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(Title) Checking of ventilation rates by CO_2 monitoring

(Authors) Lars E. Ekberg and Ove Strindehag

(Affiliation) Dept. of Building Services Engineering
Chalmers university of technology
S-412 96 Gothenburg, SWEDEN

CHECKING OF VENTILATION RATES BY CO_2 MONITORING

Synopsis

The present paper presents results from measurements of outdoor airflow rates and air change rates carried out simultaneously with measurements of the indoor concentration of carbon dioxide (CO_2) . The measurements were made both under controlled laboratory conditions and in the field. The field experiments were performed in a conference room, an assembly hall and an office room, and the laboratory investigation was carried out in a 19 m^3 test chamber.

CO_2 measurements can be successfully used to estimate the outdoor airflow rate in occupied rooms, but it is vital that the methodology takes into consideration a number of possible sources of errors. For example, it can not be presupposed that steady-state conditions prevail. However, inaccuracies due to non steady-state conditions may be reduced by a thorough analysis of the measurement results. Furthermore, it is demonstrated how the air change rate can be determined using a method based on analysis of the CO_2-concentration decay in a room.

1. Introduction

The concentration of CO_2 is frequently measured with the objective of indicating the indoor air quality or to check the outdoor airflow rates in buildings. Instruments for CO_2 measurements are often easy to use but, nevertheless, the applicability of the method is often disputed. Many of the difficulties with the interpretation of the results could be avoided by primarily regarding the method as a tracer gas method. It is also vital that the user has sufficient knowledge not only about the operation of the instruments, but also about the building and ventilation system where measurements are planned to take place.

The CO_2 concentration can be used as an indicator of pollutants from humans, and a CO_2 concentration of 1000 ppm is often referred to as a limit, below which the air quality can be regarded as acceptable. According to the olf/decipol concept [1] the limit 1000 ppm represents a situation where about 18% of persons not adapted to the pollution in question, i.e. visitors to the building, are dissatisfied with the air quality, see Figure 1.

However, the use of the CO_2 concentration as an air quality indicator is only valid in situations where the release of pollutants from sources other than humans is not a dimensioning factor. In rooms designed for a relatively high occupant density, air pollutants originating from the various indoor activities often have a dominant influence on the indoor air quality, while the importance of pollutants, for example, emitted from building materials can be expected to be confined to the first couple of months after a new building has been completed.

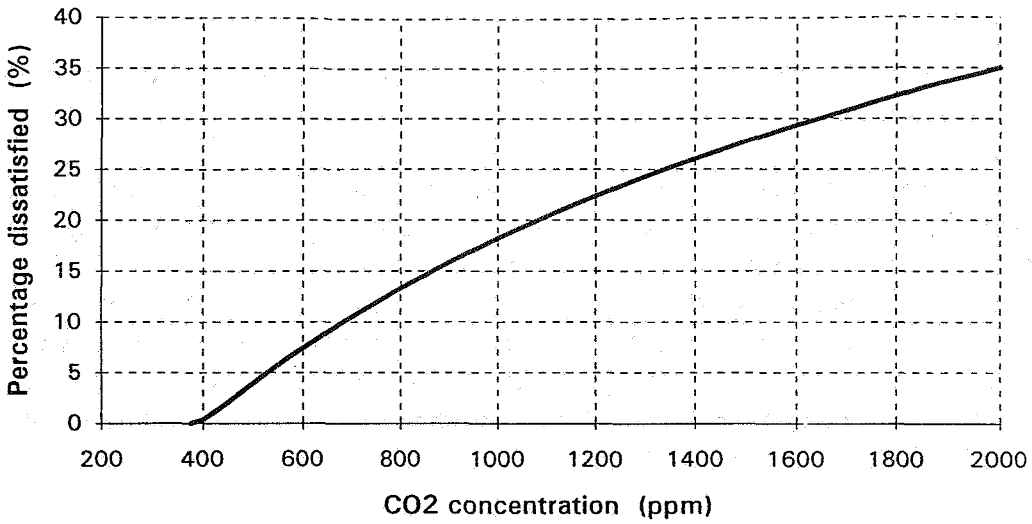

Figure 1. The perceived air quality as a function of the indoor CO_2 concentration. The function is based on the olf/decipol concept, and the calculation is carried out assuming an outdoor CO_2 concentration of 375 ppm and a CO_2 production of 18 $l \cdot h^{-1}$ per person.

