Low airflow measurements by means of gas tracing method

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Abstract. Tracer gas dilution decay method is a convenient tool for measurement of actual air exchange in building. The article presents the results of measurements of natural air exchange in the selected, airtight rooms. A two-point and multi-point method were used to collect data and calculate the results. The standard procedure for the selection of the optimal measurement time was also included. In tight spaces with low air exchange, the measurement results depend on the assumed duration of measurements. It was found that the duration of measurements of several hours and the multipoint method allow to obtain convergent results.

1. Introduction

Building air tightness became one the most important features of contemporary low energy buildings. Reduction of heat losses connected with air exchange is a necessary measure on the way to building low energy demand. Such a reduction is possible only when air exchange is controllable and such a control is possible only when building external envelope is air tight and expected air exchange is carried out through specially designed for this purpose openings and components of the installation. The aim of the ventilation is to maintain a proper hygienic conditions inside the space by introducing outdoor air into the room. In term of energy savings, it is also important to keep ventilation at the required rate to reduce heat losses. Air tightness of the building is necessary because it allows to avoid or minimize uncontrolled flow of air (and heat) through gaps and cracks in the building envelope. Penetration of warm, moist air across the building structure can be also a reason of interstitial condensation of water vapour, which results in decreasing of thermal insulation and durability of building envelope [1]. Uncontrolled cold air penetration to the inside decreases indoor microclimate conditions, causing local drafts and additional heat losses. This effect is even more important in low energy and passive buildings, where all kinds of heat losses should be minimized. In some cases, the achievement of the expected energy standard without a tight enclosure would be impossible, despite efficient thermal insulation and mechanical ventilation with heat recovery [2].

Airtight building demands special solutions and materials at design stage, extreme care and special experience at construction stage and experimental testing, finally.

One of the acts implementing the European Directive 2010/31/EU to Polish building law is regulation introduced by Ministry of Infrastructure. This regulation strengthens the requirements concerning building envelope insulation and reduction of primary energy demand. In accordance with this regulation, in residential, commercial and industrial buildings, all the opaque envelope elements and their joints must be designed and constructed to ensure complete tightness. Polish regulation recommends airtightness measurements and determination of $n_{50}$ coefficient, but this kind of testing is not obligatory.
The most popular method of building tightness evaluation is currently the pressure method, according to standard EN 9972 [3]. It allows to assess tightness of the outer building envelope in the artificially created conditions of a considerable pressure difference between the interior and the building’s external environment. It is a form of envelope quality diagnostics, but the assessment of actual air exchange in a building, especially with gravitational ventilation system and under real climatic conditions is still unknown. Approximate way of transition from pressure method to time averaged real conditions is included in EN 13789 [4]. In order to evaluate actual air exchange, gas tracing dilution methods have been developed and standardized EN ISO 12569 [5]. Practical aspects and problems connected with tracer gas concentration decay method will be discussed in this paper.

2. Air mixing and stratification
Standard [5] introduces three different tracer gas measurement methods:
- concentration decay method – the ventilation rate is obtained from the decaying curve of concentration observed after the end of the injection of tracer gas,
- continuous dose method – the ventilation rate is obtained from the concentration resulting from continuous injection of tracer gas,
- constant concentration method – the ventilation rate is obtained from the injection rate of tracer gas dosed for constant concentration in the space.

Selection of the method depends on building structure, ventilation system, fluctuations in ventilation rate and of course on the available testing equipment.

