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Challenges in achieving a high indoor air quality in an educational building

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Abstract: *Achieving a good indoor air quality in already built schools has been a challenge during the last decades. Different solutions have been proposed as an alternative to natural ventilation by opening windows. In this article we propose a simpler approach but yet effective to solve the problem. Using hybrid ventilation between hygroscopic air vent and a window fan can reduce drastically the indoor pollution. In fact, during the experimental campaign we have measured and calculated lower CO2 levels (aprox.1200 ppm) while in the non-ventilated classroom these values were approaching 2500 ppm. The humidity was also a parameter that needed to be monitored as it can influence the indoor environment. The calculations demonstrated that for 30 pupils in a classroom an airflow of 600 m^3/h is the ideal solution.*

Key words: indoor air quality, schools, ventilation systems, experimental and numerical results

Rezumat : *Realizarea unei bune calităţi a aerului interior în şcolile existente a devenit o provocare în ultimii ani. Diverse soluţii de ventilare au fost propuse şi investigate, ca alternativă la ventilarea naturală prin deschiderea ferestrelor de către ocupanţi. În acest articol propunem o metodă simplificată dar eficientă pentru rezolvarea acestei probleme. Prin utilizarea unor fante higroreglabile încastrate în tâmplăria existentă, respectiv prin montarea unui ventilator axial de fereastră se obţine reducerea drastică a concentraţiilor de CO2 din aerul interior al unei săli de clasă (până în jur de 1200 ppm), prin comparaţie cu cazul unei săli neventilate, la care concentraţia interioară poate atinge sau depăşi 2500 ppm. Umiditatea a fost de asemenea un parametru investigat în cadrul studiului. Calculele au demonstrat că, pentru o clasă cu ocupare maximă de 30 de elevi, un debit de aer introdus de aproximativ 600 m^3 /h constituie soluţia ideală.*

Cuvinte cheie : calitatea aerului interior, şcoli, sisteme de ventilare, rezultate experimentale şi numerice

1. Introduction

Acceptable indoor air quality is defined as air in which there are no known contaminants at harmful concentrations, as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction [1].

Indoor air composition is affected by the presence of several contaminants, both belonging to external air and indoor sources [2]. In fact, external air enters in the buildings by the means of ventilation of environments, so its contaminants are found in the indoor environment as well, while furnishing, building materials, people, and bad maintenance of air conditioning systems could be internal pollution causes.

Indoor air quality in schools can have a substantial impact on children's health, as an important environment where children may be exposed to pollutants and allergens. Schools should ensure a pleasant indoor environment for children away or apart from their home, as they may spend 10 hours per day at school, and at least 10 hours per year [3,4] depending on the time that they arrive at the school and the time they leave the school. It is special concerns since the pupils are susceptible to poor IAQ. Indoor air pollutants might increase the chance of both long and short term health problems among pupils and staff, reduce the productivity of teachers and degrade the pupil's learning environment and comfort [5]. A significant influence from indoor environmental quality can effect and give the influence on student attendance and performance. Studies have shown that poor indoor air quality led more illnesses, school absenteeism and asthma attacks.

As stated in the REHVA Guidebook for IAQ in schools [2], for a classroom where the main pollutant sources are associated to human occupancy, it is usual to apply the analytical assessment method based on the carbon dioxide (CO2) concentrations profiles. CO_2 is a colorless, inodorous and tasteless gas, present in the outdoor atmosphere at a concentration that nowadays is about 380 ppm (0,68 g/m^3), for a non-polluted region. Its presence in non-industrial indoor environments is due mainly to human breathing processes and tobacco smoke. It may also be originated by other combustion processes (gas heaters, fire places, ovens, etc.).

Several studies have analyzed the impact of low ventilation rates and increased CO_2 concentrations on IAQ complaints and health symptoms in buildings. It is found that high CO_2 concentrations in office buildings are associated with increased health symptoms from the occupants [6,7].

In an existing study performed for commercial and institutional buildings [8], 20 case studies have been analyzed, that found a statistical significant relation between air flow rates below 10 l/s and increased IAQ and health symptoms among the occupants. For higher ventilation rates, even 20–30 l/s/person, a significant reduction of occupant symptoms is observed but not for all studies.

A similar correlation between higher CO_2 concentrations and increased frequency of health symptoms was found as well. On the counterpart, in another study [9] it is reported that complaints on poor indoor air quality in schools were not related to low ventilation or increased CO_2 levels. Based on the results reported in [8], the EUROVEN multidisciplinary group [10] has proposed a ventilation threshold equal to

25 l/s/person, above which the IAQ and health risks may be significant. The group suggested that such a ventilation threshold is applicable to school buildings as well.

