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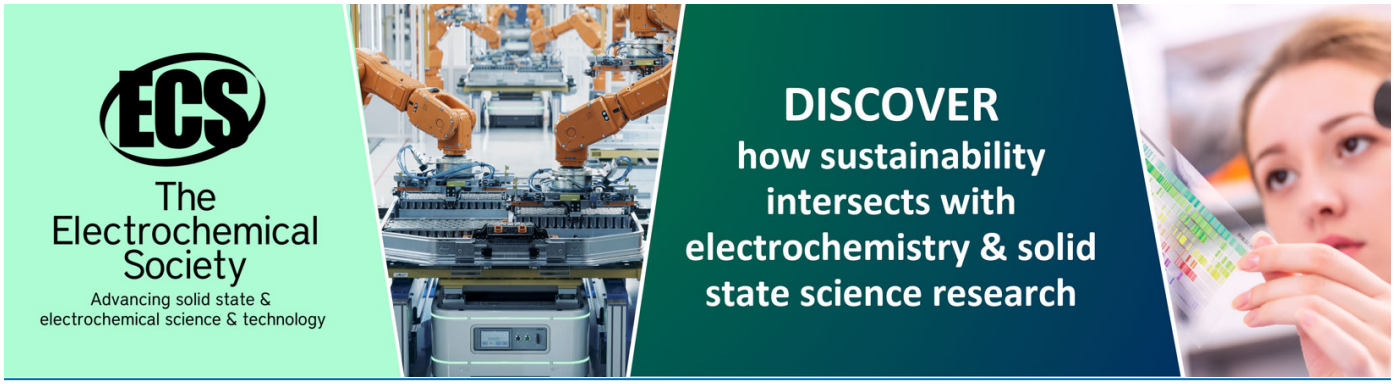

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IOP Conf. Series: Materials Science and Engineering **867** (2020) 012008 doi:10.1088/1757-899X/867/1/012008

Indoor air quality in classrooms of a newly built school

K Harčárová[1]
[1] Technical university of Kosice, Faculty of Civil Engineering, Department of Environmental Engineering, Slovakia

Abstract. The presented paper deals with the evaluation of the quality of the indoor environment in a new school building with modular construction. The required short-term measurements were carried out in two selected classrooms. Selected physical-chemical factors such as thermal comfort, sound level, lighting conditions, concentration of CO_2, particulate matter ($PM_{0.5}$-PM_{10}) and total volatile organic compounds (TVOC) were monitored. Based on the obtained results, it was shown that the values of operative temperature, relative humidity and air velocity measured in selected rooms meet the requirements given by legislation. The average CO_2 concentration was exceeded in both classes, which may lead to headaches and concentration problems in pupils. Concentrations of $PM_{2.5}$ were below the acceptable limit, while PM_{10} concentrations were exceeded in both classes. The recommended TVOC concentration of 200 μg/m^3, which does not yet cause discomfort and has no adverse health effects, was exceeded in both classrooms.

1. Introduction

Polluted indoor air is currently considered to be one of the most important determinants of environmental quality and public health. The indoor environment in schools is an important factor, as children belong to a particularly vulnerable group of population. Nowadays, it is generally known that children spend on average six hours a day and five days a week in one classroom at school. There is plenty of evidence of the potential harmful health effects of many indoor air pollutants that can be found in school environments that originate from ambient air or arise indoors from various materials, products or activities. The presence of pollutants in schools can also affect children's growth, their learning performance as well as their cultural and social development. Indoor air pollution in schools is complex and variable and can have different origins (exterior, interior) and nature (physical, chemical and biological). The most frequently monitored indoor pollutants include particulate matter ($PM_{0.5}$-PM_{10}), carbon dioxide (CO_2) and total volatile organic compound (TVOC). Kalimeri et al. evaluated the quality of the indoor air in three schools. Based on the results, it was shown that the concentrations of selected volatile organic compounds were within acceptable limits. Average indoor temperature and relative humidity during pupils occupancy ranged from 20-26 °C and from 40.1-52.2% respectively for the non-heating period and from 15-24 °C and from 31.4-50.7% for the heating period [1]. According to Simanic et al. median values of indoor air temperatures were between 19-23.5 °C in all monitored classes during school hours. The 90-percentile levels of CO_2 concentrations were below 1000 ppm in 60 of 61 classes [2]. Benett et al. found that the average indoor level of PM_{10} during the school day (30.1 μg/m^3) was significantly higher than the outdoor level (8.9 μg/m^3). A more detailed analysis of the samples revealed that the indoor PM_{10} was primarily composed of bark (soil) elements likely to be introduced into children's footwear. The presence of $PM_{2.5}$ was due to external infiltration from motor vehicle emissions [3].

