Validity of CO2 based ventilation design

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Abstract. The present ventilation design practice as well as the ventilation standards and building regulations are based on the assumption for complete mixing of air in occupied spaces. Required flow rate of outdoor air for dilution of metabolic CO2 generated by occupants is calculated to keep the CO2 concentration below certain required level. The CO2 concentration measured in the exhaust air or in the room but far from the occupants is assumed to be the same as the CO2 concentration in the air inhaled by the occupants. However, this assumption is seldom accurate, especially in spaces with closely seated occupants, such as classrooms, meeting rooms, etc. In such spaces the CO2 sources, i.e. the people, are close to each other and the CO2 concentration in the inhaled air may be much above the CO2 concentration level recommended as a limit in standards. This is because the upward free convection flow that exists around human body entrains the air with high CO2 concentration exhaled by seated people and move it to their breathing zone. Furthermore, the thermal flows generated by occupants' body interact with the ventilation flow, which often results in insufficient dilution of the generated CO2 (as well as other pollution) and high levels of CO2 concentration at the breathing zone of occupants. This problem is discussed in the present paper in detail. The discussion is supported by results of measurements in a meeting room with mixing air distribution. People were used to generate metabolic CO2 and a breathing thermal manikin was used to measure accurately the CO2 concentration in the inhaled air. The results confirmed that inhaled CO2 concentration was much higher than the one at the exhaust and that there is need for changes in the present CO2 based ventilation design practice. Possible solutions are suggested.

1 Introduction

It is well documented that environment in enclosed spaces, including buildings and vehicles, is important for occupants' health, comfort and performance. Ventilation of spaces is intended primarily to provide occupants with clean air for breathing. Ventilation air is also used for removing or supplying heat in order to provide thermally comfortable environment for occupants. However, in order to avoid the risk of draft discomfort in the occupied zone and with development of low power lighting, office equipment (PC, printers, etc.), highly performing windows and building insulation, the use of radiant heat exchange systems, e.g. chilled ceiling, floor cooling and heating for providing comfortable thermal environment increases. Thus, the focus on the importance of ventilation for providing high quality of indoor air increases.

Numerous studies document the importance of breathing clean indoor air for occupants' health, i.e. for reducing sick building syndrome (SBS) symptoms, such as headache, difficult to concentrate, etc. [1, 2]. The importance of indoor air quality for performance of office workers and learning of pupils in schools has been documented as well [3, 4, 5].

2 Required outdoor air supply

In spaces, pollution is generated by occupants (bio-effluents), building materials, office equipment, etc. The air exhaled by occupants increases the CO2 level in spaces. The generated pollution (including CO2) is diluted by supply of clean ventilation air, which in most of the cases is outdoor air around the ventilated building. At present indoor CO2 concentration is used as a simple parameter (marker) to limit the level of pollution in spaces. The international and national standards define requirements for maximum CO2 concentration indoors. For example, in the latest Building Regulation of Denmark [6] the CO2 concentration in classrooms should not exceed 1000 ppm. In this case the required outdoor airflow rate, *q (L/s)*, is calculated based on the CO2 mass balance for the ventilated space at steady state, (Eq.1), assuming complete mixing of the indoor air:

$$q = \frac{\dot{G}_{t,CO2}}{X_{i,x} - X_a} 10^6 \quad (1)$$

Where: $\dot{G}_{t,CO2}$ is the CO2 generation rate in the room at room conditions, *L/s*; $X_{i,x}$ is the maximum allowed volume fraction of CO2 in indoor air, *ppm*; X_a is the CO2 volume fraction in outdoor air, *ppm*.

Outdoor air flow rate preconditions the time, T_x, for reaching the steady state, respectively the maximum allowed concentration of CO2 in the indoor air. For example the time $T_{0.993}$ for reaching $0.993(X_{i,x} - X_a)$ is 5000V/q sec, where V is the volume of the indoor air in the room, m^3.

