VENTILATION INTENSITY IN A HIGH-RISE BUILDING AFTER COMPLETE RETROFIT OF ITS ENVELOPE

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Abstract: Retrofit of the old building stock presents a good possibility to reduce the energy consumption. However, as the envelopes of old buildings become tighter, a risk increases that the fresh outside air supplied to the indoor environment by natural infiltration can decrease below the amounts required for a comfortable indoor environment, especially in buildings where mechanical ventilation has not been installed. This study presents an efficient method to measure the ventilation intensity, demonstrated on a 40-years old high-rise office building after a complete envelope retrofit. The well-established tracer gas decay and tracer gas step-up method were employed to obtain the ventilation intensity, using the natural CO_2 produced by the occupants as the tracer gas. The measured values of the air change rate were between 0.1 and 0.7 1/h for the simple façade, whereas it ranged from 0.2 to 0.5 1/h for the double skin façade, with the windows closed. The level of compliance with ventilation requirements varied, depending on the standard and the philosophy adopted.

Keywords: CO_2 concentration, Tracer gas, Air quality, Air change rate, High-rise building

1. Introduction

With regard to the enormous potential of energy savings for buildings, gradual strengthening of the requirements on the level of energy performance has been in progress in the EU [1]. In Central Europe, the major part of buildings energy is consumed for space heating, and better energy performance shall be achieved to large extent by decreasing the heat losses by transmission by thermal insulation, and by decreasing the heat losses by infiltration by tightening the building envelope. However, the subsequent reduction of the natural infiltration of the fresh outside air, which is still

being used as the main mean of ventilation in most buildings, results in deteriorated indoor air quality, and the amount of the fresh outside air supplied indoors may not comply with the requirements on the air quality in buildings. The present study demonstrates the possibility to measure the ventilation intensity indirectly; using the natural CO_2 produced by the occupants as the tracer gas, and shows an application of this method in a new high-rise building with a new energy efficient envelope.

2. Envelope of the high-rise building

The high rise building investigated in this study is the office building of the Faculty of Civil Engineering, Slovak University of Technology in Bratislava (*Fig. 1*). With respect to the poor physical and thermo-physical conditions of the original 40-year old façade, complete retrofit of the façade was carried out recently.
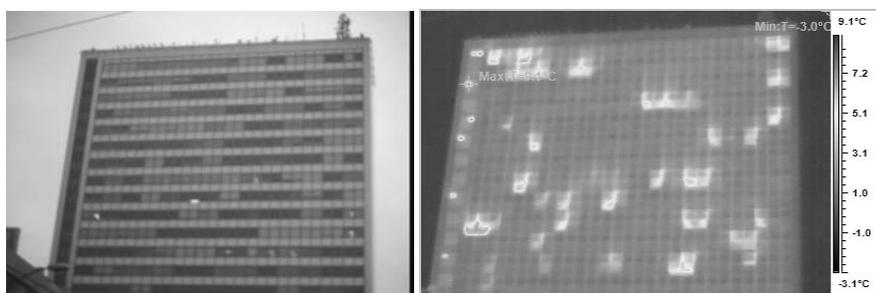
Fig. 1. View and infrared image of the double skin facade, facing South-East. The spots in the infrared image are caused by opening the inner windows into the gap between the two skins, *Photo: Michal Lukačovič*

On the North-West, the new façade is simple, with triple glazing and the possibility to open the windows to the exterior, whereas on the South-East it is a double skin façade, with a gap between the two windows, not providing any possibility to open the window directly to the exterior, but only to the gap (*Fig. 2*). Within the gap, the outside fresh air is allowed to flow, accessing the gap by openings in the façade. Both façade types contain blinds, which are installed on the inner window surface in the case of the simple façade, and in the gap between the windows in the case of the double skin façade.

