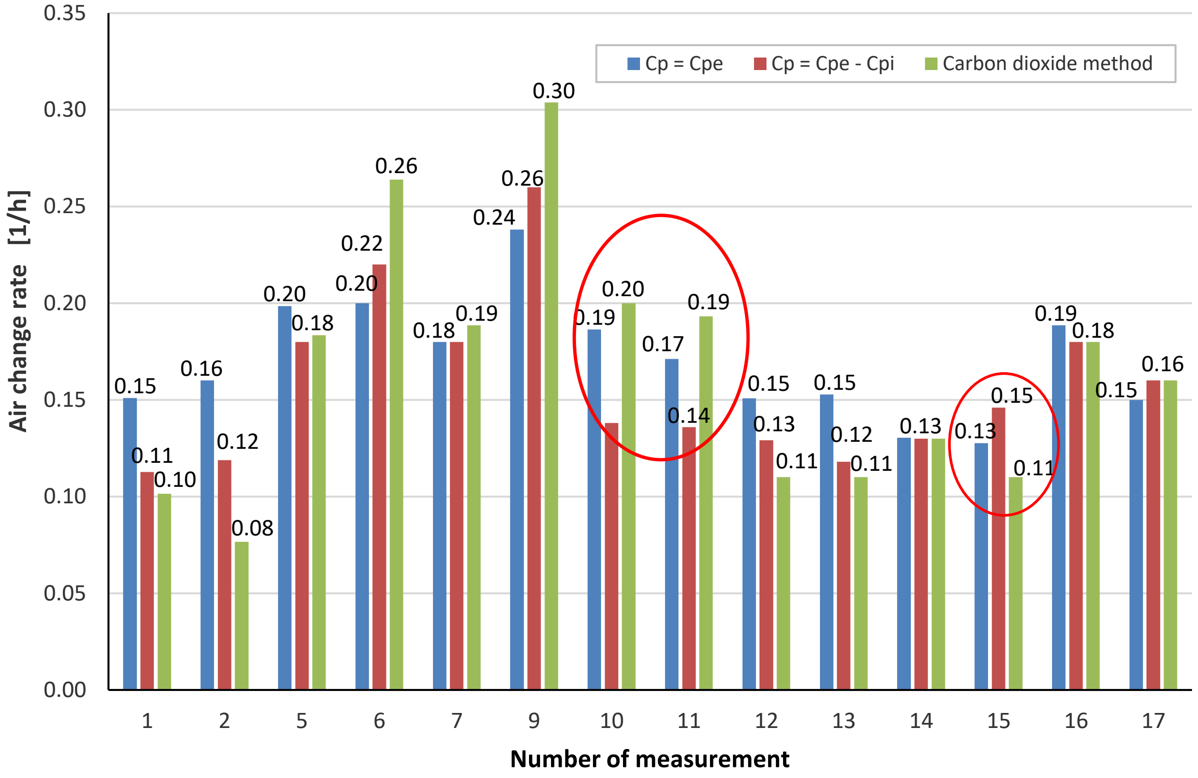

Figure 12 Comparison of the values of air change rate without considering the influence of openings $C_p = C_{pe}$ with considering the effect of openings $C_p = C_{pe} - C_{pi}$ and calculation based on experimental measurements of carbon dioxide - for lower wind speed v =1.1 m/s – 4.1 m/s.

Table 3 Comparison of calculated values of air change rate by different methods for higher wind speed

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

Table 4 Comparison of calculated values of air change rate by different methods for lower wind speed

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]**	**[%]**

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

It can be seen also the interaction of wind effects and different temperatures. On 2.12.2018 (No 7) and 1.4 2019 (No 19) was calculated the same change rate n = 0.19 [1/h] at different wind speeds w = 1.6 m/s and 6.3 m/s, however, the outside air temperature was θe = -3°C and θe = +8.3°C.