Tracer gas method may be used for determination of infiltration and ventilation rate, evaluation of ventilation efficiency, pollutant distribution, internal air flows between zones etc. [1,2,5,13,14,15,16]. According to the standard [5] the most commonly used tracer gases include: sulphur hexafluoride, nitrogen monoxide, carbon dioxide and helium. None of the tracer gases used in practice meets all of the ideal gas requirements. Two gases that are currently most often used for this purpose are: sulphur hexafluoride and CO₂. Due to easy access, relatively low costs of measuring equipment, security and versatility and easy mixing, the authors used in their research carbon dioxide. Measurements with the same tracer gas were described in [9,10,13,14,16]. Equipment used for concentration measurement is shown in figure 1. The Rotronic meter measures CO₂ concentration within the range of 0 to 5000 ppm with the accuracy of 30 ppm + 5% sensor indication. The temperature measurement range is -20 ÷ 60°C with an accuracy of up to 0.3K.

Figure 1. Carbon dioxide concentration meter Rotronic CP11 used for measurements [www.rotronic.pl].

Carbon dioxide is one of the natural compounds of atmospheric air. It is an odourless, colourless non-flammable gas, heavier than the air. The density of carbon dioxide is almost 1.5 higher than that of air. Present concentration of gas in the atmosphere is approximately 400 ppm (points per million). The use of carbon dioxide for measurements as a tracer gas requires therefore raising its initial concentration well above this value. This can be done by releasing compressed gas from the container or by exhalation by people.

The first difficulty in conducting the measurements is connected with the assumption of single zone measurement in case of multi-space building [15]. According to the European standard the uniformity of concentration within the tested space is obligatory. The concentration of tracer gas should not fluctuate more than 10% from the average value within the tested zone [5]. To meet this assumption forced mixing of air within the building seems to be necessary. In multi room zone data should be recorded separately in each room. Figure 2 presents the results of measurements conducted in office
room, 3.5 x 4 m, with gravitational ventilation, by means of six gas detectors. Fresh air was supplied and exhausted by infiltration only.

Figure 2. Percentage deviation of CO$_2$ concentration in tested room versus time.

CO$_2$ detectors were located at different height (sensor 1: 2.3 m, sensor 2: 1.7 m, sensor 3: 1.2 m, sensor 4: 0.6 m, sensor 5: 0.0 m) and in different parts of the room. Data have been gathered and stored at 10 minute intervals. Air was initially mixed. One can observe gradual increase in stratification of CO$_2$ in time. At the end of the recorded measurements, after 48 hours, all the fluctuations were still within the acceptable range but the deviations have doubled. A small but regular variation of CO$_2$ concentration in altitude was observed: above the floor (up to 1.2 m) concentration was lower than the average value and in case of the two higher located sensors recorded concentration it was higher. This tendency was getting stronger in time. It does not seem to be logical when only gas density is considered (higher density of CO$_2$ than of air), but the real mechanisms that influence the distribution of gases are much more complicated. More important than gravitational sorting is diffusion, convection and turbulences [6]. As a result air is quite well mixed and we have a chance to breath lighter than CO$_2$ oxygen even in the lowest part of atmosphere. In case of the specific building space also the other aspects of air movements within the tested space should be considered: thermal stratification, location of inlets and outlets, wind pressure distribution, ventilation shortcuts etc.

When mixing process is carried out also during the measuring period, it may affect the measured ventilation and infiltration rate, if airflow emitted from a fan directly impinges on the leakage areas in buildings [5,7,8,15].

3. Concentration 2-point decay method

In 2-point decay method the time-mean air change rate is calculated from the measurement start point to the end point. The minimum or maximum time step that should be used are not directly specified. Time-mean specific airflow rate can be calculated using the following formula [5]:

$$\bar{N} = \frac{1}{t_2 - t_1} \log_e \frac{C(t_1)}{C(t_2)}$$  \hspace{1cm} (1)

where:

$\bar{N}$ \hspace{0.5cm} mean time specific airflow rate, [1/h]

$C(t_1)$ \hspace{0.5cm} room gas concentration at “$t_1$”, [m$^3$/m$^3$]

$C(t_2)$ \hspace{0.5cm} room gas concentration at “$t_2$”, [m$^3$/m$^3$]

$t_1$ \hspace{0.5cm} start point of measurement, [h]
t₂ end point of measurement, [h].