From eq. 1 it follows that the outdoor air flow rate depends linearly on the CO2 generation rate and hyperbolically on the outdoor CO2 volume fraction. This fact suggest that CO2 generation rate in the room must be evaluated as precisely as possible.

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According to the current practice [7, 8], CO2 generation rate by a person is calculated by applying the following group of expressions:

$$\dot{G}_{CO2} = RQ.\dot{V}_{O2} \quad (2)$$

$$\dot{V}_{O2} = \frac{0.00276A_D}{0.23RQ+0.77}M \quad (3)$$

$$A_D = 0.203H^{0.725}W^{0.425} \quad (4)$$

Where $\dot{V}_{O2}$, is oxygen consumption rate, L/s; RQ=0.83 is the respiratory quotient; M is the metabolic rate per unit of surface area, met (1 met = 58.2 W/m^2); A_D is DuBois surface area, m^2; H is body height, m; W is body weight, kg.

Under the current approach models are required for three quantities – metabolic rate (M), body surface area (A_D) and respiratory quotient (RQ). ISO Standard 8996:2004 [8] provides several procedures for evaluation of metabolic rate. However, during the design of a ventilation system metabolic rate may be evaluated by two methods (Level 2, Annex B of the standard):

- Method A: the metabolic rate is determined by adding to the baseline metabolic rate the metabolic rate for body posture, the metabolic rate for the type of work and the metabolic rate for the body motion related to work speed (using group assessment tables);
- Method B: the metabolic rate is determined by means of the tabulated values for various activities.

At this Level 2 metabolic rate is evaluated with a high uncertainty, accuracy of ±20%. During the design stage the actual occupants of the space are not known and measurement of their heart rate (Level 3, accuracy ±10%) or oxygen consumption (Level 4, accuracy ±5%) is not possible. In the scope of the ISO standard 8996 [8] it is clearly stated that the included estimations, tables and the other data consider an "average" individual: a man 30 years old, weighing 70 kg and 1,75 m tall (body surface area of 1,8 m^2) or a woman 30 years old, weighing 60 kg and 1,70 m tall (body surface area of 1,6 m^2). It is also stated that users of the standard should make appropriate corrections when they are dealing with special populations including children, aged persons, people with physical disabilities, etc.

The error of predicting body surface area of an occupant by the DuBois formula is not known.

In equations 2 and 3 RQ is assumed equal to 0.83 which is not always true. The Respiratory Quotient (RQ), is a ratio between the carbon dioxide output and oxygen uptake of all cells of the body [9]. It is equal to ventilation exchange ratio (R), [9], the ratio between the carbon dioxide output and the oxygen uptake measurable with gas exchange equipment at the mouth only at respiratory steady state. In addition to this, during the day, as the intensity of person's activity and the demand for energy increase, a greater proportion of energy is usually provided by oxidation of carbohydrates and RQ, respectively R, at respiratory steady state, approaches unity [10].

All those suggest that a new approach for evaluation of CO2 emission rate by people, i.e. the CO2 generation rate in the occupied spaces, is needed for proper design of energy efficient ventilation systems.

In [11] a new approach is presented. CO2 generation rate at standard conditions (101325 Pa and 273.15 K) is evaluated by the equation

$$\dot{G}_{CO2} = 0.000569RQ.BMR.M \quad (5)$$

where BMR is basal metabolic rate in MJ/day, and M is the ratio of the human energy use associated with a particular physical activity to the *BMR* of that individual.

The analysis of BMR databases performed by the authors, [12], suggest that the Oxford database for BMR-2005 [13], is better than the BMR database used in [11], since it is balanced with respect to the subjects data included in it and is with the smallest standard error.

The CO2 generation rate by an adult person performing sedentary activity (1 to 1.2 Met) is assumed at 19 L/h [14].

The CO2 concentration in supplied outdoor air is typically assumed 400 ppm.

