ANALYSES OF CO2 TIME VARIATION RECORDS IN NATURALLY VENTILATED OCCUPIED SPACES

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Abstract: The present paper concerns the results obtained in a human subject experimental study, regarding the predefined occupant behavior with respect to aerating activities of a naturally ventilated space. During the experiment, various scenarios were investigated of different occupant’s behavior patterns with regard to the degree of window opening. Indoor air temperature, relative humidity and CO2 volume fraction, were continuously measured and recorded. CO2 concentration time variation records were analyzed separately and the time change of this parameter was considered as a main indicator to distinguish the periods of infiltration only and the periods of conscious aeration activities, performed by the occupants. The developed evaluation procedures as well as the key results from the analyses are discussed in the paper.

Keywords: Indoor Air Quality (IAQ), CO2 concentration, Occupant Behavior, Aeration

1. Introduction

There are numerous microclimate factors, having significant impact over occupant health, comfort, performance and productivity [7, 8, 11, 15]. The indoor air, for example, contains a wide range of organic and inorganic species, which normally are not present in the outdoor air. Huge part of these species are pollutants emitted by different indoor sources, like: building materials, furniture and textile materials, TV sets and other domestic electronic appliances, cleaning agents, cooking and other home activities, heating with wood and fossil fuels, indoor plants, cigarette smoke, as well as the occupant themselves and their pets. The problems connected with the increased level of the indoor air relative humidity, which may arise due to inadequate aeration, could become serious threat for the occupant’s health, comfort and workability. Moreover, occupant’s conscious and unconscious behavior patterns have a significant effect on the indoor air quality and on the microclimate as a whole [6, 10].

Various studies in this area have been conducted in recent decades and norms and standards are established describing the preferred microclimatic conditions (related to indoor air quality and thermal comfort of the occupants). But most of these studies and standards concern non-residential buildings, particularly enclosed spaces of office buildings and industrial premises where people primarily work [2, 3, 4]. This is due to the existence of huge differences between diverse buildings, and the great variety of occupants, regarding their physical differences, culture, habits, etc. There is a need to explore the complex influence of indoor air in residential buildings on the health, comfort and performance of their occupants, who spend there consciously or unconsciously the majority time of their lives. Examples of such studies are the DBH study [5] and the ALLHOME study [11, 12, 13].

The indoor air pollutants are normally diluted by outdoor air, by aeration. In spaces with uncontrolled, unorganized natural ventilation, the indoor air is replaced with outdoor air only by infiltration or by opening of doors and windows, i.e. the space is neither mechanically ventilated nor there are present means of organized natural ventilation - ATD, chimneys, local suction. The
evaluation of outdoor ACH in these spaces could be performed by the analysis of metabolic CO2 time variation records, following the ASTM standard D6425-2002.

The current study deals with the analysis of metabolic CO2 time variation in an occupied space with uncontrolled, unorganized natural ventilation under controlled conditions with respect to the occupant’s behavior. There are several reasons for the selection of such a room as the main object of the present study. The most important of them is the fact that almost all buildings in Bulgaria fall into this category. Over 90% of concrete apartment blocks in the cities are without organized ventilation and a huge percentage of the population in Bulgaria live within such multi-apartment buildings.

Usually the only way to consciously ventilate a room, without any means of ventilation, is by opening windows and doors. In most cases, this means that the only persons responsible for this action are the occupants themselves. Very often people are forced to make a choice whether to ventilate or not, and usually they have to make a compromise between thermal comfort and indoor air quality. But almost always the thermal sensation is the causative reason for the decision whether to open a window or door or not. Of course there are other factors, on which the decision depends, such as indoor and outdoor temperatures, the previous position of the window (open / closed), time of day, lack or excess of air movement (sense of draught), the intensity of solar radiation and many more. Naturally, people do not have developed sensation about the quality of the air, as opposed to thermal sensations. This makes the decision for ventilation even more difficult. Because of this fact, there is a need for experimental investigation and analyses of the mechanism of aeration in spaces without organized ventilation, to clarify and optimize this very important decision, made by the residents.

2. Aim of the experimental study

The main objective of the present experimental study is to explore the characteristics of the aeration process in residential spaces without any means of organized ventilation by analyzing the metabolic CO2 time variation records, under predefined conditions with respect to the occupant’s aeration routine. The knowledge about the characteristics of the aeration process is required for making the distinction between conscious and unconscious aeration when studying the occupant’s behavior in residential spaces, with respect to both energy efficiency and health, based on the analysis of long-term records of metabolic CO2 time variation.