The main aim of this study is to evaluate the quality of the indoor environment in the school building. Air monitoring was performed in two representative school classes. In each class, in addition to thermal, acoustic and light comfort, concentrations of CO_2, particulate matter and TVOC were also monitored.

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2. Methodology

2.1. School location and classroom characterization

The monitoring of selected physical and chemical factors of the internal environment was carried out at a primary school in the village of Veľký Biel situated in western Slovakia. The building is specific in that it is the first school building with a modular construction in Slovakia. Indoor air quality measurements were realized in winter season in two selected classes (class A and class B), which represent the types of classes in which different conditions and measured values can be expected to occur. During the measurements, there were 12 children and 1 adult in the class A and 15 children and 1 adult in the class B. In both classes, regular air exchange was ensured by natural ventilation. The classrooms were equipped by standard school furniture consisting of wooden school-desks and chairs, an interactive whiteboard, several particleboard cabinets and playing mat.

2.2. Instrumentation

All measuring instruments were located in the back of the classrooms for security reasons and to avoid disturbing the teaching process. The devices were placed approximately at a height of about 1.1 m in the breathing zone of occupants. Thermal comfort parameters, light comfort parameters and CO_2 levels were determined using a TESTO 435-4 multifunction instrument with appropriate probes (Testo, Inc.; Germany). The concentration of CO_2 was measured in classes with natural ventilation. The illuminance (E) was measured within the lighting network at a height of about 1.1 m. A hand-held noise analyzer - Brüel and Kjaer Type 2250 (Brüel & Kjaer; Denmark) was used to measure equivalent sound levels (LAeq). These measurements were carried out for 1 hour. The particulate fraction concentrations of 0.5-10 μm ($PM_{0.5}$-PM_{10}) were determined using a HANDHELD 3016 IAQ (Lighthouse Worldwide Solutions, Inc., USA) measuring instrument, which uses a laser-diode light source and collecting optics for particle detection. The measurement was performed with a real-time direct-reading device for 50 minutes. Total concentrations of volatile organic compounds were determined by a ppbRAE 3000 photoionization detector with UV lamp (RAE Systems, Inc. USA). Two-point calibration, zero and standard reference gas (isobutylene) was performed prior to measurement. All measured concentrations were converted and are expressed in toluene equivalents.

3. Results and discussions

The results of the measurements of the monitored indoor air quality (IAQ) parameters are summarized in table 1. This table also includes statistical processing of measured data.

Table 1. Summary of IAQ results in classroom A and B.

Classroom	Statistics	Indoor air temperature [°C]	Relative humidity [%]	CO_2 [ppm]	$PM_{2.5}$ [μg/m^3]	PM_{10} [μg/m^3]	TVOC [μg/m^3]	LAeq [dB(A)]	E [lx]
A	average	23.6	43.8	1238	16.0	154.6	2256	79.5	1122
	min	22.3	37.4	732	10.6	46.0	1416	71.6	-
	max	25.0	51.5	1709	20.4	272.6	3367	85.1	-
	standard deviation	0.8	4.5	293.5	3.7	78.9	581.4	5.4	-
B	average	22.4	45.2	1415	12.7	88.6	2847	73.6	364
	min	21.9	37.2	705	9.1	33.8	2490	59.1	-
	max	22.7	47.9	1615	14.0	112.4	3150	85.7	-
	standard deviation	0.2	3.6	224	1.0	17.2	174.9	12.3	-

3.1. Thermal comfort

The average air temperatures in the selected classes were 23.6 °C (class A) and 22.4 °C (class B). The average relative humidity values in the selected classes A and B were 43.8% and 45.2%, respectively. Required range of relative humidity (30-70%) according to Decree no. 259/2008 Coll. was fulfilled in all the monitored classes [4]. The average air velocity should not exceed 0.2 m/s. This legislative

requirement has been met in both cases. As can be seen in the figure 1, the air temperature during the measurement had a decreasing tendency. The lowest recorded air temperature was 22.3 °C and the highest was 25 °C. Figure 2 shows the course of temperature and relative humidity during the hourly measurement in class B. The lowest recorded air temperature was 21.9 °C and the highest was 22.7 °C.