3. Measurement location and measuring instruments

Two offices on the 6th floor, one with the simple and one with the double skin façade, and two offices on the 14th floor, one with the simple and one with the double skin façade, were investigated. The measuring device was a data logger, monitoring the room air temperature, relative air humidity and the CO_2 concentration. The loggers were installed in the selected offices at the working desk. For example, the location of the logger in the office C14/6 is in *Fig. 3*.
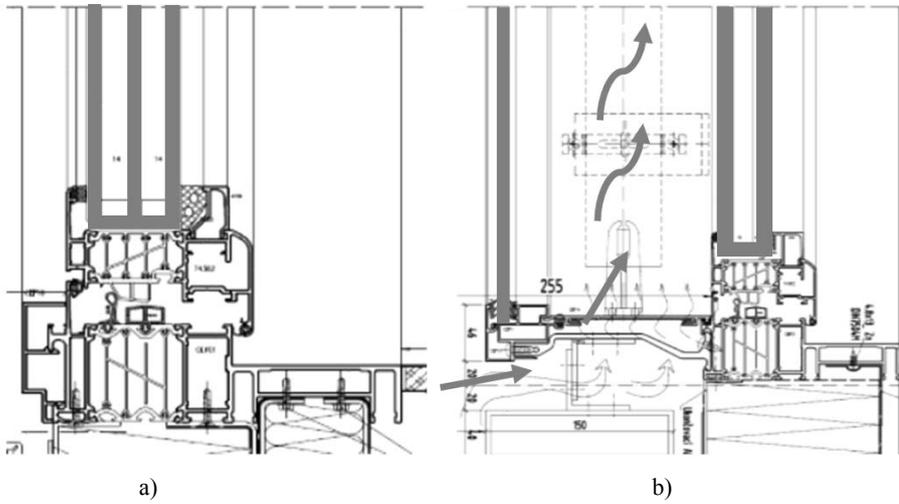
Fig. 2. a) simple façade facing North-West, b) double skin façade facing South-East
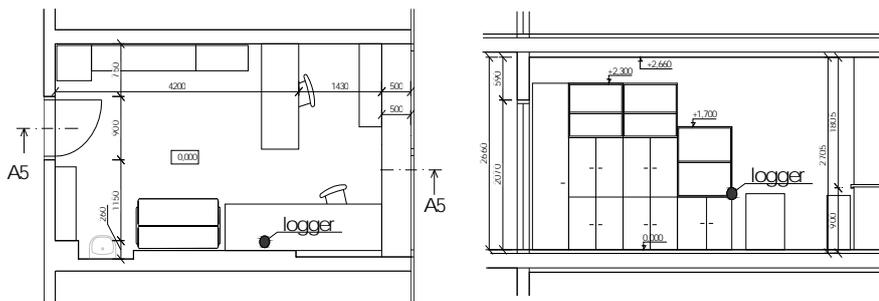

Fig. 3. Plan (left) and cross section (right) of the office C14/6 with the location of the data logger

Table I shows some of the characteristics of the offices considered in this study, relevant for the calculation of the ventilation requirements.

Table I

Some of the characteristics of the offices

Office no.	Facade	No. of occupants	Area m²	Volume m³	PCs	Carpet
C6/9	double	1	16.5	44	1	yes
C6/20	simple	1	17.6	48	1	yes
C14/6	double	1	18.3	49	1	yes
C14/19	simple	2	17.8	48	2*	yes

* One PC and one laptop. For simplification, the sensory pollution load was assumed equal for both.

4. Ventilation requirements

The required ventilation rates depend on the emission rates from pollution sources, on the requirements for acceptable indoor air quality based on health, comfort and performance, and on the philosophy adopted. An example of a difference in the philosophy adopted by different standards are the required ventilation rates prescribed by the European standard EN 15251 (2007) [2] and the American standard ASHRAE 62.1 (2007) [3]. While the ASHRAE requirements are based on perception of adapted people, the European requirements are for un-adapted people. The ventilation requirements are typically defined as the required fresh air supply in liters per second, m³ per hour, or as a number of air changes per hour. However, it is also possible to set the criteria as the maximum limit on the concentration of CO_2 indoors above the outdoor CO_2 concentration in ppm, or as the desired perceived indoor air quality in decipol [4]. The ventilation requirements, based on comfort criteria, as defined in different standards are shown in *Table II*, presented as the number of air changes per hour. The ventilation criteria for comfort are stricter than the ventilation criteria for health, thus it is assumed that when the comfort criteria are satisfied, the criteria on health are also satisfied.

5. Methodology of the infiltration measurements

The infiltration airflows were expressed as the air change rate, and were measured by tracer gas measurements. In these measurements, CO_2 was used as the natural tracer gas produced by the occupants. Two methods were used. The tracer gas step-up method, when the air change rate was calculated from the increasing CO_2 concentration due to the CO_2 produced by the occupants, and the tracer gas decay method, from the decreasing CO_2 concentration, when the occupants had left the room. A specifically designed questionnaire was distributed to the occupants to help interpreting the results of the CO_2 concentration. In the tracer gas step-up method, the ventilation intensity was calculated using the following equation:

$$C_i(t) = (C_0 - C_a) \cdot e^{-\lambda \cdot t_i} + C_a + \frac{E}{\lambda \cdot V_R \left(1 - e^{-\lambda \cdot t_i}\right)} , \tag{1}$$

where C_0 is the tracer gas concentration at the beginning on the measurement (kg/m³); C_a is the tracer gas concentration outside (kg/m³); λ is the air change rate (1/h); E is the amount of tracer gas emitted per unit time (m³/s); V_R is the volume of the room (m³); t_i is the time (h).