According to a study related to natural ventilation in schools [11], the airflow rates and the corresponding carbon dioxide concentrations collected from 62 classrooms in 27 schools from Athens, Greece, compared the existing information on the ventilation rates and carbon dioxide concentrations for 287 classrooms of 182 naturally ventilated schools, as well as for 900 classrooms from 220 mechanically ventilated schools, found that for almost 77% of the classrooms the airflow rate was below 8 l/s/person. The ventilation rate was varying between 2 and 11 l/s/person, with a median value close to 4.5 l/s/person. As it concerns the impact of indoor CO2 concentrations on window opening, it had been found that about 45% of the window openings occurred for CO2 concentrations below 1000 ppm and 70% below 1500 ppm. Also 18% of the cases are associated to indoor CO2 levels above 2000 ppm, with much higher air flows measured during the breaks period. Statistical analysis has shown that there is not any important trend or preferred CO2 level for window opening.

Another study [12], measured the IAQ in three Romanian countryside schools (one old, one renovated and one new), showing CO_2 concentrations at an average that exceeded the recommended norms at around 2000-3000 ppm during a typical school day with spikes passing 4000 ppm, approaching the 5000 ppm health hazard. The study shows that the ventilation rates are also deficient in every building 2,4 l/s/person—for renovated schools, 2,25 L/s/person—for new schools and 0,7 l/s/person—for old schools.

Contrary to that, a study [13] carried out during spring 2013 in 9 naturally ventilated primary schools of Attika basin in Greece showed that the average ventilation rates in all schools were, in general, greater than the minimum recommended ventilation rates, showing that the classrooms were well ventilated for certain cases. The increased infiltration rates for certain classrooms were attributed to increased values of wind speed and also to air leakages due to older building constructions. Also it was noted that classes using white board markers had higher VOC concentrations, as for the CO_2 concentrations, they were lower than the limit values.

Exposures to volatile organic compounds (VOCs) have been an indoor environmental quality (IEQ) concern in schools and other buildings for many years. Indoor and outdoor VOC sampling in 37 recently constructed or renovated schools across the U.S. Midwest[14] was conducted to investigate exposure in schools and potential associations with environmental parameters and building type. Outdoors, benzene, toluene, p,m-xylene, C6 and chloroform were found to be most abundant with median concentrations from 0,1 to 2,4 μg/m3. Indoors, benzene, toluene, p,m-xylene, d-limonene, and n-hexane were found most commonly with median concentrations from 0,3 to 3,5 $\mu g/m^3$.

Building inspections suggested several VOC sources, e.g., paints, cleaning products, flooring materials, air fresheners, and industry, and VOC levels were inversely associated with air exchange rates. For many compounds, the within-school variance of VOC concentrations exceeded the between-school variance, indicating the role of local sources, independent ventilation systems, and human activities. Overall, VOC concentrations were mostly low and measured concentrations in this study (2015–2016) appear to have declined from levels measured in previous decades. This suggests the effectiveness of VOC controls on outdoor sources and the widespread use of low-emission materials and products, and that these factors have offset possible increases in concentrations due to the low air exchange rates in new and "tight" buildings.

The school environment is where children spend a significant part of their young years. Children are a population group which is particularly vulnerable to environmental exposure due to their immature, growing and developing bodies [15]. This means that the impact of such exposure has the potential to go far beyond discomfort, or even ill health conditions, and can lead to a lifelong burden of disease. It is therefore of critical importance to ensure that schools are clean, comfortable and healthy environments which enable children to thrive physically and mentally.

While there is a large body of quantitative evidence on the impact of air pollution on adults, with exposure to ambient $PM_{2.5}$ being number eleventh global risk factor, quantitative understanding of the impacts on children is still limited and the outcomes of different studies inconsistent. This is a significant gap in knowledge and so more research is needed on exposure response relationships for children to find out whether the health guidelines developed based on adult's epidemiology sufficiently protect children, or whether different guidelines are necessary to protect children [16].

The health of the future generation will depend on how well the complex school environment is understood and how its design is optimized to ensure both thermal comfort and adequate ventilation to remove classroom-generated pollution, and the supply of good quality outdoor air (which means filtered if necessary). In doing this, energy usage should be an equally important focus, to prevent further combustion emissions to the environment [16].

2. Presentation of the case study

The experimental study was realized in two identical classrooms located in the National College of Mihai Viteazul in Sectorul 2, Bucharest, one of the most famous high schools. The classrooms are located on the first floor, in the middle of the building, with windows facing the west side (fig.1).

The walls are made of brick, the dimensions of the classrooms are: length 9 m, width 6.8 m, height 4.9m, resulting a total area of 61.2 m^2 and a volume of 300 m^3 (fig.2). The glazed surface is made up of three windows double-glazed windows with wooden carpentry with a crescent top and a rectangular lower part with a width of 1.5 m. In the classroom there are 34 wooden benches grouped two by two plus the chair of the teacher. The entrance door is double-sided and has a total width of 1.3m.