At constant number of occupants in a space, i.e. assuming constant CO2 generation, the ventilation rate of outdoor air, i.e. the amount of supplied outdoor air, needed to reduce the CO2 level below the recommended maximum, e.g. 1000 ppm, will depend on the CO2 concentration in the outdoor air. The typically assumed CO2 concentration of 400 ppm in the outdoor air may not be correct. In urban areas the concentration may rise to 450 ppm and more with fluctuations within the range of ±50 ppm, usually as a result of seasonal variations. Since CO2 is one of the most common by-product of all combustion processes, the CO2 concentration may be affected by strong combustion sources like chimneys of CHP units, running vehicles or low exhaust emission from local heating systems. Thus, the measurements above 500 ppm are usually interlinked with strong outdoor CO2 sources.

More advanced demand control ventilation systems supply outdoor air at changeable flow rate so that to keep the CO2 concentration level in the air exhaust from the room below a defined maximum value. This approach in the present ventilation design practice as well as in the ventilation standards and building regulations is based on the assumptions for complete mixing of air in occupied spaces. Therefore, the CO2 concentration measured in the exhaust air or in the room but far from the occupants is believed to be the same as the CO2 concentration in the air inhaled by occupants. However, this assumption is seldom accurate, especially in spaces with closely seated occupants, such as classrooms, meeting rooms, open-plan offices, etc.

3 Importance of room airflow interaction

In densely occupied rooms (lecture rooms, meeting rooms, classrooms, vehicle cabins, etc.) the CO2 sources, i.e. the people, are close to each other and the CO2 concentration in the inhaled air may be much above 1000 ppm. This is because the upward free convection flow that exists around human body may entrain the air with high

CO2 concentration exhaled by the person himself as well as by closely seated people and move it to the breathing zone. Furthermore, the thermal flows generated by occupants' body and other heat sources (e.g. windows, etc.) will interact with the ventilation flow, which may result in insufficient dilution of the generated CO2 (as well as other pollution) and high levels of CO2 concentration at the breathing zone of occupants. This can be seen in Figure 1 from the results of preliminary CFD (Computational Fluid Dynamics) simulations [15]. CO2 concentration higher than the 1000 ppm is seen around several of the simulated occupants. According to the requirements in [6] the CO2 level will be above the allowed maximum level.

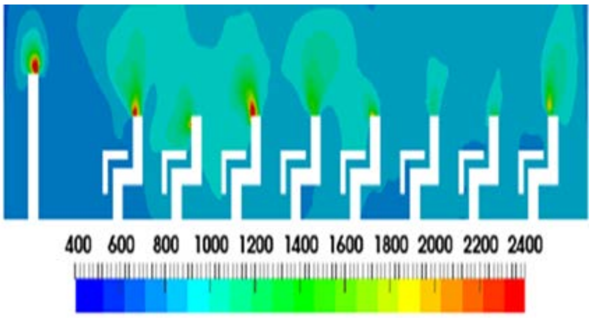

Figure 1: CFD simulation of metabolic CO2 distribution (in ppm) in a classroom with mixing ventilation.

The importance of room airflow interaction for the non-uniformity in distribution of the generated metabolic CO2 in a meeting room with six occupants was reported in [16]. The room temperature was kept at 26 °C by combined chilled ceiling and mechanical ventilation. The ventilation system supplied 44 L/s outdoor air under two air distribution patterns – mixing and displacement. Two cases, with and without buoyancy flow generated by a heated vertical surface (window) were compared. The buoyancy flows were generated by applying solar heat gain resulting in increased window surface temperature and surface temperature of the floor near to the window. The generated buoyancy flow interacted with other room flows (ventilation flow, free convection flow around occupants' body and thermal plume above occupants) resulting in increase of the exposure to metabolic CO2 by 26.9 % in the case of displacement ventilation and reduction of the exposure by 4.5 % in the case of mixing ventilation. This effect needs to be studied and considered during the ventilation design.

