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NOVEL APPROACH FOR EVALUATION OF AIR CHANGE RATE IN NATURALLY VENTILATED OCCUPIED SPACES BASED ON METABOLIC CO2 TIME VARIATION

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SUMMARY

IAQ in many residential buildings relies on non-organized natural ventilation. Accurate evaluation of air change rate (ACR) in this situation is difficult due to the nature of the phenomenon - intermittent infiltration-exfiltration periods of mass exchange between the room air and the outdoor air at low rate. This paper describes a new approach for ACR evaluation in naturally ventilated occupied spaces. Actual metabolic CO2 time variation record in an interval of time is compared with the computed variation of metabolic CO2 for the same time interval under reference conditions: sleeping occupants, air-tight space, constant indoor pressure and temperature. The proposed approach for ACR evaluation can be applied to time intervals with any length, even with varying parameters of both indoor and outdoor air, in which metabolic CO2 generation rate is known and constant. This approach makes possible evaluation of very low ACH.

INTRODUCTION

Indoor air quality in many residential buildings relies only on non-organized natural ventilation. In this case the ACR is specified by: total ACR which is the volume of room air leaving the space per unit time divided by the volume of the air in the zone; outdoor ACR which is the volume of outdoor air entering the room, at room conditions, per unit time divided by the volume of the air in the zone and basal outdoor ACR which is caused only by the air-permeability of external room boundaries and is part of actual outdoor ACR. Outdoor air as well as indoor air entering the room from adjacent spaces may contribute to the total ACR. Evaluation of basal outdoor ACR of a room in a dwelling with non-organized natural ventilation is a difficult because of the non-steady state nature of the phenomenon. The exchange of mass between the indoor air and outdoor air is driven by a fluctuating pressure difference, with small amplitude and changing sign, across the air-permeable boundaries of the dwelling and the room of interest, behaviour caused by stochastic factors - wind, stack effect and occupants activities (movement within the dwelling, opening of doors and windows, manipulating heat and impulse sources in the dwelling). ACR evaluation in residential spaces under such conditions based on analysis of metabolic CO2 time variation makes the task even more difficult because of the characteristics of CO2 source, i.e. occupants with age in a very broad range, different health status, involved in various activities, etc.

The existing techniques for ACR evaluation are based on the simplified mass balance for the room air as a whole, which assumes that outdoor air entering the room at room conditions, $\dot{V}_a$ (in m^3/s) equals flow rate of air leaving the room, $\dot{V}_r$ (in m^3/s), and for the CO2 in room air, which in volume units reads:

$$\frac{dX_r}{dt} = \frac{10^3 \dot{G}}{V_r} + X_a \frac{\dot{V}_a}{V_r} - X_r \frac{\dot{V}_r}{V_r} \tag{1}$$

where X_r and X_a are CO2 volume fraction in room air and outdoor air (in ppm), $\dot{G}$ is metabolic CO2 generation in the room (in *l/s*), and V_r is air volume in the room (in m^3). When $\dot{G} = const$ and $X_a = const$ eq. 1 is a first order linear ordinary differential equation with constant coefficients, which has an analytical solution in the form

$$X_{r(t)} = X_{r,eq} + \left(X_{r,0} - X_{r,eq}\right) e^{-B(t-t_0)}, \quad B = \frac{\dot{V}_r}{V_r} \tag{2}$$

where $X_{r,0}$ is the CO2 volume fraction in room air at the moment t_0, $X_{r,eq}$ is the equilibrium CO2 volume fraction in room air which will be reached after sufficiently long interval, and B is the total ACR (in s^{-1}), which in this case is assumed equal to outdoor ACR. From eq.1 for equilibrium conditions follows

$$X_{r,eq} = X_a + \frac{10^3 \dot{G}}{B V_r} \tag{3}$$

The “Tracer Gas Decay Technique” (D 6245-12 standard 2012) is based on the change of occupant generated CO2 and requires minimum duration of the recorded time interval equal to 1/ACR. Since for this technique $\dot{G} = 0$ and $X_{r,eq} = X_a$ from equation 2 it follows that

$$B = \frac{\ln\left(X_{r,end} - X_a\right) - \ln\left(X_{r,0} - X_a\right)}{t_0 - t_{end}} \tag{4}$$

where $X_{r,end}$ is room CO2 concentration at the end of the decay interval (t_{end}).