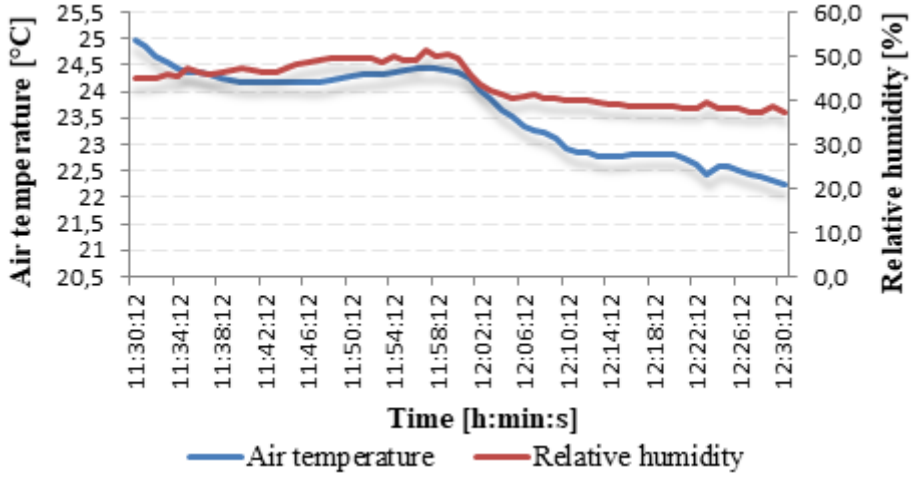

Figure 1. The course of temperature and relative humidity in class A.

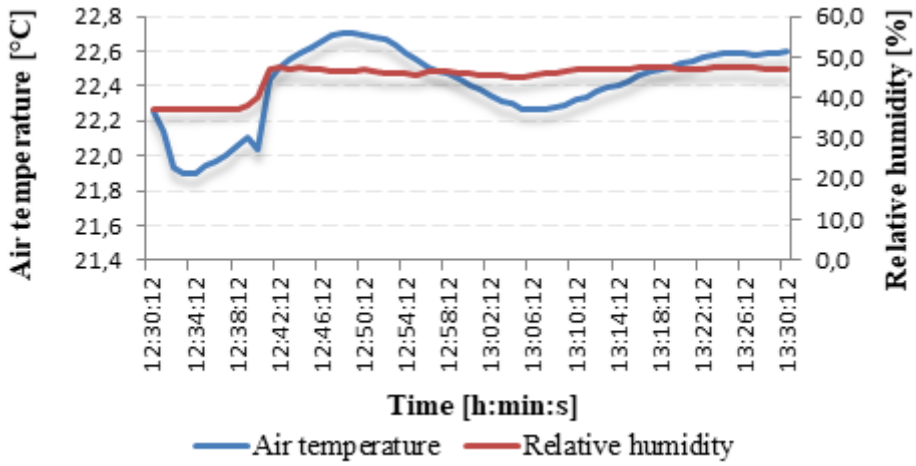

Figure 2. The course of temperature and relative humidity in class B.

3.2. Light and acoustical comfort

The average level of illuminance was 1122 lx in class A and 364 lx in class B. In the second case, the measured value did not reach the minimum allowed value of 500 lx, which is given by Decree no. 259/2008 Coll. [4]. This value was 27.2% lower than the limit value.

The measured values of equivalent sound levels (LAeq) are shown in Table 1. The lower average LAeq value was found in class B, i.e. in a class with less number of pupils. The limit value of 40 dB (A) as given by Government Decree no. 115/2006 Coll., was exceeded in both classes almost twice [5].

3.3. Concentrations of CO_2

The course of CO_2 concentrations in class A in the presence of 12 children and 1 adult is shown in figure 3. The CO_2 concentration at the beginning of the measurement was 1185 ppm and at the end 732 ppm. Figure 4 shows the course of CO_2 concentrations in class B in the presence of 15 children and 1 adult. In this class, the temperature at the beginning of the measurement was 722 ppm and at the end of the

measurement 1559 ppm. In both classes, the average CO_2 concentration values exceeded the recommended value of 1000 ppm given by Pettenkofer [6].