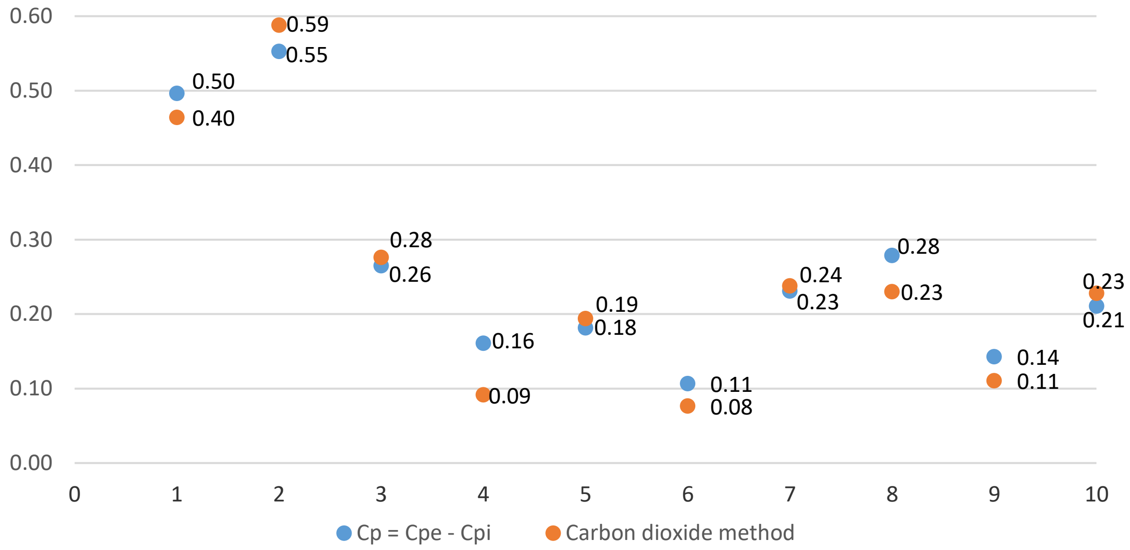

Figure 13 The difference between values of air change rate taking into account the influence of openings $Cp = Cpe - Cpi$ and the values based on experimental measurements of carbon dioxide for higher wind speed v =4.4 m/s - 10.3 m/s

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

The aim of the work was to compare and verify the various methods and the above results clearly indicate that when accepting the air permeability of the facade of the building e.g. total aerodynamic coefficient $C_p = C_{pe} - C_{pi}$ are values of air change rate comparable to the values obtained by calculation based on experimental measurements of carbon dioxide.

6. Conclusions

People spend more time at apartments than anywhere else, it is about 70%. Air exchange 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.

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 exchange 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 mould. Therefore, it is necessary to ensure an increase in the intensity of air exchange through regular and intensive ventilation by apartment users or by means of micro-ventilation.

The aim of the study was to evaluate the accuracy of the predictive value of determining the intensity of air change by comparing 2 methods – using quantifying of total aerodynamic coefficient C_p (aerodynamic quantification of buildings) and the method based on experimental measurements of carbon dioxide. This comparison can be generally applied for following conditions: single 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. 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 $C_p = C_{pe} - C_{pi}$ taking into account the air permeability of the peripheral structures and the values based on experimental measurements of carbon dioxide-are comparable and can be accepted.

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 acknowledged 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 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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References