The “Equilibrium CO2 Analysis” technique (D 6245-12 standard 2012), requires minimum duration of the test time interval of 3/ACR which is the time required to reach 95% of the equilibrium CO2 concentration in the room. Outdoor ACR is calculated from equation 3 based on measured $X_{r,eq}$, X_a and a model for calculation of $\dot{G}$, presented in the D6245-12 standard (2012). In the “Two-parameters emission technique” suggested by Stavova et al. (2006) equation 2 is used to obtain the best possible fit of the measured data on CO2 build-up in the tested room while satisfying some constrains put on the CO2 generation term, i.e. $\dot{G}_{\min} \le \dot{G} \le \dot{G}_{\max}$. For this approach, minimum duration of the test is equal to 1.5/ACR, which is the time required to reach 77.7% of the equilibrium CO2 concentration in the room.

All those techniques based on metabolic CO2 analysis are inapplicable for evaluation of basal outdoor ACR and even for total ACR of spaces in dwellings with non-organized natural ventilation because: 1) at a low ACR the methods require very long time intervals in which outdoor parameters and personal parameters are constant which in most situations is not the case and 2) they assume mass exchange with the outdoor air only (single zone) which is not always correct in case of non-organized natural ventilation. In addition to this the "Equilibrium CO2 Analysis" technique and the "Two-parameters emission technique" use a CO2 generation model which is not accurate enough as discussed in the following.

According to ASTM standard D6245-12 (2012), regardless of room air pressure and temperature, CO2 generation rate of a subject in (*l*/s) is calculated by

$$\dot{G} = \frac{0.00276RQ}{0.23RQ + 0.77} A_D M \quad \text{and} \quad A_D = 0.203H^{0.725}W^{0.425} \tag{5}$$

where RQ = 0.83 is the respiratory quotient, H is body height (in m), W is body weight (in kg), and M is metabolic rate per unit of surface area (in met, 1 met = 58.2 W/m^2). However according to ISO standard 8996-04 (2004) equation 5 gives CO2 generation rate at STPD conditions, i.e. Standard Temperature (t=0 ^{o}C) and Pressure (101.3 kPa), Dry. Hence, CO2 generation rate calculated by equation 5 should always be converted to room conditions.

ISO standard 8996-04 (2004) defines M=40 W/m^2 for sleeping people regardless of their sex and age. According to the Oxford database, Henry (2005), which provides the best known model for prediction of the basal metabolic rate with the lowest standard error, the standard estimates the basal metabolic rate correct for males aged 18–60 and females aged 10–30 years, underestimates it substantially for males aged 0–10 years and females aged 0–3 years, and slightly for males aged 10–18 and females aged 3–10 years. The standard overestimates the basal metabolic rate of males older than 60 years and females older than 30 years.

From equation 3 is clear that when "Equilibrium CO2 analysis" technique is used the uncertainty of B linearly depends on the uncertainty of $\dot{G}$. Hence, for evaluation of basal outdoor ACR in residential buildings the CO2 generation rate must be calculated as accurate as possible, as it is described by Markov (2012). From equation 3 it follows that when constrains are put on the CO2 generation term ($\dot{G}_{\min} \le \dot{G} \le \dot{G}_{\max}$), like in the "Two-parameters emission technique", explicitly are put respective constrains on both B and X_{eq}. Under such constrains any non-linear regression technique can find only a conditionally best fit for B and X_{eq} which may differ significantly from the best one.

A new approach for ACR evaluation in naturally ventilated occupied spaces that overcomes the constrains of the techniques discussed above is presented in the following.