In the tracer gas step-up method, the room volume V_R, the tracer gas concentration outside C_a, the tracer gas concentration at the beginning of the measurement C_0 and the time t_i are known. When CO_2 is used as the tracer gas, the amount of CO_2 emitted by occupants can be estimated [5], [6]:

$$E = \frac{RQ \cdot 0.00276M \cdot 0.203H^{0.725} \cdot W^{0.425}}{0.23 \cdot RQ + 0.77}, \tag{2}$$

where RQ is the respiratory quotient, i.e. the relative volumetric rates of carbon dioxide produced to oxygen consumed. The value of RQ depends on diet, level of physical activity, physical condition and is equal to 0.83 for an adult of average size engaged in light or sedentary activities; M is the level of physical activity in met; H is the body height (m); W is the body mass (kg).

Table II

Ventilation requirements for single offices based on different standards, in air change rates (h^{-1})

Calculation method	Requirements	Office / Ventilation requirement			
		C6/9	C6/20	C14/6	C14/19
CR 1752 (1998) Pollution from occupants, unadapted people	category B (20% dissatisfied) CO_2 concentration indoors less than 660 ppm above the outdoor CO_2 concentration level	0.6	0.6	0.6	1.1
CR 1752 (1998) Total pollution load, unadapted people	category B (20% dissatisfied) desired perceived indoor air quality of 1.4 decipol	2.6	2.5	2.5	3.3
EN 15251 (2007) Total pollution load, low polluting building, unadapted people	category II (20% dissatisfied) ventilation rate of 7 l/(s.person) and 0.7 l/(s.m$^2_{floor}$)	1.5	1.5	1.5	2.0
EN 15251 (2007) Total pollution load, non low polluting building, unadapted people	category II (20% dissatisfied) ventilation rate of 7 l/(s.person) and 1.4 l/(s.m$^2_{floor}$)	2.5	2.4	2.4	2.9
ASHRAE 62.1 (2013) Total pollution load, adapted people	20% dissatisfied ventilation rate of 2.5 l/(s.person) and 0.3 l/(s.m$^2_{floor}$)	0.6	0.6	0.6	0.8

The air change rate λ is then iteratively adjusted so that the constructed (calculated) curve is fitted to the measured curve of the increasing CO_2 concentration. When the least square curve is found, the approximated curve constructed based on (1) is adjusted to fit to the least square curve to obtain as good a match between the two curves as possible (*Fig. 4*).

In the tracer gas decay method, the part of the mass balance equation involving production of the CO_2 by humans vanishes, as no people are present during the decay. (2) is then simplified as follows:

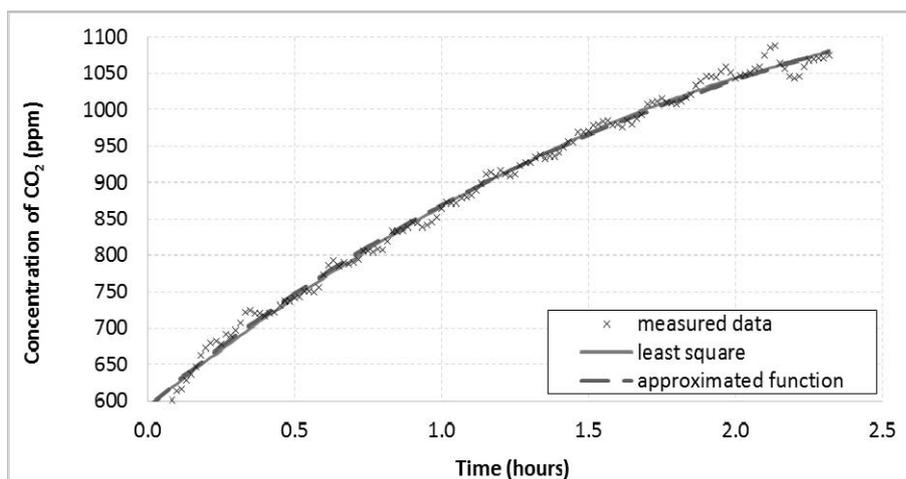$$C_i(t) = (C_0 - C_a) \cdot e^{-\lambda \cdot t} + C_a. \tag{3}$$

Fig. 4. Fitting of the approximated function (dashed curve) to the measured curve of increasing CO_2 concentration (stars) according to the least square method (continuous curve)

The air change rate λ is calculated from (3) iteratively. However, it is also possible to calculate the air change rate directly, using the logarithmic form:

$$\ln(C(t) - C_a) = -\lambda \cdot t + \ln(C_0 - C_a). \tag{4}$$

From this linearized form it is possible to directly calculate the ventilation intensity λ. An example of such linearized form is shown in *Fig. 5* with the least square equation.