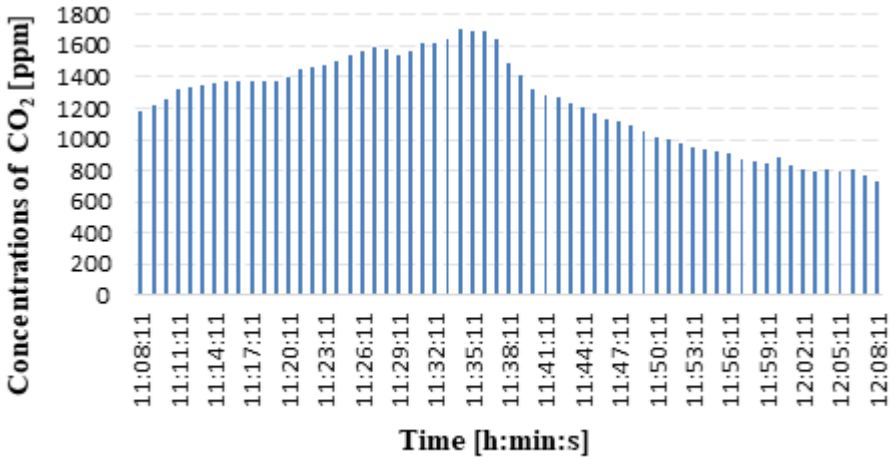

Figure 3. The course of CO_2 concentrations in class A.

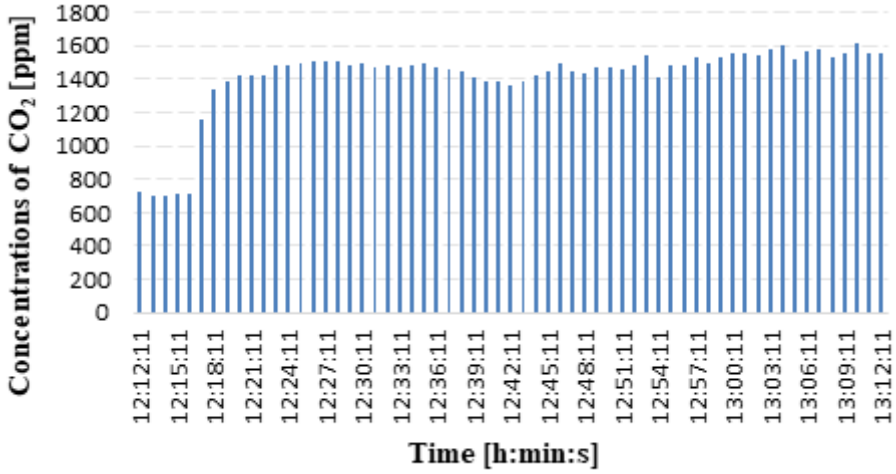

Figure 4. The course of CO_2 concentrations in class B.

3.4. Concentrations of particulate matter

In class A, $PM_{2.5}$ concentrations ranged from 10.63 µg/m^3 to 20.38 µg/m^3 and PM_{10} concentrations from 45.97 µg/m^3 to 272.60 µg/m^3. In the class B, $PM_{2.5}$ concentrations ranged from 9.07 µg/m^3 to 13.97 µg m^3 and PM_{10} concentrations from 33.82 µg/m^3 to 112.36 µg/m^3. The average concentrations of $PM_{2.5}$ and PM_{10} in the classes were 15.96 µg/m^3 and 154.63 µg/m^3 for class A and 12.65 µg/m^3 and 88.65 µg/m^3 for second class B. The maximum permissible value of PM_{10} particulate concentration is according to Regulation 210/2016 Coll. 50 µg/m^3 [7]. This limit value is set for 24-hour human exposure. The measurement of the particulate matter concentrations did not take 24 hours, but to understand the really high levels recorded in the selected classes, the measured values were compared with this limit value. Concentrations of PM_{10} in class A were three times higher than the limit value, which represents a 67.7% exceedance of this limit value. In class B, it was observed that this limit was exceeded by 38%. Figure 5 and 6 show the course of particulate matter concentrations of all measured fractions over 50 minutes of measurement. As can be seen, concentrations fluctuated because measurements were made under natural ventilation conditions.