1. Bornehag, C.G Sundell C.G; Hägerhed-Engman, L; Sigsgaard, T. Association between ventilation rates in 390 Swedish homes and allergic symptoms in children, *Indoor Air. 15* **2005**, 275-280. DOI: 10.1111/j.1600-0668.2005.00372.x
2. Sundell, H; Levin, W.W; Nazaroff, W.S; Cain, W.J; Fish, D.T; Grimsrud, F; Gyntelberg, Y. Li, A.K; Persily, A.C; Pickering, J.M; Samet, J.D; Spengler, S.T; Taylor, C.J; Weschler, Ventilation rates and health: multidisciplinary review of the scientific literature, *Indoor Air. 21* **2011**, 191-204. DOI: 10.1111/j.1600-0668.2010.00703.x
3. Wargocki, P; Sundell, J; Bischof, W; Brundrett,G; Fanger,P.O; Gyntelberg, F; Hanssen,S.O; Harrison, P; Pickering, A; Seppanen, O; Wouters,P; Ventilation and health in non-industrial indoor environments: report from a European Multidisciplinary Scientific Consensus Meeting (EUROVEN), *Indoor Air. 12* **2002** 113-128. • DOI: 10.1034/j.1600-0668.2002.01145.x
4. Asikainen A., Hänninen O., Brelih N., Bischof W., Hartmann T., Carrer P., Wargocki P. The Proportion of Residences in European Countries with Ventilation Rates below the Regulation Based Limit Value. *International Journal of Ventilation*: September **2013**, Vol. 12, No. 2, pp. 129-134. https://doi.org/10.1080/14733315.2013.11684007
5. STN 73 4301 – *Dwelling buildings*, Slovak Republic Office of Standards, Metrology and Testing: Bratislava, Slovakia; **2005**
6. Chmúrny I: *Tepelná ochrana budov*, Jaga Bratislava, **2003**;
7. Aynsley, R.M; Melbourne, W; Vickery, B.J; A*rchitectural aerodynamics*. London: Applied science publishers LTD, **1977**. ISBN 0-85334-698-4; https://www.worldcat.org/title/architectural-aerodynamics/oclc/569295778
8. Meroney, R.N; Neff, D.E; Birdsall, J.B. Wind-tunnel simulation of infiltration across permeable building envelopes: energy and air pollution exchange rates. San Francisco: 7th international symposium on measurement and modeling of environmental flows international mechanical enginnering conference, **1995**. https://www.osti.gov/biblio/435757
9. Székyová, M; Boďo, R; Ihradský, J; Vetranie. STU Bratislava: **2002**. ISBN 80-227-1681-2.
10. Kleiven, T; Natural ventilation in buildings. Trondheim: *Norwegian university of science and technology*, **2003**. URN: NBN: no-7242. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/231090
11. Bielek, M; Bielek, B. et al. Vplyv stavebných materiálov a konštrukcií na kvalitu života. Parametrizovanie energeticko-environmentálneho hodnotenia stavebných konštrukcií a budov. *Aerodynamika budov pre kvantifikáciu ich prirodzeného vetrania*. Bratislava: PROFING, spol. s.r.o., **2005**.
12. Drkal, F; Lain, M; Schwarzer, J; Zmrhal,V. Vzduchotechnika. Praha: *Evropský sociální fond*, **2009**.
13. Katunský, D; Katunská, J; Bullová, I. Solution of the air flow in the ventilated facade and its effect on the thermal characteristics of the peripheral wall, in: 18 th International Multidisciplinary Scientific GeoConference, SGEM **2018**; Albena; Bulgaria, Code 142873, ISBN, 978-619-7408-52-2, DOI: 10.5593/sgem2018/6.3/S27.091
14. Muehleisen, R.T; Patrizi, S. A new parametric equation for the wind pressure coefficeint for low-rise buildings. *Energy and buildings*, **2013**. https://doi.org/10.1016/j.enbuild.2012.10.051
15. Ginger, J. D. Internal pressures and cladding net wind loads on full-scale low-rise building. *Journal of structural engineering*, **2000**. DOI: 10.1061/(ASCE)0733-9445(2000)126:4(538)
16. Chen J.H; Chen, CH.H. A study on the wind pressures of the partial enclosed buildings in the view of net pressures. Taipei: *The seventh Asia-Pacific conference on wind engineering* **2009**. http://14.139.190.172/cgi-bin/koha/opac-detail.pl?biblionumber=6583&shelfbrowse_itemnumber=6583
17. Thampi, H; Dayal, V; Sarkar, P. P. Finite element modeling of interaction of tornado with a low-rise timber building. North Carolina: *The fifth international symposium on computational wind engineering*, **2010**. https://www.researchgate.net/profile/Vinay_Dayal/publication/267545369_Finite_element_modeling_of_interaction_of_tornado_with_a_low-rise_timber_building/links/5464bb840cf2a8cf007bffed.pdf
18. Cóstola D; Blocken B; Hensen, J.L.M. Overwiev of pressure coefficient data in building energy simulation and airflow network programs. *Building and Environmemnt*, **2009**. https://doi.org/10.1016/j.buildenv.2009.02.006
19. Montazeri H; Blocken B. CFD simulation of wind-induced pressure coefficients on buildings with and without balconies: Validation and sensitivity analysis. *Building and Environment*, **2013.** https://doi.org/10.1016/j.buildenv.2012.11.012
20. STN EN 1991-1-4: **2007**, Eurocode 1: Actions on structures. Part 1-4: General actions. Wind actions, https://www.phd.eng.br/wp-content/uploads/2015/12/en.1991.1.4.2005.pdf