3. Methods

The long-term recording of indoor air parameters in a bedroom, with no means of organized ventilation, under the prescribed behavior of the only occupant (O1) of the apartment is presented schematically on Figure 1.

In the room there is a heater with a thermostatic valve and a mattress as the only piece of furniture. During the experiment concerned, the apartment was inhabited by one 29 years old male person (78 kg/177 cm) and no changes were introduced in the bedroom with respect to furniture and thermostatic valve set point. He was the only source of CO2 in the bedroom and the apartment. Each morning he performed aeration activities following the plan of the experiment – opening of the window at a prescribed level and leaving the room as well as closing the window after a prescribed interval and leaving the room.

There is a PVC framed "tilt and turn" type window with glazing unit in the room. Both the door of the bedroom and its frame were further sealed with rubber strap and dual nylon curtain. This is done in order to reduce the inflow of indoor air from the other zones of the flat into the investigated space. In this way the time variation of the indoor air temperature, the relative humidity and the CO2 volume fraction during the experiment is caused only by the actions of the
occupant and the interactions between the indoor environment and the ambient environment. A small fan is installed in the room for achieving as perfect mixing of the room air as possible. It was put automatically in operation every hour for an interval of 15 minutes.

The time variation of indoor air parameters was recorded by three measuring systems (S1 to S3) and the one of outdoor air parameters was recorded by the U23 measuring instrument.

Fig. 1- Scheme of the investigated room

4. Experimental set-up

Experiment was conducted in an apartment with an approximate area of 90 m², which is on the 8th floor of a newly constructed building in the town of Sofia, Bulgaria. The investigated room covers an area of 14 m², its height is 2.7 m, and the room volume is 37.8 m³. The window measures 210 cm length and 132 cm in height. The window wing measures 60 cm in length and 122 cm in height (Figure 2).

Fig. 2- Positions of window wing opening
As the window is the only way for outdoor air supply to the room, the degree of inward opening of its wing (different predetermined cross-sectional area, through which the air change takes place) determines the investigated cases. To ensure the required angle of turning of the window wing during aeration, a special device is made to fix its exact position. During the experiment the window wing was turned and fixed in 5 different positions: 11.25° (referred to as A-Y1, 12.5% opening of the wing), 22.50° (A-Y2, 25%), 45.00° (A-Y3, 50%), 67.25° (A-Y4, 75%), and 90.00° (A-Y5, 100%). Only one fixed tilt position of the window wing opening was used during the experiment referred to as Y-P1.

Below the window there is an air heater, consisting of 12 aluminum sections, measuring 95 cm in length, 58 cm in height, and 8 cm in depth. Room temperature is adjusted by a thermostatic valve with 5 grades.

Indoor environment parameters were measured and recorded by HOBO data-loggers. The measuring systems S1 and S2 comprise a HOBO Telaire-7001 CO2 measuring instrument connected to a HOBO U12-012 data logger. System S3 is simply a HOBO U12-012 data logger. The HOBO U12-012 data logger allows the continuous measurement of air temperature and relative humidity as well as the illumination. It allows as well recording of the external voltage signal. In the case of system S1 and S2 this was the voltage signal generated by the HOBO Telaire-7001 CO2 measuring instrument. The location of the measuring systems is presented in Figure 1 and is consistent with the standards for measuring the parameters of the microclimate and the specificity of the investigated room.

The outdoor air temperature and the relative humidity were measured and recorded by a HOBO U23-01 Pro v2 Temp/RH data logger, stuck on the outer surface of the window pane.

The experiment is conducted during the heating season of winter 2010/2011.

5. Investigated Scenarios

The only change to the habits of the occupant of the apartment is related to his aeration routines. He was asked each day to get out of the bed around 9:00 AM, to open the window and fix it at one of the prescribed positions A-Y1 to A-Y5 or A-P1 and to leave the room for a period of at least 1.5 hours. After closing the window he was asked to leave the room and to enter it again at the time for night sleep. During the last day of the experiment, the last scenario, he was asked to get out of the bed and immediately to leave the room without any aeration activities.

Totally 7 scenarios of aeration are studied.