Procedures for calculation of the outdoor airflow rate required to achieve an acceptable indoor air quality are available [2, 3]. Such calculations are based on knowledge about the relative importance of different types of pollution sources (e.g. building materials, office machines and persons) and assumptions about how the concentrations of the pollutants emitted from various sources should be added in order to describe the indoor air quality adequately. Although these assumptions differ between different recommendations, and often can be regarded as quite rough, the resulting recommendations are in approximate accordance. For example, The Nordic Committee on Building Regulations recommends 10.5 $l \cdot s^{-1}$ per person in offices without tobacco smoking [3], while The American Society of Heating Ventilating and Air-Conditioning Engineers suggests a minimum of 10 $l \cdot s^{-1}$ per person in the same type of room [4]. The calculation procedure presented in [2] results in recommendations over quite a wide span since a number of parameters, that may vary from case to case, are included in the calculations. The outdoor air quality, the pollution load from people depending on the physical activity and the pollution load from building materials are examples of parameters that should be considered using the olf/decipol concept.

Although different approaches are used, several international recommendations of minimum outdoor airflow rates lie between 7 and 10 $l \cdot s^{-1}$ per person. Significantly higher values are often recommended for rooms where tobacco smoking may occur, or in buildings where other strong pollution sources can be expected.

Several factors influence the prevalence of discomfort, allergies and other types of health related problems. The knowledge about these factors is still limited, but there are strong indications that there is a correlation between low outdoor airflow rates and discomfort and health problems. Thus, it is important to have access to methods for checking outdoor airflow rates. Two importrant features of such methods are that they should be both reliable and easy to use.

The present paper shows results from measurements of outdoor airflow rates and air change rates carried out simultaneously with measurements of the CO_2 concentration indoors. Field experiments were performed in a conference room, an assembly hall and an office room, and laboratory measurements were carried out in a full-scale test chamber. Typically, there is a good agreement between outdoor airflow rates obtained by steady-state CO_2 measurements and simultaneous measurements using calibrated throttle flanges. Furthermore, it is demonstrated how the air change rate can be accurately determined by analysis of the CO_2-concentration decay in a room.

2. Materials and Methods

The CO_2 data were collected using an instrument based on photoacoustic spectroscopy (PAS), which measures the absorption of infrared light at a wavelength of 4.4 μm. The instrument enables a maximum sampling frequency of 2 min^{-1} and a computer-controlled solenoid valve system enabled automatic switching between up to four sampling locations in sequence. The time required for switching between measurement locations, purging the sampling tube and taking a sample was about 2 minutes. According to the manufacturer the lowest detectable CO_2 concentration is 1.7 ppm and the repeatability of the measurement is ±1.7 ppm. The linearity of the output signal is ±1% and the inaccuracy of the measured concentration is estimated not to exceed ±5% of the measured value, including the inaccuracies in the calibration procedure.

The equipment described above was also used for measurements of sulphur hexafluoride (SF_6) used as a tracer gas. The detection limit for SF_6 is 0.005 ppm and the repeatability is ±0.005 ppm. The inaccuracy of the measured concentration is estimated not to exceed ±5% of the measured value, including the inaccuracies in the calibration procedure.

A part of the investigation was carried out in a test chamber with an internal free volume of 19.3 m^3. The airflow rate in the chamber can be varied between a few $l \cdot s^{-1}$ and about 50 $l \cdot s^{-1}$, which means that the chamber can be operated with air change rates up to about 10 h^{-1}. The airflow rate in the chamber was determined using a calibrated throttle flange in the exhaust air duct, over which the pressure drop was measured. The chamber was operated with a static pressure of +10 Pa relative to the ambient air. At this pressure the air leakage from the chamber through its envelope is 1.0 $l \cdot s^{-1}$. The inaccuracy of the measured airflow rate in the test chamber is estimated not to exceed ±5% of the measured value. Also in the field study, the airflow rates were determined using throttle flanges with a maximum inaccuray of ±5%.

3. Outdoor CO_2 concentrations

Figure 2 shows the result from measurements of CO_2 over an eleven-day period in the outdoor air 3 meters above ground level, outside an office building located close to a busy street in Göteborg. The CO_2 concentrations show pronounced variations with time, with office hour averages (8am - 5pm) between 348 and 416 ppm. The average concentration for the entire period presented is 377 ppm, and the maximum value is 435 ppm. Furthermore, it should be noted that the measured CO_2 concentrations show a significant co-variation with simultaneously measured concentrations of carbon monoxide. Carbon monoxide in the outdoor air can often be used as an indicator of traffic emissions. Consequently, there is a strong indication that the observed variations of the outdoor CO_2 concentration is a result of varying traffic intensity on the street close to the measurement location. Similar results have been presented previously [5], including the possible influence of both traffic and other outdoor pollution sources.