4 Problem validation

Experiments with people were performed to demonstrate the problem existing with CO2 exposure estimation when the present method of ventilation rate calculation based on the metabolic CO2 are used. Another important aim was to demonstrate that the recommended in the standards location of CO2 sensors are not always appropriate and can lead to unreliable control of the ventilation system and thus of CO2 exposure of occupants. In the following results showing difference between CO2 concentration measured in the inhaled air and CO2 concentration measured at the exhaust as it is typically done in practice are shown only. The results of the study will be published in a following paper.

4.1 Method

A laboratory test room with dimensions of 4.2 x 4.1 x 2.9 m^3 was furnished to resemble a meeting room for eight occupants (Figure 2). The room was ventilated by mixing ventilation. The outdoor air was supplied from two ceiling slot diffusers, 0.472 m x 0.02 m, (Figure 2). The supplied outdoor air was discharged over the ceiling as shown in Figure 2. In addition to the ventilation a chilled ceiling was used to maintain the room air temperature at 26 °C. The chilled ceiling was made of panels cooled by water. The panels covered 75% of the surface of the ceiling. A table 1.4 m x 2.0 m in size was placed in the middle of the room.

Seven persons were seated around the table (reading book, writing or working on a tablet/mobile phone). A breathing thermal manikin was used to resemble the eighth person. The seated manikin was dressed (clothing insulation 0.8 clo). The surface temperature of the manikin was kept as the skin temperature of an averaged person in state of thermal comfort. The manikin exhaled through the nose and inhaled through the mouth. The exhalation volume flow rate was set to be constant at 6 L/min. The frequency of breathing was 10 times per minute. The breathing cycle was: 2.5 sec inhalation, 2.5 sec exhalation and 1 s pause. Details on the design of the breathing manikin are provided in [17]. The exhaled air was mixed with CO2. The CO2 concentration in exhaled air was 53585 ppm. An outdoor air flow rate of 57 L/s was needed to maintain the CO2 concentration at the exhaust around 1000 ppm.

The following experimental procedure was applied: the thermal manikin was placed in the room beside the table and was switched on to generate heat as an average person. The breathing function did not operate. The heat generated by the seven persons was simulated with heaters with cylindrical shape. When the temperature reached the aimed steady-state level the seven persons entered the test room and sat around the table. The heaters were switched off and removed from the room. The breathing function of the manikin was turned on.

During the entire experiment the environment in the test room was monitored, including air velocity, temperature and humidity, surface temperature of walls, ceiling and floor, supplied rate of the ventilation air, temperature of the water in and out of the chilled ceiling, CO2 concentration at numerous points (supply and exhaust air, in the air inhaled by the manikin, at the three walls and at several heights in the room. The measuring instruments were carefully calibrated before the measurements and complied with requirements (uncertainty, characteristics, etc.) recommended in the standards. In the following only data obtained from the CO2 concentration measurements in the air inhaled by the manikin and air exhausted from the test room are

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presented to support the discussion in this paper. The CO2 concentration in the air inhaled by the manikin was measured in the artificial lung. The presented in the following results are corrected for changes of the CO2 concentration in the supplied air.

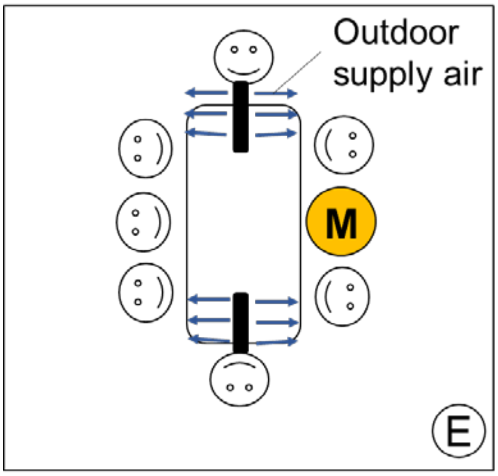

Figure 2: Set up in the test room. M – breathing thermal manikin, E – exhaust.

4.2 Results and discussion

The CO2 concentration measured in the air inhaled by the manikin and in the exhaust air is shown in Figure 3. The time average CO2 concentration for the steady state period (approx. 40 min) of the temperature and CO2 concentration in the test room is shown in the figure.