6. Results

Time variation of CO2 volume fraction in the investigated room from 22:00 on 29.01.2011 to 10:46 on 06.02.2011, totally 180 hours and 46 minutes (10846 minutes), is presented on Figure 3. There are 29 clearly distinguishable intervals in this record:

- 9 periods of steep CO2 build-up: totally 3754 minutes (34.611% of the time), room is occupied;
- 12 periods of slanting CO2 decay: totally 5730 minutes (52.831%), CO2 decay caused by infiltration, the longest period is marked with "C";
- 6 periods of steep CO2 decay: totally 636 minutes (5.864%), CO2 decay caused by aeration, these periods are marked with "A-Y1" – "A-Y6" and "A-P1", representing the aeration at different levels of window wing opening;
- 2 periods at which CO2 instrument was out of operation due to low battery, totally 726 minutes (6.694%).
The first analysis of a CO2 record follows the EN 15251:2007 standard. The characterization index used here is the length of time interval in which indoor air CO2 volume fraction ($X_{in}$) is lower than the required one by the corresponding category level of CO2 ($\Delta X_i$) concentration above the outdoor CO2 concentration ($X_{out}$). Outdoor CO2 concentration near the building at ground level is $X_{out}$=400 ppm. There are 4 categories of CO2 concentration above outdoor concentration in the EN 15251:2007 standard. For this particular experiment these levels are as follows:

- category I – $X_{in} \leq X_{out} + 350$ ppm = 750 ppm;
- category II – $X_{in} \leq X_{out} + 500$ ppm = 900 ppm;
- category III – $X_{in} \leq X_{out} + 800$ ppm = 1200 ppm;
- category IV – $X_{in} > X_{out} + 800$ ppm > 1200 ppm

These CO2 levels are given on Figure 1 with different type of lines.

Indoor CO2 concentration fulfills the requirement of EN 15251:2007 standard for category I 55.67% of the time, for category II 62.80% of the time, for category III 73.15% of the time, and for category IV 26.85% of the time. In other words 77.6% of time when the room is occupied the indoor CO2 level is above 1200 ppm. The maximum observed CO2 concentration during the experiment is 2147 ppm.

The second analysis of CO2 record is based on the ACH evaluation procedure described in the ASTM D6245-2002 standard. Following this guide, no CO2 generation inside the zone, ACH is evaluated for the six intervals with aeration decay (A-Y1 to A-Y5 and A-P1) and for the longest interval with infiltration decay (C) and the results are presented in Table 1.

### Table 1

<table>
<thead>
<tr>
<th>Interval</th>
<th>Window opening</th>
<th>Interval length</th>
<th>ACH-S1</th>
<th>ACH-S2</th>
<th>NC-S1</th>
<th>NC-S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-Y1</td>
<td>12.5%</td>
<td>107 minutes</td>
<td>3.277</td>
<td>3.368</td>
<td>5.844</td>
<td>6.006</td>
</tr>
<tr>
<td>A-Y2</td>
<td>25.0%</td>
<td>119 minutes</td>
<td>8.352</td>
<td>8.071</td>
<td>16.565</td>
<td>16.007</td>
</tr>
<tr>
<td>A-Y3</td>
<td>50.0%</td>
<td>94 minutes</td>
<td>15.376</td>
<td>12.296</td>
<td>24.089</td>
<td>19.264</td>
</tr>
<tr>
<td>A-Y4</td>
<td>75.0%</td>
<td>106 minutes</td>
<td>20.092</td>
<td>17.714</td>
<td>35.496</td>
<td>31.295</td>
</tr>
<tr>
<td>A-Y5</td>
<td>100.0%</td>
<td>105 minutes</td>
<td>24.544</td>
<td>18.551</td>
<td>42.952</td>
<td>32.464</td>
</tr>
<tr>
<td>A-P1</td>
<td>Falling frame</td>
<td>99 minutes</td>
<td>2.887</td>
<td>2.921</td>
<td>4.764</td>
<td>4.820</td>
</tr>
<tr>
<td>C</td>
<td>Closed</td>
<td>999 minutes</td>
<td>0.113</td>
<td>0.107</td>
<td>1.881</td>
<td>1.782</td>
</tr>
</tbody>
</table>

**Fig. 3.** Time variation of CO2 volume fraction during the experiment in the investigated room.
Here ACH-S1 and ACH-S2 stay for ACH evaluated in the corresponding interval based on the indoor CO2 concentration raw data, the inter-calibration is not taken into account, the record of system S1 and S2, respectively. The NC-S1 and NC-S2 values give information for the number of air changes happened in the corresponding period. In each period the ACH evaluated by the analysis of system S2 CO2 record differs from the one evaluated by the analysis of system S1 CO2 record. This difference ranges from -24.4 % for the A-Y5 period to +2.78% for the A-Y1 period.