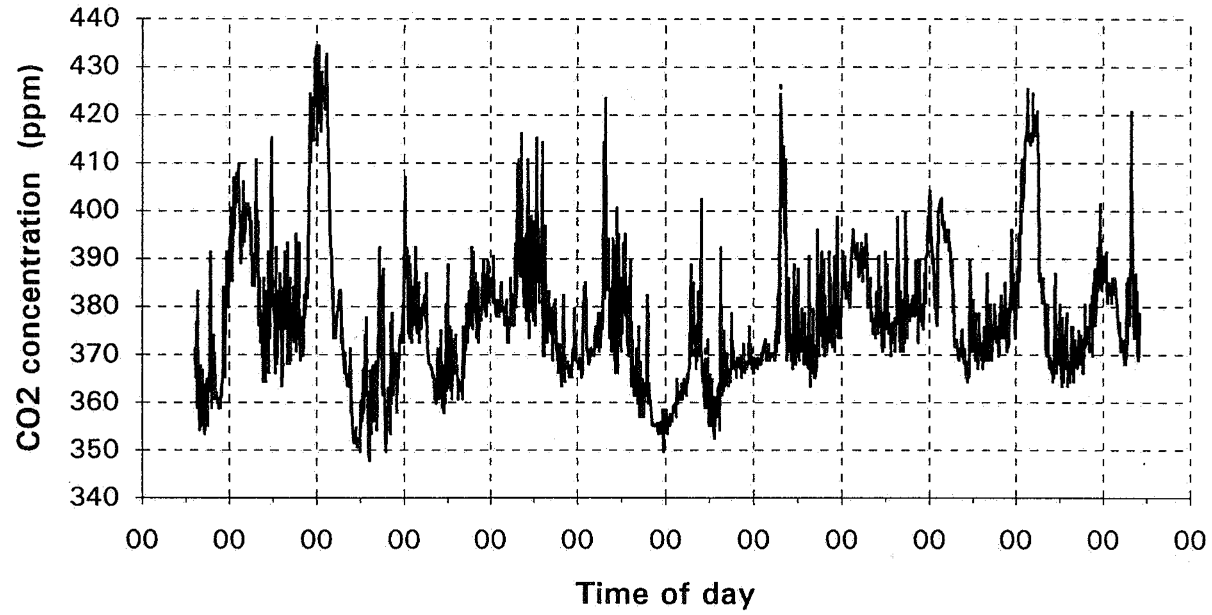

Figure 2. Concentrations of CO_2 outside an office building located close to a busy street in Göteborg.

Corresponding measurements of CO_2 were also carried out in a location not directly influenced by traffic or other sources of outdoor pollution. These measurements were made in the countryside about 25 km from the centre of Göteborg, and in this case the concentrations ranged from a minimum of 355 ppm up to a maximum of 375 ppm, with an average value of 363 ppm. This set of data did not show any drastic variations with time.

4. Occupant-generated CO_2

The human production of CO_2 and other bioeffluents have been found to vary approximately linearly with the level of physical activity [2, 4]. For adults the metabolic CO_2 production varies from about 10 $l \cdot h^{-1}$ per person when sleeping up to about 170 $l \cdot h^{-1}$ per person at high levels of physical activity. For persons at sedentary activities (1.0-1.2 met), such as office work, the CO_2 production is about 19 $l \cdot h^{-1}$ per person [2]. The corresponding figures according to [4] are 18 $l \cdot h^{-1}$ per person at a metabolic rate of 1.2 mets. However, the CO_2 production may vary between individuals depending on, for example, body weight. Physical activities in the range between sedentary and high level exercise correspond to the range 1 to 10 mets (1 met equals 58 W/m^2 skin area., i.e. approximately 100 W for an average person). Also the generation of olfactory pollutants can be expected to increase with the metabolic rate.

For children, the relationship between the CO_2 production and the metabolic rate is different compared to that for adults. In, for example, kindergardens an activity level of 2.7 met, corresponding to a CO_2 production of 18 $l \cdot h^{-1}$ per person is a realistic assumption [2]. Also in schools with children aged between 14 and 16 years, the CO_2 production is about equal to that for an adult at sedentary activity, 19 $l \cdot h^{-1}$ per person. It may be noted that, according to the same reference, the olfactory pollution load per person is about 20-30% higher for children than for adults producing the same amount of CO_2.

