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Indoor CO_2 measurements in Serbian schools and ventilation rate calculation

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ABSTRACT

The indoor air quality in schools is very important for health and learning abilities of children. The primary indoor CO_2 source in classrooms is the respiration of school building occupants. Also, CO_2 comes from outside as a result of fossil fuels combustion. CO_2 concentration depends on a ventilation rate, size of the classroom, number of occupants and their activity and time they spend in school building. Unfortunately, ventilation rates in schools were not often measured, even in cases when inadequate ventilation caused pupils' health problems and their absence from school. The increase in indoor CO_2 concentration above the outdoor concentration is considered as a good surrogate for the indoor concentrations of bio effluents. This paper presents the research of ventilation rates in five naturally ventilated schools in urban and rural areas in Serbia during the heating season. CO_2 concentrations were measured outdoor and in three classrooms for five working days, continually. Ventilation rates are calculated based on measured concentrations of CO_2. The results have shown that classrooms in Serbian schools have inadequate ventilation during the heating period. Mean value of carbon dioxide concentration has often been exceeding 1000 ppm.

1. Introduction

Numerous studies, related to indoor air quality in non-residential and non-industrial buildings (offices, schools, etc.), were performed in Europe, America and Asia in last decades. They have mostly indicated presence of symptoms that are generally referred to the SBS (sick building syndrome) symptoms characterized by World Health Organization as: eye, nose and throat irritation, a sensation of dry mucous membranes and skin, mental fatigue, difficulty in concentration, headache, nausea and dizziness, difficulty in breathing and tight chest, stuffy, blocked and runny nose, etc. Till 1999, twenty studies (with close to 30,000 subjects), investigated the correlation of ventilation rates with human responses, and 21 studies (with over 30,000 subjects), investigated the carbon dioxide concentration connection with these responses. They found out that ventilation rates below 10 l/s per person can enhance the appearance of SBS, and increase in ventilation rate up to 20 l/s per person can significantly decrease appearance of the symptoms. On the other hand, carbon dioxide studies have supported these with findings that carbon dioxide concentrations below 800 ppm can repress sick building syndrome [1].

Indoor air quality in teaching areas can significantly affect students' activities, especially in classes with small children age from 7 to 10 since their bodies are still developing. This age group is very susceptible to respiratory infections typically reported as SBS symptoms resulting in frequent absence from school [2,3]. In addition, their learning performance depends primarily on the mental concentration which is directly related to the fresh air level in the classroom.

During their stay in school, children are exposed to many indoor air pollutants generated from indoor sources and to air pollutants that enter the building with outdoor air. Although CO_2 itself is not an indoor air pollutant and health is affected by other contaminants, increased CO_2 concentration is an indicator of insufficient ventilation. The outdoor concentration of carbon dioxide can vary from 350 to 400 ppm [4] or higher in areas with high traffic or industrial activity. The primary indoor source of CO_2 is respiration of the students whereas the level of indoor CO_2 also depends on: the number of occupants, how long the classroom has been occupied, the entering amount of outdoor fresh air, the size of the classroom and the outdoor CO_2 concentration.

Concentration of other indoor generated pollutants, especially human bio effluents, can be roughly correlated with the difference

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between the indoor and outdoor CO_2 concentrations in the air [5]. The high level of CO_2 concentration points to insufficient ventilation of indoor space. The level of indoor CO_2 has become widely used as an indicator of indoor air quality and surrogate for the ventilation rate measuring with relatively inexpensive real-time digital air monitoring equipment for carbon-dioxide concentration measurement. Also, CO_2 is used as an indicator of ventilation control optimization for different occupancy schedules [6]. Mean value of indoor CO_2 concentration [7] is used for evaluating the quality of ventilation. It has been concluded that the improvement of mechanical ventilation rate can directly contributes to the quick dilution of indoor air pollutants and non-uniformity of indoor pollutant distributions increase with the mechanical ventilation rate.

There is a widespread use of mechanical ventilation in the world, especially in the public buildings. Initially, the most important thing is to know the infiltration process, in order to reduce energy consumption. Reduction of energy consumption, on the other hand, may lead to significant deterioration of the indoor air quality. In order to minimize the energy along with maintaining the corresponding IAQ (indoor air quality) within a user-defined range, usually is developing optimization model [8]. The ecological aspect has become very important, so there is a need to take maximum advantage of the possibilities of natural ventilation [9].

By the ASHRAE standard, the lowest minimum of ventilation rate is 8 l/s per person and recommended ventilation rate is 10 l/s [10]. Human producing carbon-dioxide rate varies mainly with the duration and intensity of physical activity. For the sedentary activity (in offices, schools, dwellings, laboratories) metabolic rate is 1.2 [11] and corresponds to carbon-dioxide production of 0.3 l/s per person (Appendix C of Standard 62). Based on mass balance calculations and the assumption that outdoor CO_2 concentration is 400 ppm, this corresponds to a steady-state indoor concentration of approximately 900 ppm [12].