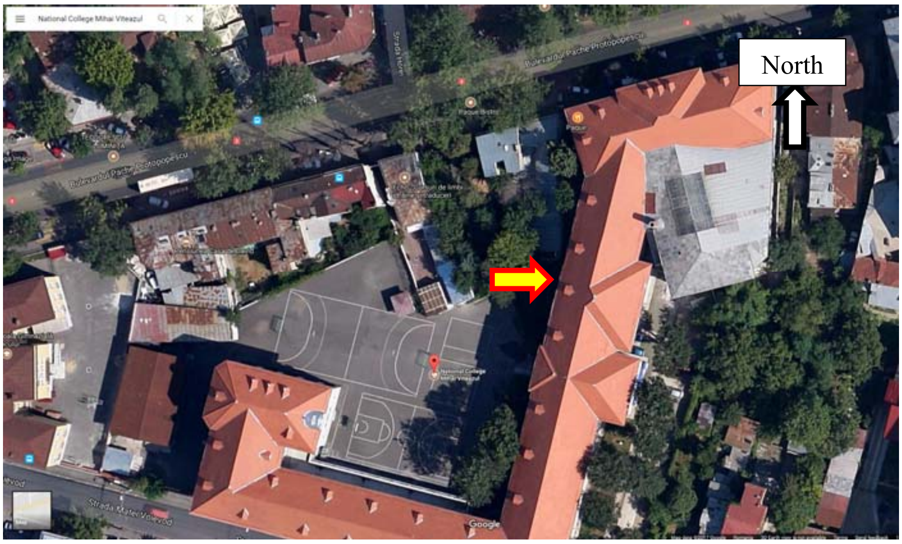

Fig. 1 – Position of the classroom

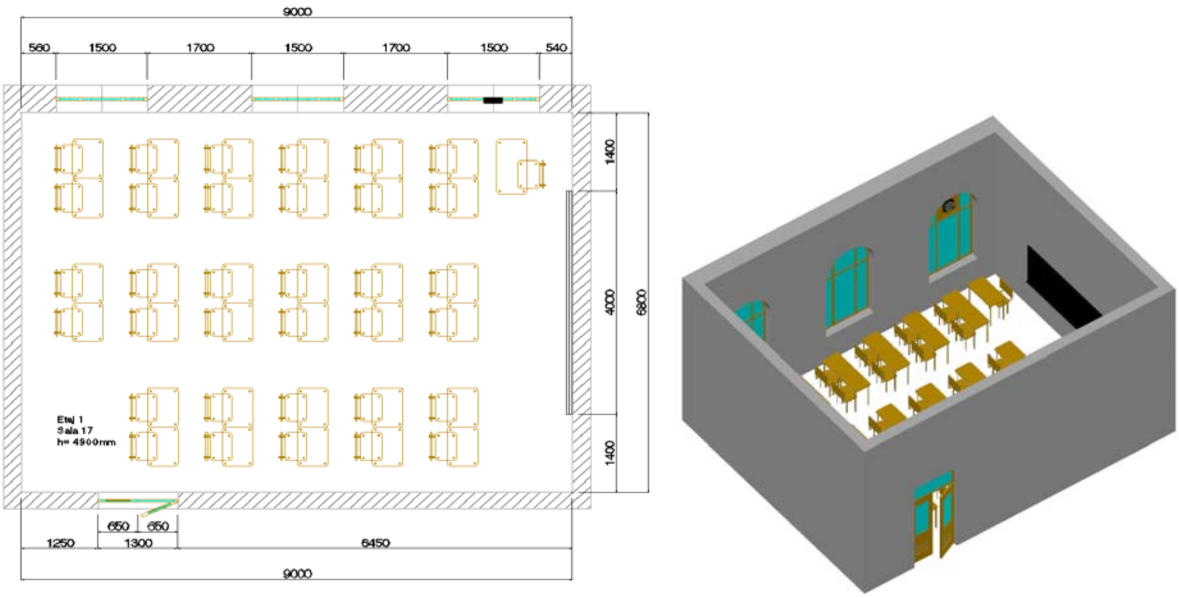

Fig. 2 – Classroom dimensions and 3D Model

The study was realized for classroom S16 – non ventilated and classroom S17 – ventilated with two strategies. The main ventilation system is an assembly consisting of a reversible fan (can insert or evacuate air from the classroom) of the axial type, mounted at the top of the window in front of the classroom, the air can be introduced or discharged through it. At the bottom of the entrance doors of the classroom behind the classroom in diagonal with the fan there are mounted transfer grids in order to let the vicious air come out of the classroom or get cleaner air from the corridor. The maximum airflow rate of the fan is 600 m3 / h. The fan is also equipped with an automatic closing flap, when the fan is off, the grid will close. Both the fan and transfer grilles are painted in the color of the carpentry (brown) in order not to stand out and not to spoil the layout of the course room.