6. Results

Fig. 6 shows the air change rate obtained by the tracer gas step-up method in the offices on the sixth floor (C6/20) and on the 14th floor (C14/19), respectively, both with the simple façade. In the other two offices investigated in the present study, the measured data is not suitable for the application of the tracer gas step-up method. The error bars in the figure indicate absolute values of the measurements uncertainty. In the tracer gas step-up method, the uncertainty of the measurement is associated mainly with the uncertainty in the exact determination of the room volume, the outdoor CO_2 concentration and the amount of CO_2 produced by the occupant. Therefore, the lower confidence limit is constructed by decreasing the CO_2 production by 1 l/s, decreasing

the CO_2 concentration outside by 10 ppm, and by increasing the room volume by 5%. Similarly, the upper confidence limit is constructed by increasing the CO_2 production by 1 l/s, increasing the CO_2 concentration outside by 10 ppm, and by decreasing the room volume by 5%. The true values of air change rate are assumed to lie within the error bars. Only measurement periods when the concentration increase was stable for at least about one and half hour were taken to account to assure that the results are reliable.
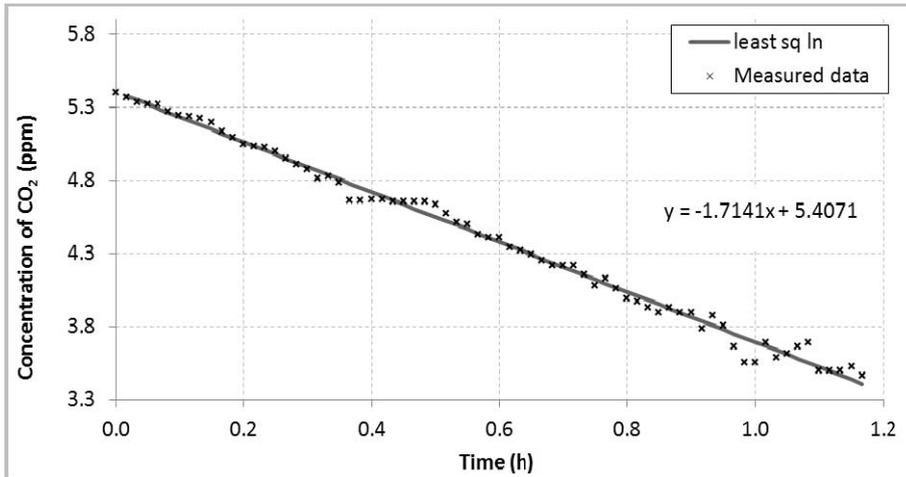

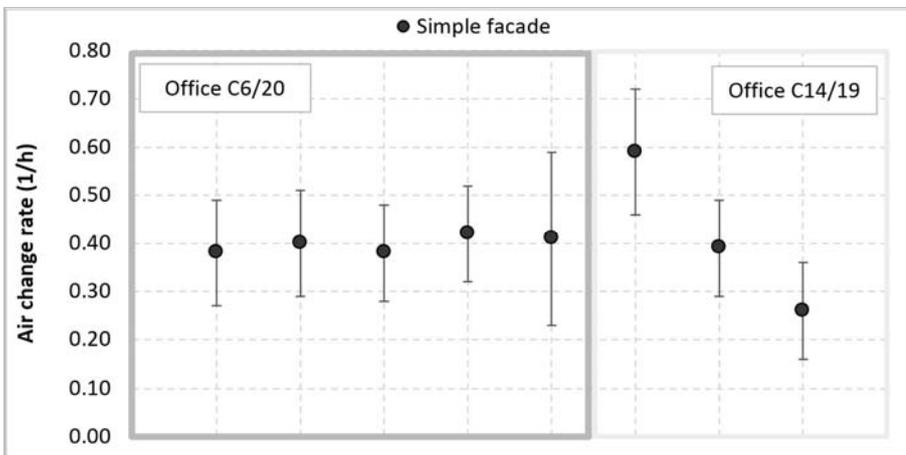*Fig. 5.* Logarithmic form of the CO_2 decay