BACKGROUND OF THE NOVEL APPROACH

In occupied spaces with non-organized natural ventilation room air (system, *r*) interacts with the surroundings, i.e. outdoor air (*a*) and air in the adjacent space (*d*), in various ways: indoor air escapes to outdoor, through the window ($\dot{m}_{r,w}$) and/or through the chimney ($\dot{m}_{r,c}$), if any, and/or to the adjacent spaces ($\dot{m}_{r,d}$). Part of this air is replaced by some amount of outdoor air ($\dot{m}_a$) and/or air from the adjacent spaces ($\dot{m}_d$). Schematic diagram of the mass exchange between the system and the surroundings is presented on Figure 1.

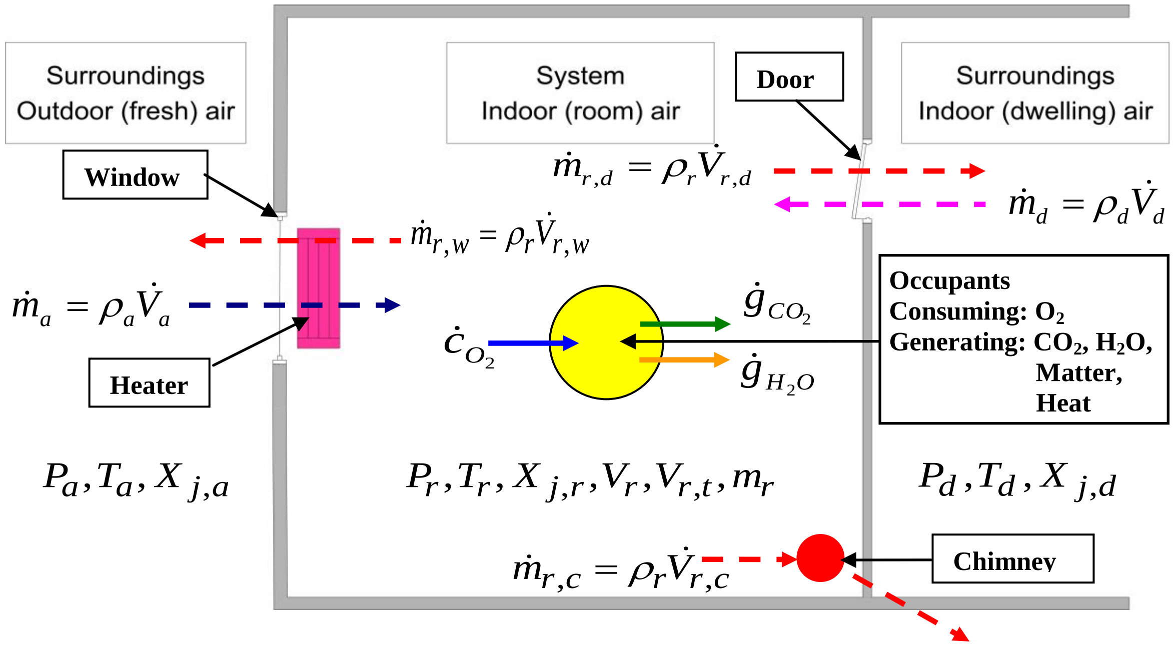

Figure 1. Schematic diagram of mass exchange between the system and the surroundings