The introduction of fresh air into the classroom is done by means of a double deflection grid, the latter being able to control and direct the air both horizontally and vertically in order not to disturb the occupants of the classroom. Noise reduction was made using a specially designed and created noise attenuator for this type of fan or classroom. Sound reduction was satisfactory, Inside the classroom is a noise below the limit imposed by norms.

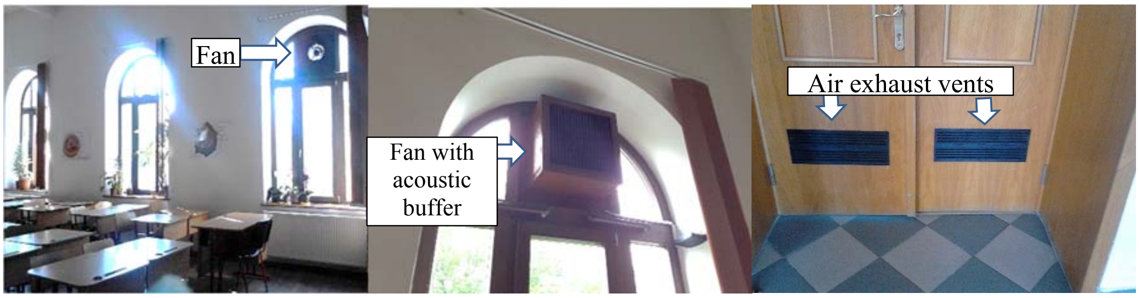

Fig. 3. Photos of the ventilation system

The secondary ventilation system consists of the hygroscopic air vents mounted in the upper part of the window carpentry frame. On each window, two grids with a maximum flow rate of 30-45 m^3/h were installed, resulting in a maximum total flow rate of 180 m^3/h in the classroom. This type of ventilation system has no energy consumption and does not require maintenance. Each grid is provided with an actuator handle in which the closed, open or automatic operation can be set. Automatic operation means opening and closing the grid depending on the humidity inside it. When students enter the room, the relative humidity will increase, so the grid will open to allow fresh air to enter the room, as they leave the classroom, the humidity decreases and the grids will close to maintain a humidity preset in the working area.

3. Monitoring the indoor air quality by numerical and experimental methods

Setting of Indoor Air Quality is made by dividing it in IDA categories depending on building destinations, activities and the type of pollution (Table 1). For civil buildings the main source of pollution is represented by human bio-effluents and the air quality for non-smoking rooms is categorized by accepted CO_2 levels above outdoor air levels, according to Table 2.

Table 1

Classification of indoor air quality (I5-2010) IDA = Indoor air

Category	Description
IDA 1	High indoor air quality
IDA 2	Medium indoor air quality
IDA 3	Moderate indoor air quality
IDA 4	Low quality of indoor air

Table 2

Categories of indoor air quality according to CO2 concentration above outdoor air levels concentration (I5-2010, EN 16798-1:2016)

Category	Corresponding CO_2 concentration above outdoors [ppm]	
	Typical range	Differential CO_2
IDA 1	≤ 400	350
IDA 2	400-600	500
IDA 3	600-1000	800
IDA 4	≥ 1000	1200

To be in compliance with Romanian Norm I5 about indoor air quality, was calculated the difference between CO_2 levels measured inside and outside the building. This way, building was considered in one category from Table 1. The maximum measured outdoor air level of CO_2 was 510 ppm, and the minimum was 380 ppm. 420 ppm will be considered as reference value. Figure 4 shows the evolution of the CO_2 levels in case of non-ventilated room S_{16} during the experimental study (4-5 April 2017).

If we trail the variation of difference inside/outside levels of CO_2 (continuous line) we will see that the values are located in the interval 1500-2000 ppm, even 2300 ppm when the classroom is full of people during several hours. Any exceedances with more than 1000 ppm of the inside/outside levels of CO_2 setting the S_{16} classroom in IDA4 category of ambiance (low quality of indoor air). During the second day were obtained values even twice, values corresponding of IDA 4 category.