Fig. 6. Air change rate measured in two offices with simple façade
by tracer gas step-up method

Besides of the tracer gas step-up method, the tracer gas decay method was used to calculate the air change rate, when the occupants had left the room and the CO_2

concentration started to decrease. The linearized form of the tracer gas decay equation (4) was used, which allowed to calculate the air change rate directly (i.e. not by iteration). The 95% confidence interval to account for imprecise estimation of the CO_2 concentration outdoors was obtained by varying the concentration by ±10 ppm. The total uncertainty was obtained by adding the two uncertainties, thus the uncertainty to account for the discrepancy between the estimated value and the measured data [7], and the uncertainty due to imprecise estimation of the CO_2 concentration outdoors. Graphical representation of the air change rate measured by the tracer gas decay method is in *Fig. 7*.
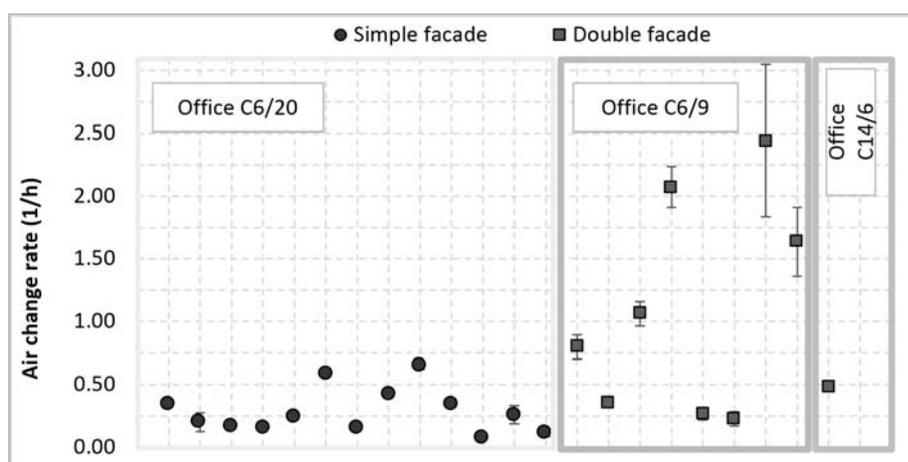

Fig. 7. Air change rate measured by tracer gas decay method

7. Discussion

The measured values of the air change rate for the offices with the simple façade are between 0.1 and 0.7 1/h. Nearly all of these values were obtained in the same office on the sixth floor, C6/20. From the questionnaire and personal communication it was found that the windows were never open. The variation in the air change rate can be explained by changes in the pressure of the outside air on the façade (the infiltration increases in windy weather), and to lower extent by infiltration of the air from adjacent spaces to the office and uncertainty of the measurements.

For the offices with the double skin façade, the values of air change rate are more scattered. All values but one were obtained in the office on the sixth floor, C6/9. Low values of 0.2 to 0.5 1/h represent the ventilation intensity with the windows and door closed. The high values in the range from 1.6 to 2.4 1/h were probably achieved by partial opening one of the windows, and the consequently increased infiltration of the fresh air from the exterior to the room. The variation in the air change rate can be explained in the same manner as for the simple façade.

The values of air change rate obtained with windows and doors closed are lower than required for ventilation of offices. The values are closest to the requirements of

ASHRAE 62.1 (2007) [3], based on the perception of people not adapted on the indoor air, and thus less strict than the requirements as defined in EN 15251 (2007) [2] and CR 1752 (1998) [4]. A partial solution to remediate the air quality lower than required could be removing some of the pollution sources, or to replace them with ones emitting less pollution.

8. Conclusion

Depending on the standard and the philosophy adopted, the requirements on the indoor air quality can vary substantially. The results of air change rate measurements confirmed that the new facade is tight, i.e. the infiltration of the outside air is low, and thereby the heat loss in cold winter conditions is decreased. However, the negative consequence of this high air tightness is the ventilation intensity lower than recommended by standards. This situation could be at least partially improved by removing the pollution sources, such as old carpet, old books, etc.

Although the concentration of CO_2 in the offices was relatively low due to the low density of occupants per square meter of the floor, indicating a good air quality, the results of ventilation intensity showed that the air quality may be lower than required for a comfortable indoor environment. Although the CO_2 concentration is a good air quality indicator in spaces, where people and their activities are the main source of pollution, it does not take into consideration the pollution from building materials, furniture and carpets, which are likely an important pollution source in this study. Thus, the concentration of CO_2 as the indoor air quality indicator should be used with care in spaces similar to those investigated in this study.

Acknowledgement

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