System composition ($X_{j,r}$) is changed continuously since room air is in a ceaseless interaction with the occupants who consume oxygen from it (with a rate of $\dot{c}_{O_2}$ in g/s) and release back to it heat, mass, carbon dioxide gas ($\dot{g}_{CO_2}$) and water vapor ($\dot{g}_{H_2O}$). Outdoor air parameters absolute pressure (P_a), absolute temperature (T_a) and composition vector ($X_{j,a}$) varies with time, during the day and annually, due to weather changes, and they precondition variation of corresponding system parameters (P_r,T_r,$X_{j,r}$) and air parameters in the adjacent spaces (P_d,T_d,$X_{j,d}$). Temperature variation in the system causes respective variation of system mass (m_r). When one or several occupants enter or leave the room volume, system mass and system composition vector are changed stepwise. Taking into account all these and assuming that air behaves as a homogeneous mixture of four ideal gases and perfect mixing exists within the system volume, mass balance for the system ($j=0$) and for the individual species - oxygen ($j=1$), carbon dioxide ($j=2$), water vapour ($j=3$) and inert gas ($j=4$), in mass units reads:

$$\frac{dm_{j,r}}{dt} = \dot{m}_{j,M} + \dot{m}_{j,a} + \dot{m}_{j,d} + S_j - m_{j,r} B \qquad (6)$$

where $\dot{m}_{j,a}$ and $\dot{m}_{j,d}$ are, respectively, mass flows of outdoor air and air from the adjacent space entering the room, $\dot{m}_{j,r}$ is mass flow of room air leaving the room, $\dot{m}_{j,M}$ is mass source of corresponding species, and $\dot{m}_M = \dot{g}_{CO2} + \dot{g}_{H2O} - \dot{c}_{O2}$ for $j = 0$. S_j is source of mass due to step change of system volume $V_{r,t}$, which is calculated by

$$V_{r,t} = V_r - \sum_{p=1}^{N_p} V_p \qquad (7)$$

where V_r is volume of air in the system, N_p is number of occupants present in the room and V_p is the volume of each occupant present in the room.

For the periods with $V_{r,t} = const$, taking into account equation of state for ideal gas mixtures, mass balance of the system, in volume units, solved against the total ACR (B), reads

$$B = \frac{\dot{V}_r}{V_{r,t}} = \frac{R_r T_r P_a}{R_a T_a P_r} \frac{\dot{V}_a}{V_{r,t}} + \frac{R_r T_r P_d}{R_d T_d P_r} \frac{\dot{V}_d}{V_{r,t}} + \frac{\dot{V}_{M,r}}{V_{r,t}} + \left(\frac{\dot{V}_{dT}}{V_{r,t}} + \frac{\dot{V}_{dR}}{V_{r,t}} - \frac{\dot{V}_{dP}}{V_{r,t}} \right) \qquad (8)$$

where R_a, R_d, and R_r is ideal gas constant of outdoor air, air in the adjacent space and the system, respectively; $\dot{V}_a$ is volume flow of outdoor air entering the room at outdoor conditions, $\dot{V}_d$ is the flow of air from the adjacent space (“dwelling”) entering the room at the conditions in the adjacent space, and $\dot{V}_{M,r}$ ($\dot{m}_M = \rho_r \dot{V}_{M,r}$) is source of mass in volume units at room conditions. In equation 8 volume flow rates $\dot{V}_a, \dot{V}_d, \dot{V}_r$, and $\dot{V}_{M,r}$ are non-negative variables while volume flow rates in the brackets, which accounts for the variation of system temperature, system pressure and system composition, may change their sign. These flows, arising from the accumulation term in equation 6, are defined as follows:

$$\frac{\dot{V}_{dT}}{V_r} = \frac{1}{T_r} \frac{dT}{dt}, \quad \frac{\dot{V}_{dP}}{V_r} = \frac{1}{P_r} \frac{dP_r}{dt}, \quad \frac{\dot{V}_{dR}}{V_r} = \frac{1}{R_r} \frac{dR_r}{dt} \qquad (9)$$

Typically $\dot{V}_{dP}$ and $\dot{V}_{dR}$ may be neglected but for air-tight occupied spaces $\dot{V}_{dR}$ is important.