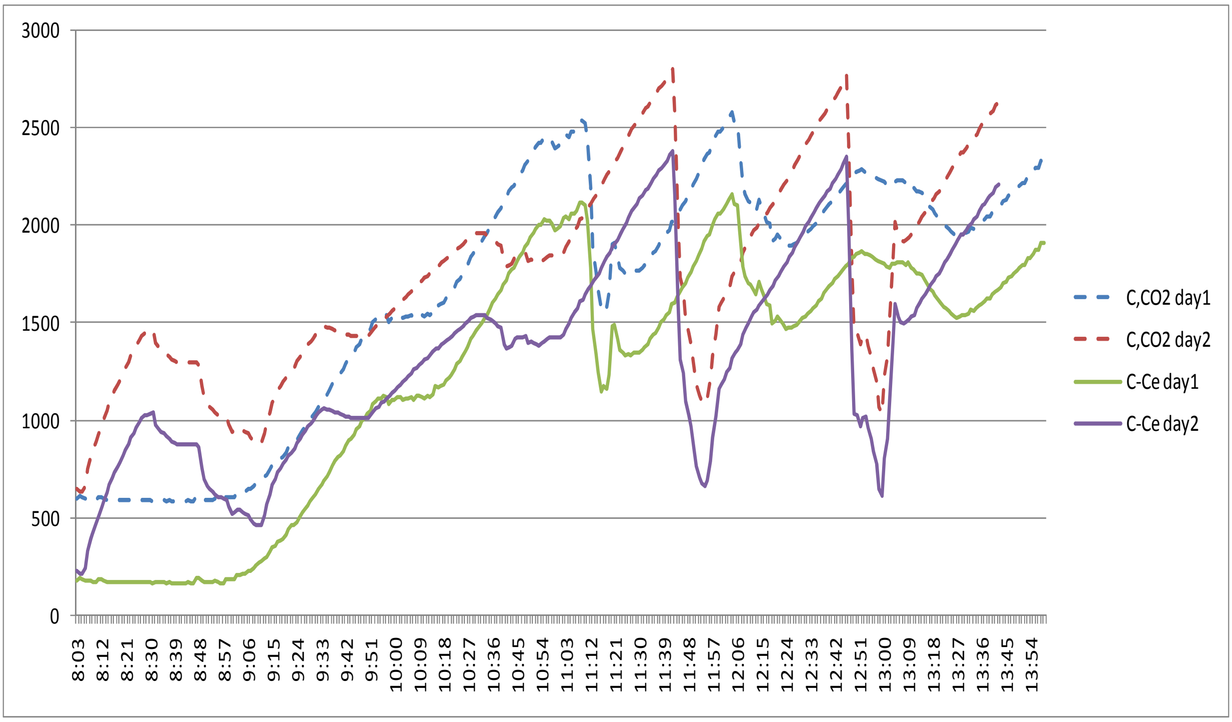

Fig. 4. CO_2 inside levels and inside/outside levels difference for non-ventilated classroom S16

Due to the fact that the classroom was ventilated with a constant flow of fresh air of 450 m3/h and the number of occupiers of the room was moderate as value (between 12 and 24 persons), difference between CO_2 levels inside and outside only 700 ppm maximum, which led to category IDA 3 for the classroom S17 (moderate quality of indoor air). If the fresh air flow rate is increased, the situation can be improved. The situation can be improved if the flow of fresh air is increased by operating the fan at higher speed. The need to increase the air flow becomes a must due to fact of increasing the number of people in the room with the purpose to maintain quality of indoor air at least in the class IDA3.

In accordance with the national I5 Norm, for rooms where the ambient criteria are determined by the human presence, indoor air quality will be ensured through the ventilated fresh airflow which is determined according to the destination of the rooms, the number of occupants and their activity and the pollutant emissions of the building (from the construction elements, finishes, furnishing and the installations).

Relation (1) expresses this idea, by summing required fresh air flow needed for humans with the fresh air flow needed for the room's surfaces and type of building.

Accordingly, the required air flow rate, q [m3/h]:

$$q = N * q_p + A * q_B \qquad (1)$$

where: N - number of persons,

q_p –fresh air flow rate for person, [m3/h/pers], from Table 3

A - floor surface area, [m2],

q_B- fresh air flow rate per 1 m2 of floor [m3/h/m2], Table 4.

Table 3

Fresh airflow rate for one person (Norm I5:2010)

Category ambiance	Predicted Percentage of Dissatisfied PPD [%]	Flow rate per person [m^3/h]
I	15	36
II	20	25
III	30	15
IV	> 30	< 15

Depending on the pollutant emissions, buildings are classified in: very low polluting buildings, low polluting buildings and polluting buildings (table 4).

Table 4.

Fresh airflow rate for 1 m^2 of surface (Norm I5:2010)

Category ambiance	Flow rate per m^2 floor area [m^3/h (m^2)]		
	very low polluting buildings	low polluting buildings	others
I	1.8	3.6	7.2
II	1.26	2.52	5.0
III	1.1	1.44	2.9
IV	lower than the values for category III		

For the two classrooms considered - S_{16} and S_{17} the required air flow needed for ventilation can be determined using relation (1) and considering the ambient class II/III and building as very low polluting. It is assumed that are no pollutant emissions from construction materials and furniture. For a maximum number of people in the room will result an air flow rate of 830 m^3/h for ambient class IDA2 and an air flow rate of 510 m^3/h for IDA3.

This preliminary/fast method for determining the air flow rate required for ventilation will be validated via calculation of air flow rate that results as difference between pollutant concentration and pollutant gas flow rate released into the room. This method is regularly used for ventilated spaces and is described in the following. Indoor pollution in schools studied in this paper comes from the outside air, and from the inside sources, e.g. humans. This study analyzes the pollution with carbon dioxide and humidity. Gaseous pollutants entering in rooms depend only on the degree of pollution and can be reduced by the use of special filters, which are not the subject of our research.