According to the European standard 12569 [5] in order to achieve a good precision of measurements, the difference between initial concentration of tracer gas and at the end of test should be "sufficiently greater" than the equipment measurement error. What is a specific feature of the two-point concentration approach, the measurement method permits temporal change in ventilation rate which is in fact inevitable in real testing conditions lasting for many hours.

Presented and discussed below results of measurements have been carried out in office space, designed for four people performing light work and using desktop computers. Tested office is located on the second floor of the five-storey building. External wall of this space with two large windows is oriented north, figure 3. Doors with dimensions of 0.85 x 2.00 m are located in the southern wall of the room. Office space is ventilated by gravitational system with air supply via infiltration through windows and exhaust through ventilation duct of 18 x 18 cm, placed at a height of 2.35 m above floor.

Figure 3. Tested office room and location of the 3 CO₂ sensors [9].

Three CO₂ Rotronic meters have been located as shown in figure 3, at least 2 meters away from office workers, who were the only source of carbon dioxide in this tests [10]. Two meters (1 and 3) were placed at the same height, i.e. 0.75 m above the floor, the last one (2) on the shelf, 1.75 m above the floor. Presented below results of carbon dioxide concentration were averaged for these 3 meters. Observed concentration differences always remained within the required range of 10%.

Figure 4 shows gradually increasing concentration of exhaled gas during the working day, up to 2000 ppm. Irregular changes of diagram, especially the concentration drops were caused by window opening and changing number of occupants. It should be noted that all the time concentration values significantly exceeded the requirements set in this respect for office rooms (1000 ppm) [10]. Indoor air quality in this room was very poor, gravitational ventilation practically did not work in test conditions.
Continuous carbon dioxide decay started at 4.00 pm, when all the office workers left room at the same time for business trip. Initial concentration at this moment, metabolically generated earlier by four people working in the office room, was 1472 ppm, figure 5.

The process of concentration decay was very slow, due to inefficient ventilation. Decay curve has the form of a regular exponential function. After 24-25 hours (150 readings) CO$_2$ concentration decay may be practically treated as linear function when internal concentration value, ca. 500 ppm, is still higher than the external (400 ppm).

External air temperature on Friday, September 29-th, recorded by the automatic meteorological station in ca. 500 m distance from monitored building [http://meteo.ftj.agh.edu.pl].
Meteorological data for testing period have been measured by automatic station belonging to nearby located AGH University and are available on the university’s website. Figure 6 shows the daily values of the external air temperature during the first day of measurement. Cyclic temperature changes are of a sinusoidal nature. Diurnal average air temperature was equal to 10.73 °C, minimum value 5.14 °C and maximum 17.04 °C. On the second day of testing thermal conditions were similar with average temperature 10.65 °C. Diurnal average wind speed was 1.28 m/s with prevailing direction: east-south. Based on the meteorological data review, it can be proved that the external conditions around the building were subject to the moderate and regular changes. If stack effect is considered as a most important driving force of natural ventilation it should follow the regular external air temperature fluctuation, figure 6. However, the internal air temperature was also subject to minor changes because of the weekend set back temperature. On Friday at 3.00 pm. it was equal to 20.4 °C and 48 hours later only 17.7 °C.

Figure 7 shows the values of mean specific airflow rate versus duration of the measurement period, calculated by means of two point decay method. According to the European standard, airflow rate is always calculated for the whole period, from the measurement start point to the end point.

![Figure 7](image-url)  
**Figure 7.** Calculated specific air flow rate vs. length of measurement period, two point decay method.

The results strongly depend on the length of the measurement period. Airflow rate is in the tested office space extremely low. Low airflow rate explains why during the working hours the concentration of exhaled carbon dioxide increased so intensely even though users were opening windows. Additionally it must be expected that the accuracy of measurement of such a small value will be low.