For the periods when $V_{r,t} = const$, mass balance of each species in volume units reads

$$\frac{dX_{j,r}}{dt} = \frac{10^3 \dot{V}_{j,M,r}}{V_{r,t}} + \frac{T_r P_a}{T_a P_r} X_{j,a} \frac{\dot{V}_a}{V_{r,t}} + \frac{T_r P_d}{T_d P_r} X_{j,d} \frac{\dot{V}_d}{V_{r,t}} - X_{j,r} \left(B + \frac{\dot{V}_{r,dP}}{V_{r,t}} - \frac{\dot{V}_{r,dT}}{V_{r,t}} \right) \qquad (10)$$

where $\dot{V}_{j,M,r}$ is mass source of species in volume units (in *l*/s) at room conditions. All details for calculation of $\dot{m}_{j,M}$ (in g/s) are already presented elsewhere (Markov 2012), and its conversion to volume units at room conditions is performed by

$$\dot{V}_{j,M,r} = \dot{m}_{j,M} \frac{R_j T_r}{P_r} \qquad (11)$$

THE NOVEL APPROACH

The time variation of indoor air composition under different conditions can be simulated based on mass balance equations 8 and 10, together with the 4 species ideal gas model of the indoor and outdoor air and the expressions for species generation/consumption, presented by Markov (2012), assuming homogeneity and perfect mixing of the system. Four procedures for evaluation of ACR under various conditions are elaborated. First a period must be selected for analysis of metabolic CO2 time variation in the room. The analysis must be performed only for the periods when occupants are sleeping, i.e. $V_{r,t}$ = *const* and metabolic rate of each occupant is close to the basal metabolic rate. Under such conditions first derivative of CO2 signal will be positive and continuous. Since first derivative of CO2 signal could be evaluated only numerically the sampling interval of room CO2 must be no longer than 60 s.

Air-tight analysis. Equation 8 reveals that, due to the source of mass in the system, there is always an amount of air leaving the room without being replaced by air from the surroundings. This amount of air leaving the room at constant system parameters (pressure, temperature and air volume) and under air-tight conditions, $\dot{m}_a = 0$ and $\dot{m}_d = 0$, following Markov (2012) and taking into account expression 11, is calculated by

$$B_{ref} = \frac{1}{V_{r,t}} \sum_{j=1}^{4} \dot{V}_{j.M,r} \qquad (12)$$

B_{ref} is the minimum possible total ACR for an occupied room at given pressure and temperature. Time variation of system mass and mass of all species under these conditions is

$$m_j = m_{j,\infty} + \left(m_{j,0} - m_{j,\infty}\right) e^{-B_{ref}\left(t-t_0\right)} \qquad (13)$$

where $m_{j,0}$ is mass of the species at t_0, and $m_{j,\infty} = B_{ref}^{-1} \dot{m}_{j,M}$ is equilibrium mass of the corresponding species.

Total ACR analysis. For the selected period, based on equations 12 and 13, a reference case is established computationally with the time variation of the highest possible value of CO2 concentration in the room - $X_{2,r,ref}$. Total ACR in the period is evaluated by analysis of the variation of $X_{2,r,ref}$ and the measured CO2 time variation under the actual conditions ($X_{2,r,act}$). At each moment (t) in this period $\left(X_{2,r,ref} - X_{2,r,act}\right)V_{r,t}$ is a measure of the evacuated volume of CO2 from the system in the interval $\left(t - t_0\right)$ due to its replacement by air from the surroundings. In an arbitrary case, since $V_{r,t} = const$, one part of the volume of air leaving the system is replaced by outdoor air and the other part is replaced by air from the adjacent space. Evacuated volume of CO2 by replacement is calculated from

$$\overline{\dot{V}_{2,evac}}\, 10^{-6} = \left(X_{2,r,ref} - X_{2,r,act}\right)\frac{V_{r,t}}{t - t_0} = \left(\overline{X_{2,r,act}} - \overline{X_{2,a}}\right)\overline{\dot{V}_{a,r}} + \left(\overline{X_{2,r,act}} - \overline{X_{2,d}}\right)\overline{\dot{V}_{d,r}} \qquad (14)$$