Theoretical analysis of pollution in rooms was realized by applying the premises of the general theory of diffusion of gaseous pollutants in enclosed spaces. As sources of pollution were considered emission from people and the goal was to dilute them to concentration limit allowed, through ventilation with fresh air flow.

Since these pollutants are also found outside, the study recommend to make a preliminary determination to find out the increase of inside levels over the outside air level; such an approach is also made by "Design Execution and Maintenance' Norm of ventilation and air conditioning equipment I5/2010".

The following assumptions are considered for calculation, assumptions which are satisfied by real situations:

- M = flow rate emission of pollutant, constant during the time period τ,
- D = air flow rate, steady for the time period τ

Notations: C - concentration at time τ, V - volume of enclosure, e –outside, 0 – initial.

The equation of equilibrium for a given pollutant expresses the fact that the flow rate of pollutant entering the room during dτ period increases the concentration of pollutant - dC in volume V:

$$(D\,Ce + M - D\,C)\,d\tau = V\,dC \qquad (2)$$

To integrate, we will separate the variables:

$$-\frac{D}{V}d\tau = \frac{dC}{C-\frac{M}{D}-Ce}$$

By integrating between the limits τ = [0, τ] and C = [C0, C], we get:

$$-\frac{D}{V}\tau = ln\frac{C-\frac{M}{D}-Ce}{C_0-\frac{M}{D}-C_e};$$

$$e^{-\frac{D}{V}\tau} = \frac{C-\frac{M}{D}-Ce}{C_0-\frac{M}{D}-Ce}$$

This way we have the variation in time of the pollutant concentration:

$$C = C_0 e^{\frac{-D\tau}{V}} + \left(\frac{M}{D} + Ce\right) \cdot (1 - e^{\frac{-D\tau}{V}}) \qquad (3)$$

Equation (3) is very similar to the physical reality and allows to follow evolution of the concentration of each pollutant in the conditions of a perfect blend and of lack of interaction between pollutants. Exponential variation of concentration also allows setting of the air flow rate required for a volume V, which it is confined to a concentration value allowed, C_{adm}.

Considering that the time $\tau \rightarrow \infty$, the resulting air flow rate necessary D_{nec} for diluting the flow rate of pollutant M:

$$D_{nec} = M/(C_{adm} - C_e) \qquad (4)$$

The analytical model presented has been applied separately for the two gaseous pollutants: carbon dioxide and humidity. The calculations were done using relation (3) and considering: classroom volume V = 300 m^3, flow rate of CO2 produced by one person, in the circumstances, in sitting posture, M = 29300 mg/h.

It was assumed that the initial level of CO_2, prior to persons populate the classroom, there was no difference between inside and outside levels of CO_2 (C_e = 420 ppm).

The study was started with unventilated room S16 and was considered in the real situation a maximum number of people in the room (30 people).The variation of carbon dioxide level was tracked over time [ppm], carbon dioxide produced by humans.

In the following figure (fig.5) is represened the variation of the CO2 concentration for an airflow rate of 130 m3/h, which corresponds to an air exchange rate of 0,4 air exchanges/hr. Graph is made for interval 9-12 and axis of abscissa is expressed in minutes.

This airflow rate resulted from calculation, for a better setup of the calculated values of CO_2 levels (C_{calc}) from the measured ones C_{mas}. It can be noted that because fresh airflow rate is too small, level rose far above the accepted thresholds : (C-C_e = 500 ppm) for a room IDA2 air quality class, and (C-C_e = 800 ppm) for room IDA3 air quality class. The presented situation corresponds to a relatively airtight and non-ventilated room.

In the next chart was represented the evolution of CO_2 concentration measured in the classroom (dotted line) and the concentration of inside air above the outside air (continuous line). Number of persons being maximum, CO_2 concentration reaches alarming values of above 2500 ppm.

At the bottom of the graph is marked the evolution of the CO_2 concentration and the concentration of inside air above the outside air in the hypothesis that the room would be filtered with a fresh air flow rate of 450 m^3/h and secondary of 600 m^3/h (an air exchange rate of 2 air exchanges/hr - ACH). This value of fresh airflow rate it's just the airflow needed for IAQ class IDA3, and class IDA2 respectively. In the last case, the difference between outside and inside levels of CO_2 wouldn't exceed 600 ppm.