21. Richards, P. J., and R. P. Hoxey. Wind loads on the roof of a 6 m cube. *Journal of Wind Engineering and Industrial Aerodynamics* 96.6-7 **2008**: 984-993. https://doi.org/10.1016/j.jweia.2007.06.032
22. Bitsuamlak, G; Tecle, A. S. Full-scale external and internal pressure measurements for a low-rise building. Florida international university, **2009**. http://www.ihrc.fiu.edu/wpcontent/uploads/2012/05/HLMP
23. Doudak G; McClure G; Smith, I. Stathopulos, T. Comparison of field and wind tunnel pressure coefficients for a light-frame industrial building. *Journal of structural engineering*, **2009**. https://ascelibrary.org/toc/jsendh/135/10
24. Al Zoubi F; Li, Z; Wei, Q; Sun, Y. Wind tunnel test and numerical simulation of wind pressure on a high-rise building. *Journal of Chongqing University*, **2010**. ISSN 1671-8224. http://www.cnki.com.cn/Article/CJFDTotal-CQDX201001008.htm
25. Amin, J. A; Ahuja, A. K. Experimental study of wind-induced pressures on buildings of various geometries. International *Journal of Engineering, Science and Technology*, **2011**. https://www.ajol.info/index.php/ijest/issue/view/8314
26. Amin, J. A; Ahuja, A. K. Effects of side ratio on wind-induced pressure distribution on rectangular buildings. *Journal of Structures*, **2013**. https://doi.org/10.1155/2013/176739
27. Ginger J. D; Letchford, C. W. Net pressures on a low-rise full-scale building. *Journal of wind engineering and industrial aerodynamics***, 1999.** https://doi.org/10.1016/S0167-6105(99)00075-6
28. Bielek M., Bielek B. Aerodynaická kvantifikácia budovy pre určenie prietoku vzduchu a energetického režimu prirodzeného fyzikálního medzipriestoru, In: *7. vedecká konferencia Budova a energia 2007*, Podbanské 5.-7.12.**2007**.
29. Bielek , M; Černík, P; Tajmír, M. Aerodynamika budov. Fyzikálne problémy účinkov vetra na budovy a ich okolie. Bratislava: ALFA, **1990**. ISBN 80-05-00632-2.
30. Holmes, J. D. Mean and fluctuating internal pressures induced by wind. Colorado: Proceedings of 5th AIVC, **1979**. https://www.aivc.org/sites/default/files/members_area/medias/pdf/Airbase/airbase_00824.pdf
31. EN ISO 12569: Thermal performance of buildings and materials — Determination of specific airflow rate in buildings — Tracer gas dilution method **2017** https://www.iso.org/standard/69817.html
32. Benedettelli, M; Naticchia, B; Carbonari, A.; Pascucci, M; Testing of a Tracer Gas Based Measurement Procedure to Assess Air Change Rates in Buildings.**. 2015,** 10.22260/ISARC2015/0025
33. Sherman M. H., Tracer gas techniques for measuring ventilation in a single zone, Building and Environment, Vol 25, No 4,p. 365-374. **1990**, ISSN 0360-1323, https://doi.org/10.1016/0360-1323(90)90010-O
34. Persily, A. Evaluating building IAQ and ventilation with indoor carbon dioxide. Transactions American society of heating refrigerating and air conditioning engineers, pp. 193-204. **1997** https://www.osti.gov/biblio/349956-evaluating-building-iaq-ventilation-indoor-carbon-dioxide
35. Kisilewicz, T., Nowak-Dzieszko, K. Low airflow measurements by means of gas tracing method. IOP Conference Series*: Materials Science and Engineering,* 415 (1), art. no. 012030, **2018** DOI: 10.1088/1757-899X/415/1/012030
36. Nowak, K., Nowak-Dzieszko, K., Marcinowski, A. Analysis of ventilation air exchange rate and indoor air quality in the office room using metabolically generated CO_2.IOP Conference Series: *Materials Science and Engineering, 415 (1)*, art. no. 012028, **2018**, DOI: 10.1088/1757-899X/415/1/012028
37. Weining, Z.,et al. "Test on Ventilation Rates of Dormitories and Offices in University by the CO_2 Tracer Gas Method." *Procedia Engineering*, vol. 121, 2015, pp. 662–666, doi:10.1016/j.proeng.2015.08.1061
38. Cui, S.,Cohen,M., Stabat,P., Marchio,D.,CO_2 tracer gas concentration decay method for measuring air change rate, *Building and Environment*, Volume 84, **2015**, Pg. 162-169, https://doi.org/10.1016/j.buildenv.2014.11.007
39. Laussmann, D; Helm, D. Air Change Measurements Laussmann, D; Helm, D. Air Change Measurements Using Tracer Gases: Methods and Results. Significance of air change for indoor air quality. *Chemistry, Emission Control, Radioactive Pollution and Indoor Air Qualit*y SP. ED1 - Nicolas Mazzeo. **2011**, DOI: 10.5772/18600, Rijeka. https://doi.org/10.5772/18600
40. Katunský, D., Nemec, M., & Kamenský, M. Airtightness of Buildings in Slovakia. In *Advanced Materials Research* (Vol. 649, pp. 3-6). Trans Tech Publications Ltd. **2013,** https://www.scientific.net/AMR.649.3
41. Ferdyn-Grygierek, J., Baranowski, A., Blaszczok, M., & Kaczmarczyk, J. Thermal diagnostics of natural ventilation in buildings: An integrated approach. *Energies*, *12*(23), 4556, **2019** https://doi.org/10.3390/en12234556