5. Determination of outdoor airflow rates

If a tracer gas is released at a constant rate in a room the steady state concentration in the exhaust air will equal the sum of the outdoor concentration and the concentration determined by the ratio between the tracer gas generation rate and the outdoor airflow rate. If the ventilation is characterised by complete mixing the steady state concentration will be equal in each location of the room.

As indicated in the previous section, a CO_2 production of 18 $l \cdot h^{-1}$ per person can be assumed in many cases. The outdoor airflow rate can then be calculated from equation (1) if the measurement is carried out under conditions of steady-state.

$$\dot{V} = \frac{5000}{C_i - C_o} \tag{1}$$

where

$\dot{V}$ = outdoor airflow rate $(l/s, p)$
C_i = indoor concentration (ppm)
C_o = outdoor concentration (ppm)

A prerequisite for a correct application of equation (1) is that neither of the following assumptions are violated:

-steady-state conditions prevail
-the CO_2 production is constant
-the outdoor concentration is correctly assessed
-the measured indoor CO_2 concentration represents the average concentration in the room.

Measurements in a conference room showed a good agreement between airflow rates measured using a throttle flange in the supply air duct and the airflow rates calculated from measured steady-state CO_2 concentrations. The measurements were carried out in 1991 in a location not directly influenced by outdoor sources of CO_2. The data presented below refer to measurements when the room was occupied by 14 adults at sedentary activities and it is assumed that the CO_2 production was 18 $l{\cdot}h^{-1}$ per person, and that the outdoor CO_2 concentration was 360 ppm. After 3 hours both the CO_2 concentration and the supply airflow rate were almost constant at 840 ppm and 145 $l{\cdot}s^{-1}$ respectively. From the CO_2 data the airflow rate could be calculated to 146 $l{\cdot}s^{-1}$.

Good agreement between measured and calculated airflow rates were also shown at tests carried out in an assembly hall dimensioned for 60 persons [6]. The ventilation of the hall is provided by a system with variable-air-volume (VAV system). The results from three tests performed with 30, 51 and 44 persons respectively are presented below. Steady-state conditions prevailed during the first two tests, while equilibrium was not reached during the last one.

With 30 persons in the hall, the measured CO_2 concentration was 750 ppm and the measured airflow rate was 430 $l{\cdot}s^{-1}$. A calculation of the outdoor airflow rate in a way corresponding to the procedure described above, gives a value that is 10% less, i.e. about 385 $l{\cdot}s^{-1}$. With 51 persons in the hall, the measured CO_2 concentration and the measured airflow rate was 820 ppm and 550 $l{\cdot}s^{-1}$ respectively, which is in good agreement with the calculated value 554 $l{\cdot}s^{-1}$.

As mentioned, equilibrium was not reached during the test with 44 persons in the hall. The test was terminated 50 minutes after the occupants entered the hall. At this time, the CO_2 concentration was 1020 ppm and the supply airflow rate 270 $l{\cdot}s^{-1}$. Considering the free volume of the hall (390 m^3), the CO_2 concentration can be expected to have reached about 87% of the steady-state concentration, assuming conditions of complete mixing. The calculated airflow rate will then equal 290 $l{\cdot}s^{-1}$, which is about 7% higher than the airflow rate measured with the throttle flange.

6. Non steady-state conditions

If equilibrium is not reached during the measurement period the data cannot directly be used for determination of the outdoor airflow rate. However, if the measurement period is sufficiently long, it is possible to make a more or less rough estimation of the steady-state concentration by regression analysis of the data using an exponential function. From the steady-state concentration calculated, the outdoor airflow rate can then be obtained using a mathematical relation similar to that shown in equation (1).

Field measurements

Other methods for analysis of non steady-state CO_2 concentrations can be based on determination of the time constant for the ventilation system. Such a method is to measure the decay of CO_2 when the room has been left unoccupied after a certain period of occupancy. Figure 3 shows the result from such a measurement carried out in an office room ventilated by mechanical exhaust ventilation. The sampling interval was 2 minutes and a sampling sequence with two samples in the exhaust air followed by one sample in the outdoor air was selected. The time constant obtained from this set of data is 0.58 h, which corresponds to an air change rate of 1.72 h^{-1}. Before an exponential curve was fitted to the measured indoor concentration the background outdoor concentrations were subtracted. Before the person left the room an attempt was made to mix the air by walking around in the room for a few minutes.