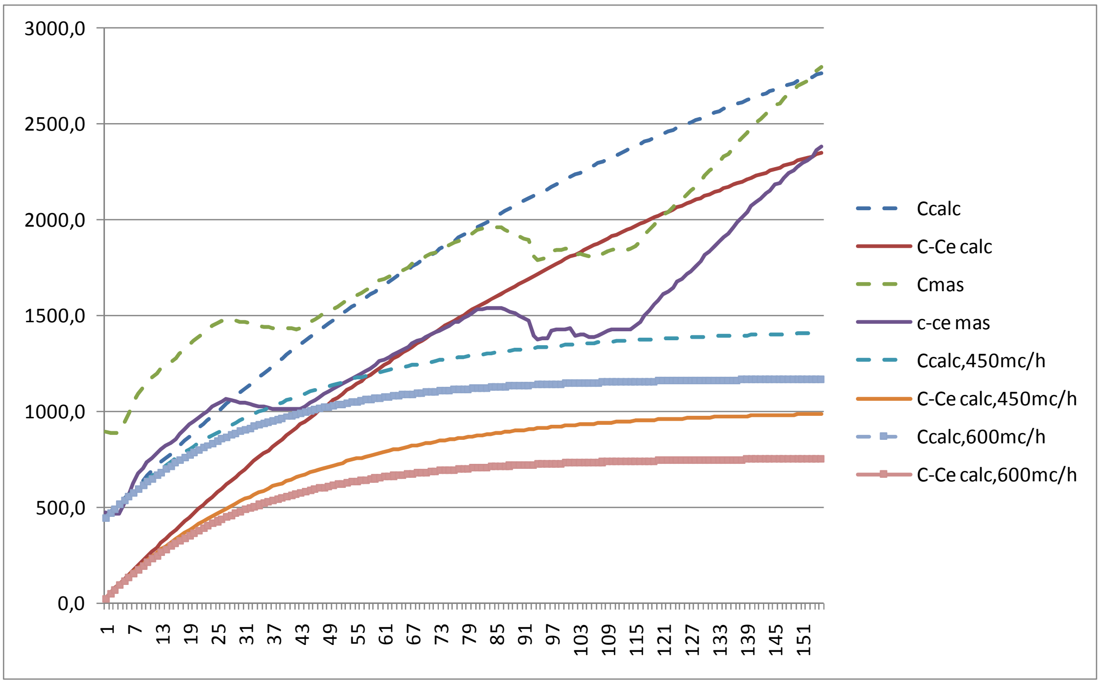

Fig. 5. CO_2 levels calculated and measured for the nonventilated room S16 with different ventilation rates.

In case of S16 classroom it is noticed that fresh air flow rate is not provided, and natural ventilation by opening windows is for the majority of the time insufficient, is dependent on weather conditions and the behavior of occupants.

In the second day of the study, the calculations were made for ventilated classroom S17. The room was mechanically ventilated with constant fresh air flow rate of 450 m3/h (second gear for installed fan), and the number persons was 24.

The chart shown below was made during interval 10-12, when 24 persons were present. The level of carbon dioxide calculated with relation (3) and represented by curve Ccalc,24pers, approximates very well the variation curve of measured concentration (Cmas) for the analyzed room. Also, it can be observed that the difference between levels of CO_2 outside/inside reaches 600 ppm value corresponding to IDA2 air quality class.

It can therefore be concluded that the air flow introduced by the fan is the one needed to achieve an adequate ventilation of classroom for an average grade of occupation. If the number of persons would be maximum (30-32) this airflow of the fan would not be enough for ventilation, and the classroom would fit in the class IDA3 or class IDA4.

For a minimum number of persons in classroom (12 people) indoor air quality can fit in the category of ambiance IDA1 ($C-C_e$ = 350 ppm).