42. Weerasuriya, A. U., Zhang, X., Gan, V. J., & Tan, Y. A holistic framework to utilize natural ventilation to optimize energy performance of residential high-rise buildings. *Building and Environment*, *153*, 218-232. **2019** https://doi.org/10.1016/j.buildenv.2019.02.027
43. Craig, S. The optimal tuning, within carbon limits, of thermal mass in naturally ventilated buildings. *Building and Environment*, *165*, 106373. **2019** https://doi.org/10.1016/j.buildenv.2019.106373
44. Conceição, E., Gomes, J., & Awbi, H. Influence of the airflow in a solar passive building on the indoor air quality and thermal comfort levels. *Atmosphere*, *10*(12), 766. **2019** https://doi.org/10.3390/atmos10120766
45. Raji, B., Tenpierik, M. J., Bokel, R., & van den Dobbelsteen, A. Natural summer ventilation strategies for energy-saving in high-rise buildings: a case study in the Netherlands. *International Journal of Ventilation*, 19(1), 25-48. **2020** https://www.tandfonline.com/doi/full/10.1080/14733315.2018.1524210
46. Fahad Alomirah, H.; Moda, H.M. Assessment of Indoor Air Quality and Users Perception of a Renovated Office Building in Manchester. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1972. doi: 10.3390/ijerph17061972
47. Tam, C.; Zhao, Y.; Liao, Z.; Zhao, L. Mitigation Strategies for Overheating and High Carbon Dioxide Concentration within Institutional Buildings: A Case Study in Toronto, Canada. *Buildings* **2020**, *10*, 124. DOI: 10.3390/buildings10070124
48. Lu, C.-Y.; Lin, J.-M.; Chen, Y.-Y.; Chen, Y.-C. Building-Related Symptoms among Office Employees Associated with Indoor Carbon Dioxide and Total Volatile Organic Compounds. *Int. J. Environ. Res. Public Health* **2015**, *12*, 5833-5845. https://doi.org/10.3390/ijerph120605833
49. Stabile, L.; Massimo, A.; Canale, L.; Russi, A.; Andrade, A.; Dell'Isola, M. The Effect of Ventilation Strategies on Indoor Air Quality and Energy Consumptions in Classrooms. *Buildings* **2019**, *9*, 110. doi:10.3390/buildings9050110