Figure 4 shows a simultaneously measured decay curve for the tracer gas sulphur hexafluoride (SF_6). The air change rate obtained by the SF_6 measurement is 1.64 h^{-1}, which deviates by 5% from the rate obtained by the CO_2 measurement.

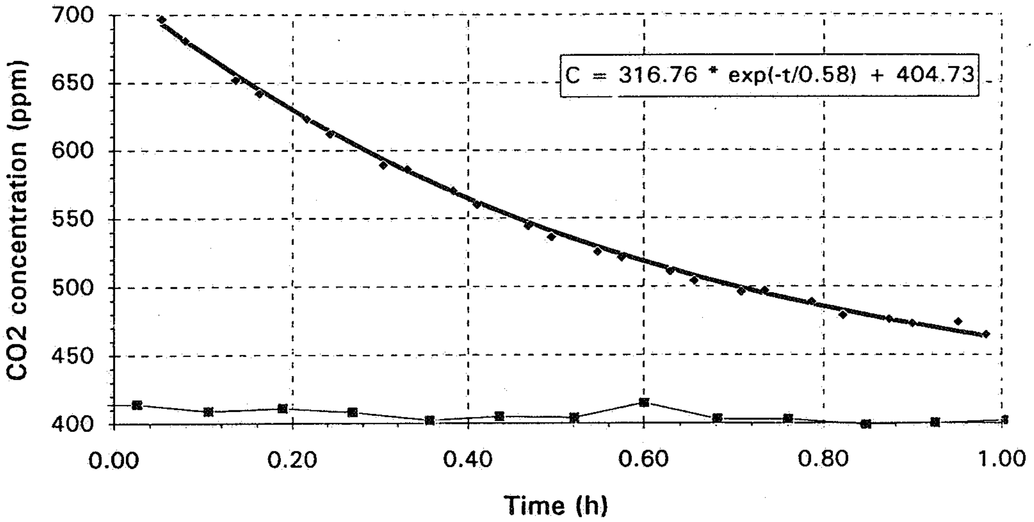

Figure 3. The CO_2 concentration in an office room with mechanical exhaust ventilation. Prior to the measurements the room was occupied by one person, who left the room at the time t=0.

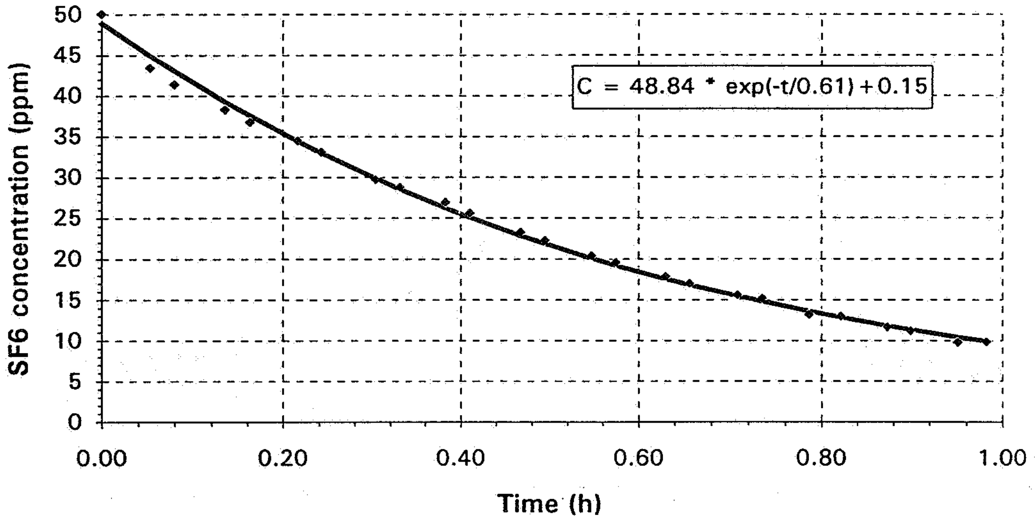

Figure 4. The decay of SF_6 measured in the office room simultaneous with the CO_2 concentration measurements shown in Figure 3.

Laboratory measurements

The results from measurements carried out in the test chamber described above are shown in Figure 5. The capacity of the supply air fan and the exhaust air fan were controlled in order to maintain an air change rate of about 2 h^{-1}. When using a throttle flange the exhaust airflow rate was determined to 10.8 $l \cdot s^{-1}$, while measurements using an exhaust-hood/anemometer attached to the exhaust outlet gave the result 10.2 $l \cdot s^{-1}$.