Time mean specific airflow rate changes strongly with the length of the measurement period. Observed changes do not follow fluctuation of external air temperature. The most important issue for the person conducting the measurements is the question what is the right time of measurements, and consequently which of the results shown in the graph is correct.

The standard [5] provides an iterative procedure for estimating the optimum decay time $T_m$ which minimizes the estimation error. Gas concentration measurement variance is specific to the used equipment, so the minimum of the propagation error function has been found. For two-point decay method the following equation should be applied:

$$ (N \cdot T_m)_{np=2} = 1.108 \, 857 \, 552 \, 88 \ldots $$  

where $N$ is the initially estimated value of specific airflow.

The optimum decay time $T_m$ is determined from equation (2) and then used to read appropriate CO₂ concentration value. Based on the selected values of gas decay a new value of airflow may be calculated [11]. If the difference between initial estimation and calculated $N$-value is lower than 5% of calculated
value, the result can be considered acceptable. If not, the whole procedure should be iteratively repeated with the calculated N-value substituting the initially estimated one.

In case of the considered measurements it was assumed that \(N_{\text{est}}\) is equal to 0.1 [1/h], so the optimum decay time \(T_m\) is 11.09 h. Low air exchange rate means that the optimum time of measurement must be very long. Carbon dioxide concentration at 3.10 am (11 hours and 10 minutes after 16.00 pm) was 665 ppm. \(N_{\text{calc}}\) value for this period is equal to 0.066 1/h. Difference between \(N_{\text{est}}\) and \(N_{\text{calc}}\) is bigger than 5%, so the new \(N_{\text{est}}\) value is equal now to 0.066 1/h. The next \(T_m\) value calculated on this basis is equal to 16.8 hours, concentration at 8.50 is 557 ppm and \(N_{\text{calc}} = 0.055\) 1/h. Because the difference of 17% is still significantly bigger than 5%, the next iteration is necessary. The third \(T_m\) value calculated on the new basis is equal to 20.16 hours, concentration at 13.30 is 520 ppm, \(N_{\text{calc}} = 0.049\) 1/h and the difference equal to 11%. After the fourth iteration \(N_{\text{calc}}\) is 0.044 1/h and difference 10 %, after the fifth step \(N_{\text{calc}} = 0.041\) 1/h and difference 7%. Because the acceptable results were not obtained after “few steps” (required convergence was not achieved), the measurements should be taken again.

In case of the selected room, its ventilation systems and atmospheric conditions during the tests, it turned out that obtaining a reliable result is difficult or even impossible. In the conditions of light wind and a small temperature difference in the tested airtight room there was hardly any air change. During the second day of measurements, air temperature inside the building was only 1 K higher than the maximum outside temperature. With such small driving forces of air infiltration, each change in conditions translated instantly into the result of measurements. Figure 8 shows the results of measurements carried out according to a very specific scenario. It was assumed that airflow testing lasted for one hour only and was conducted for each hour separately. The results of measurements made at one-hour interval are listed next to each other, figure 8. The diagram shows how the air exchange rate based only on short 1-hour measurements, would depend on the chosen moment of measurement.

![Figure 8. Calculated specific air flow rates for one hour measurement periods.](image)

The airflow values, calculated for one hour intervals, differ significantly, although the graph of concentration decay shown in the figure 5 gives the general impression of a continuous and regular line. However, in case of extremely low air exchange in tested space and long lasting decay time, even the small momentary fluctuations of concentration may result in a noticeable change of airflow measure. The aim of above analysis was only to check the variance of short period data and to prove that such a testing approach is useless.