Indoor air quality research, conducted in 156 schools in Washington and Idaho during the period 2000–2001, has shown that a significant number of schools have ventilation deficiencies. They found out that 42% of regular and 66% of portable classrooms under investigation had CO_2 levels above 1000 ppm regardless of whether they had or didn't have mechanical ventilation system [13]. In 2006, research of IAQ in 10 old and 10 new classrooms in University of Tianjin in China has been performed beside dormitories, reading rooms and conference rooms. Temperature, RH (relative humidity), and CO_2 concentrations were continuously monitored for 12 h in each room, and out of the buildings simultaneously. Using decay method, AERs were derived from CO_2 concentration decay curves obtained when rooms were unoccupied. They found average air exchange rates in classrooms between 1.1 and 1.6 h^{-1} [14]. In Greece, they were investigated air flow and the associated indoor carbon dioxide concentrations in 62 classrooms of 27 naturally ventilated schools in Athens. They found that a flow rate was higher in only 23% of measured classrooms, than the recommended value of 8 l/p/s (which correspond to about 1000 ppm of CO_2 concentration), during the teaching period. About 52% of the presented classrooms had average indoor CO_2 concentration higher than 1000 ppm [15].

In Serbia, this kind of research has not been conducted before and therefore it is of great importance.

2. Method

Ventilation rates can be calculated from indoor and outdoor carbon dioxide measurements based on fact that ventilation is the only significant process for carbon dioxide removal. In naturally ventilated schools carbon-dioxide in a classroom comes with outdoor air and depends on environment. From the other side, it can be generated indoor by occupants' exhalation and strength of that source is based on the number of occupants and their activity. Taking into account that classrooms are spaces with high occupancy per square meter, indoor carbon dioxide concentration exceed outdoor concentration considerably. With the assumption that inside air is well mixed, the air exchange rates are calculated on the basis of indoor and outdoor carbon-dioxide concentrations by the decay method. The time derivative for indoor concentration of air contaminant in general [16] is given by:

$$V\frac{dC}{dt} = Q \cdot C_o - Q \cdot C(t) + S - k \cdot C(t) \tag{1}$$

Formula (1) is given in general for whichever indoor contaminant. The change in CO_2 concentration dC/dt = inflows − outflows + sources − degradation; C_o, $C(t)$ are outdoor and indoor contaminant concentrations, respectively; Q are air flow into/out of the building; S is the indoor emission source of the contaminant; k is the first-order degradation constant.

For the conservative contaminant such as CO_2, there is no degradation, i.e. $k = 0$. Besides that, if there is no indoor source of CO_2, i.e. $S = 0$, Equation (1) will become much simpler:

$$V\frac{dC}{dt} = Q \cdot (C_o - C(t)) \tag{2}$$

This assumption is valid for the period that starts at the end of the last lesson (when pupils leave the classroom) and ends when the indoor and outdoor concentrations of CO_2 are almost equal. In this case, integration of the Equation (2) will give following formula for the determination of the indoor CO_2 concentration:

$$C(t) = C_o + [C(0) - C_o] \cdot e^{-\frac{Q}{V}t} \tag{3}$$

where $C(0)$ is the indoor CO_2 concentration at time $t = 0$; Q/V is air exchange rate (AER). After rearranging, Equation (3) will give the following:

$$AER = \frac{1}{t}\ln\frac{(C(0) - C_o)}{(C(t) - C_o)} \tag{4}$$

3. Measurements

Indoor air quality is in very high correlation with outdoor air quality and depends on number of indoor (people, furniture, paints, etc.) and outdoor (industry, traffic, combustion, etc.) pollutants' sources emitting pollutants into the atmosphere with different level of intensities. Assuming that the air quality is not the same in rural and urban areas, five locations were chosen for this analysis to cover variety of environments. Monitoring of indoor and outdoor CO_2 concentrations was performed in five primary schools placed at different locations in Serbia during the heating season. One village school was chosen as a representative of rural area, three schools from towns as representatives of small urban areas and one school from the city as a representative of big urban area. The measurements were conducted in three classrooms (three indoor measuring points) and one outdoor measuring point of each school continually for five working days from Monday to Friday (including occupied and unoccupied periods of time). During occupancy, between 20 and 30 pupils, age from 7 to 10, were present in each classroom. Carbon dioxide sensors were placed in the selected classrooms at approximately about 1.1 m above the floor, away from the windows and doors, and at least 1 m from occupants. Measuring range of CO_2 sensors was between (0–10,000) ppm with