The system S1 and S2 records of CO2 time variation (X-S1 and X-S2, respectively) in the arbitrary selected period from 22:00 on 30.01.2011 to 2:00 on 1.02.2011 are presented on Figure 4.

![Figure 4](image.png)

**Fig. 4** - Comparison of S1 and S2 records of CO2 time variation for an arbitrary selected interval

Though these records are visually identical they generate a difference of -3.36% in the ACH for the A-Y2 period.

The inter-calibration of the two systems produces a linear relation between their readings

\[ X_{S2} = a + bX_{S1} \] (1)

with the coefficient of determination \( r^2 = 0.99738075 \). The values of the coefficients in equation 1 are \( a = 5.9855756 \) ppm и \( b = 1.0012962 \). They are in the middle of the 95% confidential interval [2.333999070, 9.637152170] with range 7.30315 ppm for \( a \), and [0.996499398, 1.006092927] with range 0.00959 for \( b \). The two systems have similar behavior but the readings of S2 system are higher than the readings of S1 system. The CO2 field in the room may be considered homogeneous during the whole experiment. This conclusion is made on the basis of the small range of the interval in which are enclosed the mean values of the largest deviations of \( X_{S2} - X_{S1} \) in the different type of periods (build-up, aeration decay, infiltration decay) as well as the short length of the intervals in which the non-homogeneity is pronounced the most.

The third type of analysis of the CO2 records is the analysis of the time variation of the first derivative of the CO2 concentration. The time variation of the first derivative of the CO2 concentration, evaluated numerically by the left differences, for the period from 22:00 on 30.01.2011 to 2:00 on 1.02.2011 is presented on Figure 5. The three types of intervals - build-up, infiltration decay and aeration decay, are clearly distinguishable.

During the first infiltration decay (from 22:00 on 30.01.2011 to 01:11 on 31.01.2011) the first derivative fluctuates around -0.00037 ppm/s with a standard deviation of 0.04465.

During the first build-up (from 01:12 on 31.01.2011 to 08:58 on 31.01.2011) the first derivative fluctuates around 0.05391 ppm/s with a standard deviation of 0.05875.

During the aeration decay (from 08:59 on 31.01.2011 to 10:59 on 31.01.2011) the mean value of first derivative -0.19849 ppm/s and the standard deviation is 0.55470.
During the second infiltration decay (from 11:00 on 31.01.2011 to 00:41 on 1.02.2011) the first derivative fluctuates around -0.00077 ppm/s with a standard deviation of 0.04013.

During the second build-up (from 00:42 on 1.02.2011 to 02:00 on 1.02.2011) the first derivative fluctuates around 0.07855 ppm/s with a standard deviation of 0.06264.

The fluctuations of the CO2 first derivative are caused by both the mixing process in the room characterized by different time scales and the instrument noise. Nevertheless, the statistical characteristics of CO2 first derivative in the different type of periods shows that it could be used as a criterion for distinguishing between conscious aeration (aeration decay), which characterizes the habits of the occupants, and unconscious aeration (infiltration decay), which characterizes the air permeable elements of the system, in those cases for which there is lack of information about the aeration routines of the occupants.

7. Conclusions

The results achieved demonstrate clearly the importance of the occupant’s behavior for the parameters of the indoor environment. The data confirm that, in rooms without organized ventilation, the indoor air quality depends entirely on the aeration activities, provided by the occupants. Looking at both extremes, namely regular opening of windows and doors or non-aerating the living space shows significant differences in the quality of the air in the space.

In all conscious activities performed by the occupant, the aeration is achieved with ease and in a short time.

In the cases without performing aeration actions, the air quality in the study area is poor and in half of the period CO2 concentration is above 1200 ppm. The results show that it is better to allow continuous aeration of the space than to aerate it once per day.

A major problem due to the reduced air exchange in the regimes without aeration actions is the retention of moisture in the room, and the retention of the various pollutants in the air, including carbon dioxide.

The analyses of CO2 first derivative record could be used as a criterion for distinguishing between conscious and unconscious aeration, which may characterize the habits of the occupants, when there is lack of information about their aeration routines.
References