where $\overline{X_{2,r,act}}$, $\overline{X_{2,a}}$ and $\overline{X_{2,d}}$ are the mean values of $X_{2,r,act}$, $X_{2,a}$ and $X_{2,d}$ in the interval $\left(t - t_0\right)$; $\overline{\dot{V}_{a,r}}$ and $\overline{\dot{V}_{a,d}}$ are mean values of flow rate at room conditions of outdoor air and air from the adjacent space entering the room in the interval $\left(t - t_0\right)$. Minimum flow of room air leaving the system ($\dot{V}_{r,\min}$) is calculated from equation 14 when assuming it is replaced by outdoor air only and maximum flow of room air leaving the system ($\dot{V}_{r,\max}$) is reached when it is replaced by air form the adjacent space only:

$$\dot{V}_{r,\min} = \overline{\dot{V}_{a,r}} + \dot{V}_{M,r} \text{ and } \dot{V}_{r,\max} = \overline{\dot{V}_{d,r}} + \dot{V}_{M,r} \qquad (15)$$

For identification of the possible range of total ACR in each case this procedure must be completed for the two boundaries of 95% confidence interval of CO2 generation.

Outdoor ACR analysis. For identification of outdoor ACR in the selected period room CO2 time variation under various combinations of $\dot{V}_a$ and $\dot{V}_d$ for $\dot{V}_r$ in the interval $\left[\dot{V}_{r,\min}, \dot{V}_{r,\max}\right]$ must be simulated and compared with measured CO2 time variation. In the ideal case, in addition to room CO2 time variation, time variation of system pressure and temperature, as well as pressure, temperature and CO2 concentration of both outdoor air and indoor air in the adjacent space must be recorded. Usually, under stable atmospheric conditions, outdoor pressure changes slowly causing slow change of system pressure and pressure of the adjacent space. Thus ratios of outdoor pressure and pressure of the surroundings to system pressure will equal unity. Based on the example presented in Markov (2012), ratios of system ideal gas constant to ideal gas constant of both outdoor air and air in the adjacent space (eq. 8) could be assumed equal to unity. Identification of $\dot{V}_a$ and $\dot{V}_d$ within the selected period must be performed for the 95% confidence interval boundaries of CO2 generation term. Thus 95% confidence interval for $\dot{V}_a$ and $\dot{V}_d$ will be evaluated too.

Two free parameters empirical model. For long enough periods with smooth CO2 build-up in the room the "Two-parameters emission technique" (Stavova et al. 2006) can be improved with the following modification. First, the two parameters in the model established by eq. 2 (X_{eq} and B), must be evaluated by a non-linear fitting procedure. Then from eq. 3 the 95% confidence interval boundaries for CO2 generation term ($\dot{G}_{EM,95,\min}$ and $\dot{G}_{EM,95,\max}$) must be evaluated based on the data for 95 % confidence interval of X_{eq} and B. This 95% confidence interval must be compared with the confidence interval of $\dot{G}$, ($\dot{G}_{95,\min}$ and $\dot{G}_{95,\max}$), based on CO2 generation model in Markov (2012). Outdoor ACR equals (B–B_{ref}), when the confidence interval of $\dot{G}$, [$\dot{G}_{95,\min}, \dot{G}_{95,\max}$], includes the whole confidence interval of $\dot{G}_{EM}$, [$\dot{G}_{EM,95,\min}, \dot{G}_{EM,95,\max}$]. When these confidence intervals overlap at least at 50%, then it could be assumed that outdoor ACR equals (B–B_{ref}). When $\dot{G} < \dot{G}_{EM}$ and their confidence intervals doesn't overlap then B is the total ACH, i.e. the air leaving the room is partly replaced by outdoor air and partly by air from the adjacent space. In this situation "Basal outdoor ACR analysis" must be performed.