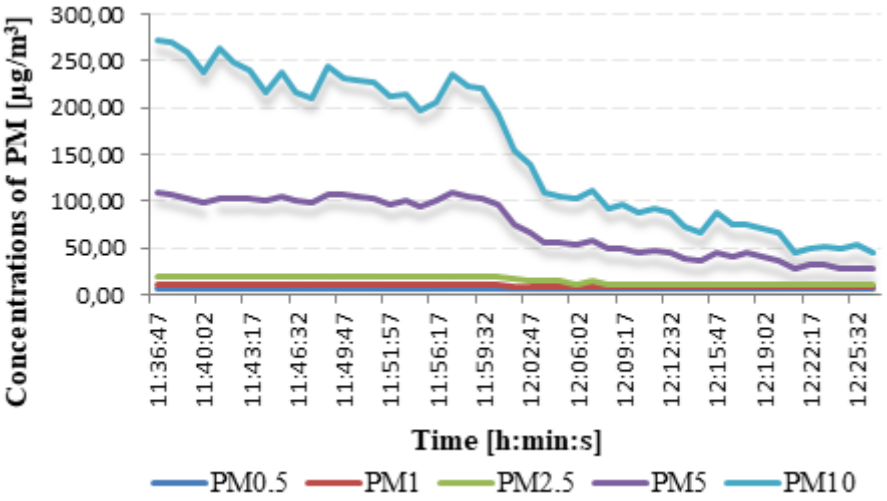

Figure 5. The course of $PM_{0.5}$-PM_{10} concentrations in class A.

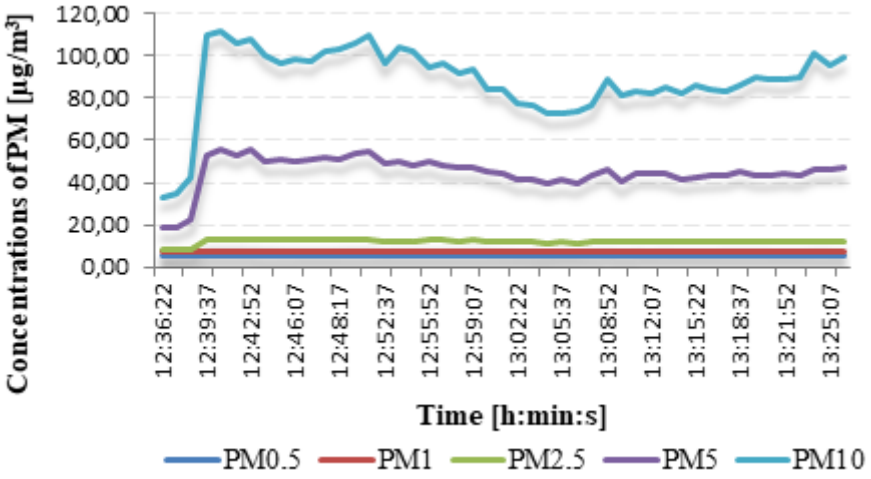

Figure 6. The course of $PM_{0.5}$-PM_{10} concentrations in class B.

3.5. Concentrations of total volatile organic compounds

In class A, concentrations ranged from 1416 to 3367 µg/m^3 with an average value of 2256 µg/m^3. In class B, concentrations ranged from 2490 to 3150 µg/m^3 with an average value of 2847 µg/m^3. The recommended concentration of TVOC, which does not yet cause discomfort or adverse health effects according to Mølhave with a value of 200 µg/m^3, was exceeded several times in both classes [8]. In class A the limit value was exceeded by 91.1% and in class B by 93%. A significant decrease in TVOC concentrations was observed in class A, as the air exchange in the class was ensured by natural ventilation.

4. Conclusion

The average relative humidity values in the selected classes were 43.8% and 45.2%, respectively. Based on the measurement, it can be concluded that the relative humidity has reached the optimum range of 30-70% given by legislation. The permissible air velocity for the activity class should be $0 \leq 0.2$ m/s. This legislative requirement has been met in both cases. The average level of lighting in class B did not reach the required limit set by legislation. The lower average LAeq value was found in the second class, i.e. in a class with less pupils. The limit value of the equivalent sound level was almost doubled in both classes compared to legislative values. The average CO_2 concentration was exceeded in both classes, which can cause discomfort and concentration problems. Concentrations of CO_2 mostly fluctuated

because pupils were present in the classroom and natural ventilation was maintained in the classroom. Higher $PM_{2.5}$ and PM_{10} concentrations were observed in the first class. In both cases, the concentrations were fluctuating, as the measurements were carried out under natural ventilation. The recommended TVOC concentration of 200 $\mu g/m^3$, which does not cause discomfort or adverse health effects according to Mølhave, was exceeded in both classes by 91.1% and 93%. On this basis, it can be assumed that pupils and teachers may experience health problems due to high concentrations of TVOC.

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Acknowledgments

This study was financially supported by Grant Agency of Slovak Republic to support of project No. 1/0307/16 and project NFP313010T578.