4. Multi-point concentration decay method

The multi-point concentration decay method can be used when the gas concentration decay process can be measured multiple times at intervals ranging from several minutes and around one hour [5,11]. Currently available measuring devices allow to record easily a big amount of data even every couple of minutes. An important assumption of this method is that the ventilation rate does not fluctuate over time. The least square method is applied when multi-point concentration decay method is used [5]. In the multi-point concentration decay method the specific airflow rate is calculated using equation (3).
\[
N = \left( \sum_{j=1}^{n_p} t_j \right) \cdot \left( \sum_{j=1}^{n_p} \log_e C(t_j) \right) - n_p \cdot \left( \sum_{j=1}^{n_p} t_j \cdot \log_e C(t_j) \right) \\
2n_p \cdot \left( \sum_{j=1}^{n_p} t_j \right)^2 \left( \sum_{j=1}^{n_p} t_j \right)^2
\]

where:

- \( N \) estimated specific airflow rate,
- \( t_j \) j-th elapsed time from the beginning of decay process, \( t_1 = 0 \),
- \( C(t_j) \) measured gas concentration at time \( (t_j) \),
- \( n_p \) total number of measured elapsed time points (\( n_p \) is \( \geq 3 \)).

Based on the data recorded during the above presented test, the multi-point decay rate was calculated for two intervals of sampling: \( \frac{1}{2} \) hour and 1 hour, table 1.

### Table 1. Airflow rate calculated by means of multi-point concentration decay method

| decay period | interval | number of samples | \( N \) [1/h] |
|--------------|----------|------------------|---------------|
| 3 hours      | \( \frac{1}{2} \) hour | 7                | 0.0757        |
| 3 hours      | 1 hour   | 4                | 0.0753        |
| 5 hours      | \( \frac{1}{2} \) hour | 11               | 0.0736        |
| 5 hours      | 1 hour   | 6                | 0.0735        |
| 10 hours     | 1 hour   | 11               | 0.0693        |
| 11 hours     | \( \frac{1}{2} \) hour | 23               | 0.0678        |
| 11 hours     | 1 hour   | 12               | 0.0672        |

Results of calculation do not practically depend on the selected interval of measurements, but they are slightly sensitive to the length of sampling period. The measurement time of up to 5 hours allows obtaining convergent measurement results. However, further extension of the measurement period causes that the difference between successive results increases, reaching the value of more than 11% difference in case of 11-hour measurement. This result is no longer acceptable, although 11 hour sampling period is still much shorter than the optimum time \( T_m \) (15 hours) according to the earlier mentioned standard procedure. Once again, it should be stated that low airflow rate is the cause of measurement problems and significant difficulties with convergence of the results.

### 5. Conclusions.

Measurement of air exchange with the trace gas method requires specific knowledge, experience and practical skills from the person carrying out the measurements.

The method of conducting the measurements must to some extent be matched to the properties of the tested object. This applies, for example, to the choice of two or multi-point method.

Particular difficulties arise when very tight building is tested. Measurement of the small values usually involves big difficulties. In the case of the low airflow rate (below 0.1 h\(^{-1}\)) it may be difficult to obtain convergence of results and final definite result of measurements, especially when using two-point decay method.

Results of measurements are sensitive to the sampling time. The optimum decay period, suggested by the standard procedure to minimize the effects of concentration measurement errors, is in case of a tight building very long and does not help to achieve expected accuracy. As it was stated in European standard EN ISO 12569, the concentration decay measurements should not last longer than several hours. These two approaches are in fact contradictory in case of a low airflow. Authors observed that testing period longer than 6 hours is not improving accuracy of the results.
It was not possible to isolate in the above presented results the impact of the changes of external conditions. It can be expected, however, that the change in the outside temperature could have resulted only in a limited change of the air infiltration to the tight space. Such fluctuations may additionally complicate testing process in a way that is difficult to predict. The above results, obtained for two and multipoint measurement method and sampling period 3-6 hours, are pretty close to each other. However, it must be stated that multipoint sampling method yielded more consistent results.

According to authors’ observations, after initial forced mixing uniform concentration of carbon dioxide in air was easily achieved and sustained in the tested spaces with low specific airflow.

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