The discussed above techniques are applied and compared for the example in Figure 2, which presents a record of CO2 time variation in an occupied room with non-organized natural ventilation. During the night periods 1, 2, and 3 two occupants (a male - aged 54, weight 88 kg, height 169 cm and a female - aged 52, weight 68 kg and height 159 cm) are sleeping in the room and during the day period 4 only the male subject is sleeping in the room.

By the "Equilibrium CO2 analyses" ACR in period 3 is 0.555±0.110 1/h when evaluated according to ASTM D6245-12 and 0.634±0.121 1/h based on the metabolic CO2 generation model by Markov (2012). ACR predicted for period 2 by the novel "Two free parameters empirical model" is 0.715±0.035 1/h. The novel "Total ACR analysis" technique applied to period 1, which is only a small part of period 2, predicts an ACR of 0.614±0.149 1/h. The difference in the predictions by the "Equilibrium CO2 analyses" described in the ASTM D6245-12 method and the three novel techniques is up to 28.8%, while the difference in the predictions by the three novel techniques is 14.1%. The second part of the CO2 record in

Figure 2 doesn’t have an equilibrium period and therefore the “Equilibrium CO2 analyses” technique can’t be applied. The novel “Two free parameters empirical model” applied to the period 4 predicts a total ACR of 0.72±0.1 1/h. ”Tracer Gas Decay Technique” can’t be applied for the entire CO2 record in Figure 2 because occupants’ activities during the decay periods are not known. Comparison of the standardised techniques and the novel techniques with detail physical measurements is under progress and will be reported in a following paper.

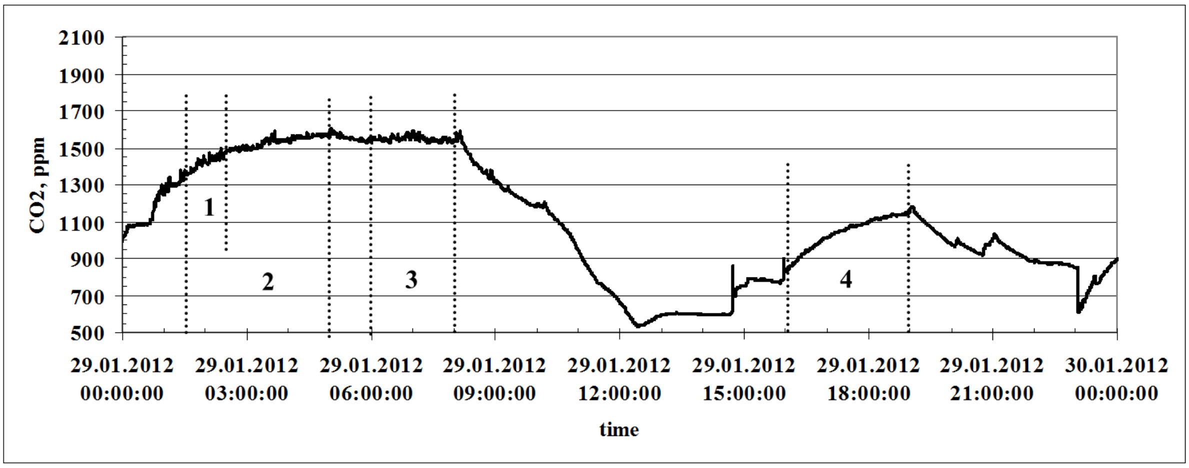

Figure 2. ACR analysis in an occupied room

CONCLUSIONS

The presented mathematical model reveals the complex nature of the mass exchange phenomenon in occupied spaces with non-organized natural ventilation as well as the reasons, which make the known procedures for ACR analysis not always applicable to such spaces.

A novel approach for CO2 time variation analysis and a set of 4 logically connected procedures are presented that make possible the evaluation of total ACR, outdoor ACR as well as basal outdoor ACR in occupied spaces with non-organized natural ventilation under wide range of conditions in time periods of any length. This approach requires measurement of time variation of room CO2, pressure and temperature as well as of the temperature and CO2 of both outdoor air and air in the adjacent space(s).

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