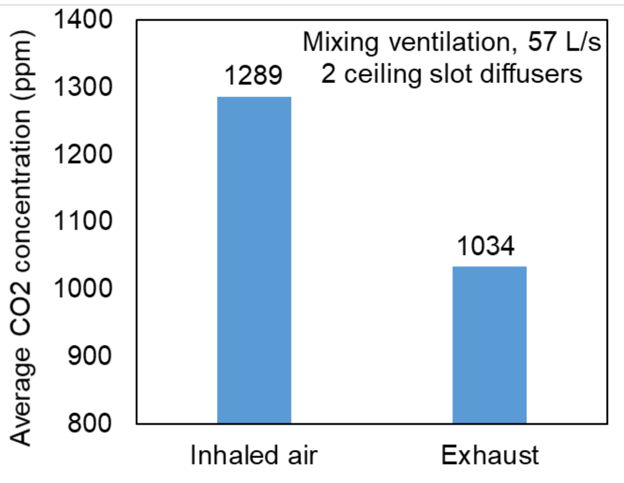

Figure 3: Average CO2 concentration in the air inhaled by the manikin and in the exhaust air.

The results in the figure show difference of 25% in the CO2 concentration in the inhaled air and the air exhausted from the room. The manikin was exposed to higher CO2 concentration than the concentration at the exhaust. These results concurred with the recently reported results [18]. In [18] the elevated CO2 concentration in the inhaled air is attributed to the personal CO2 bubble generated in the breathing zone due to the exhaled air, i.e. occupant re-inhaled part of his/her exhaled air. In our experiment the manikin exhaled through the nose and inhaled from the mouth. The air was exhaled from the nose as two free jets inclined around 45° downward and spreading apart each other in horizontal plan [17]. These jets were partially mixed with the upward free convection flow existing around the manikin, especially in front of the manikin and transported upward to the mouth where it was inhaled. This phenomenon has been studied in detail in [19, 20]. However this effect may not exist when exhalation is from the mouth and there is a pause (in average of 1 s) between exhalation and inhalation because the free convection flow with remove the exhaled air above the person. Another reason for the result reported in this paper can be the concentration of CO2 sources (people and manikin) around the table. The air in front of them above the table was insufficiently mixed and diluted with the ventilation air because of the interaction between the thermal plumes above the occupants with the flows supplied from the diffusers.

5 Practical implications

Some of the practical implications of the discussed above problem are:

- The use of the CO2 concentration measurements in the exhaust air for assessment of occupants' is not reliable;
- Due to the complex airflow interaction in rooms measurements by CO2 sensors attached on walls may not provide information on the CO2 concentration in the air inhaled by occupants;
- The control of airflow rate supply to rooms based on CO2 measurements in exhaust air or by CO2 sensors attached on walls may not be reliable.

6 Recommendations

The present results as well as results of previous studies confirm that complete air mixing in rooms seldom exists because of complex and almost not possible to control airflow interaction. There is need to either revise the requirements in the standards related to CO2 exposure (also exposure to other indoor pollutants) and control of ventilation rate based on CO2 measurements or develop new air distribution strategies. In rooms with mixing ventilation it is possible to define requirement for CO2 concentration at exhaust that is lower than the maximum allowed exposure to CO2. In order to define the value of the CO2 concentration at the exhaust research under different typical for practice combinations of ventilation rate, strength and location of heat sources (including occupants), etc. is needed. It is suggested in [20] to use desk or ceiling fan in addition to the room ventilation in order to elevate the air velocity and achieve better mixing of the room air. This approach has several disadvantages, e.g. risk of draught at the low range of comfortable room temperature. The disadvantages of the used at present total volume ventilation and the need for new approach to design room ventilation is discussed in [21]. New air distribution methods, such as non-uniform air distribution focused on the occupied areas, stratum ventilation, personalized ventilation, etc. will make it possible to control the airflow interaction in spaces and comply with realistic requirements defined in updated standards.

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