The period of occupancy was not long enough to reach concentration equilibrium, but the steady-state concentration (above the outdoor concentration) can be estimated to 497 ppm by extrapolation of the measured data. Under the assumption that the CO_2 production in the chamber was 18 $l \cdot h^{-1}$, this procedure indicates an outdoor airflow rate of 10.1 l/s. The time constant for the ventilation system is calculated to 27 minutes by analysis of the concentration decay curve measured after the person had left the chamber. The internal free volume of the chamber is 19.3 m^3, which gives an outdoor airflow rate of 12.1 l/s.

Since the air leakage through the envelope of the chamber is known (1.0 $l \cdot s^{-1}$ at a static pressure of +10 Pa) the results from all of the methods used can be compared. A summary of the outdoor airflow rates determined with the different methods is given in Table 1.

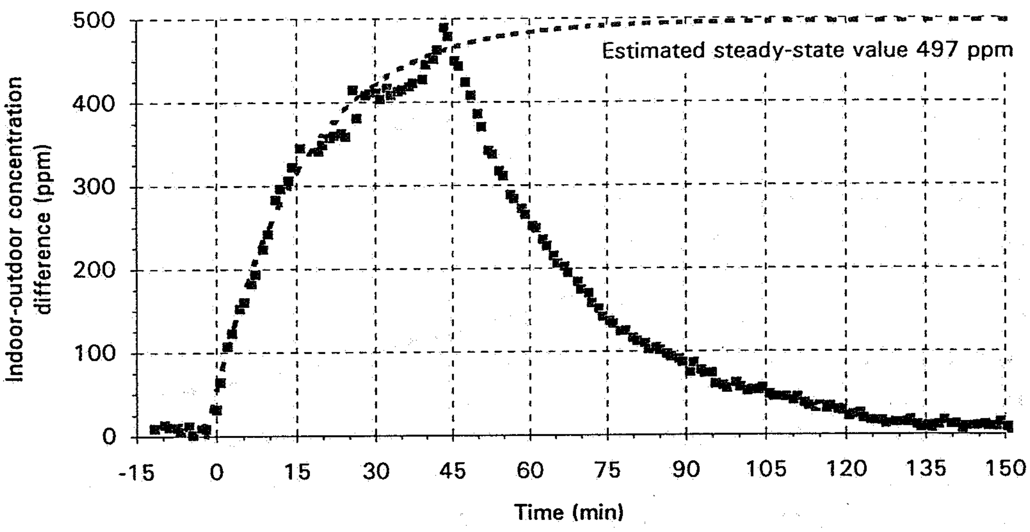

Figure 5. CO_2 concentrations measured in a full-scale test chamber. The broken line shows extrapolated data using an exponential function.

Table 1. The results obtained by different methods for determination of the outdoor airflow rate in the test chamber.

Method	**Outdoor airflow rate** ($l \cdot s^{-1}$)
Throttle flange	11.8
Exhaust-hood / anemometer	11.2
CO_2-concentration decay	12.1
CO_2 steady-state estimation	10.1

7. Discussion and Conclusions

Measurements of CO_2 concentrations indoors can be a valuable tool for determining the outdoor airflow rates and air change rates. However, there are a number of factors that may lead to unacceptable measurement errors, but accurate results can often be obtained if the planning of the measurements include consideration of these possible sources of errors. It is a prerequisite that the measurements are carried out by a person who

- is familiar with the operation of the instruments being used,
- is aware of the limitations of the method, and
- has sufficient knowledge about the building and the ventilation system where measurements are to be carried out.

It cannot be presupposed that the outdoor CO_2 concentration is constant with time, especially not in locations influenced by vehicle exhaust. In addition to traffic, industries and other outdoor sources may influence the CO_2 concentration in the outdoor air. Therefore, measurements in the outdoor air should be carried out continuously or at least before and after the indoor measurements. If more than one instrument is used in the same investigation, the correlation between the concentrations measured by the different instruments should be established.

Assessment of the outdoor airflow rate under steady-state conditions requires accurate information about the total CO_2 production in the room, and that occupancy is constant during a period long enough to allow the concentration to reach equilibrium. This is easily checked in single rooms, but may be practically impossible to check if the measurement is carried out with the objective of determining the airflow rate in a whole building.

The air change rate can also be accurately determined by analysis of the decay of the CO_2 concentration in a room. One prerequisite for this is that the initial concentration is sufficiently high compared to the outdoor concentration.

8. References

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