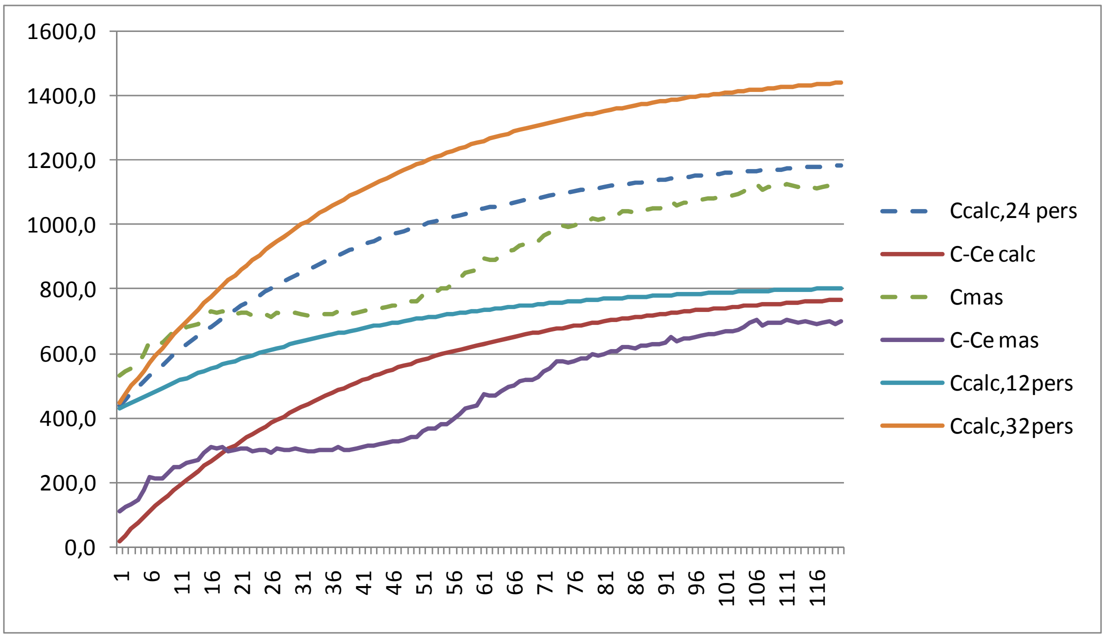

Fig. 6. CO2 levels calculated and measured for the ventilated room S17 and for different occupation ratios

For the study of variation in humidity of the air in the classroom it has been used the same pattern like in case of the study of pollution with CO2. In the following figure is given comparative variation of the moisture content x (g vap./kg a.u.) of indoor air, for a fresh air flow rate of 180 m^3/h.

The calculation was done for ventilated room S_{17} (day 1), classroom that has windows, each window is equipped with 2 hygroscopic air ventis which introduce a fresh air flow depending on the relative humidity of the air. The maximum flow of air that can be inserted through a grid is 30 m^3/h for each grid, so a total maximum fresh air flow of 180 m^3/h.

It was been considered that the moisture generated by each persons is 63 g/h, and 32 persons were in the classroom. Calculation of moisture content of indoor air was achieved for an hour (8-9) in the x-axis being represented time in minutes.

In figure 5 we can see that the variation of the humidity content in the classroom, determined for a fresh airflow rate of 180 m3/h, is far from the variation of moisture content measured xmas (that resulted from measurement of indoor air temperature and relative humidity).In conclusion, a value of 0.6 air exchanges/hr of air exchange rate is insufficient to achieve a good quality of the air in the room. It is noted that the humidity in the air does not meet the conditions of comfort and air quality. If the fresh air flow rate introduced would be 600 m^3/h (2 air changes/hr), then the curve of moisture content of calculated values (x_{calc}) would approximate very well the curve of measured values, and indoor air quality would be optimal in order that educational process to take place in good condition.

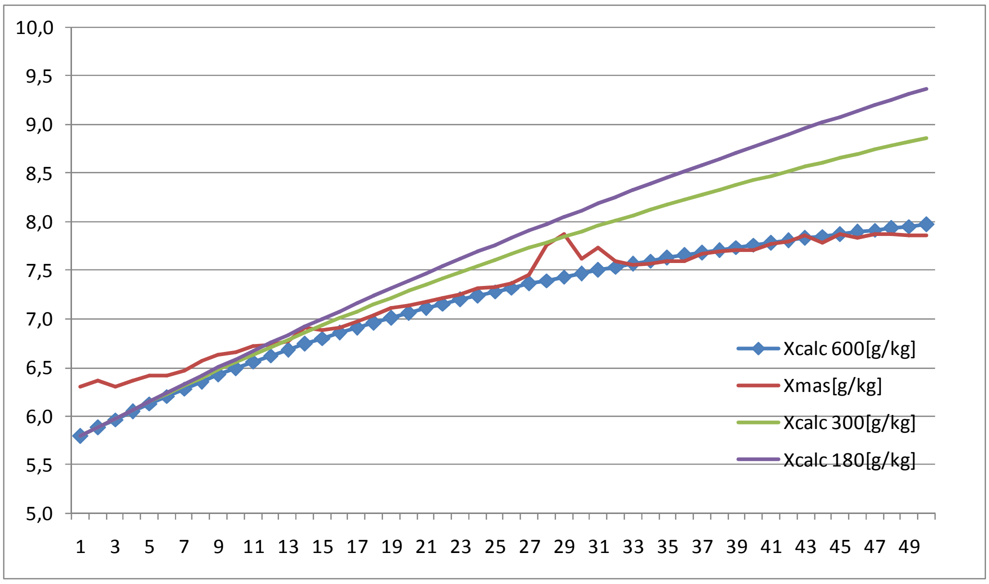

Fig. 7 – Humidity content calculated and measured for different fresh airflow rates (600, 300 and 180 m^3/h)

4. Conclusions

In this article an extensive experimental campaign was realized with the purpose to test two ventilation strategies. The first one consisted of using hygroscopic air vents and the second one by using a window fan. The efficiency of the ventilation systems was compared with an identical classroom situated at the same floor as the test room. The results showed that in the non-ventilated room the CO2 levels can go up to 2500 pppm overpassing the actual norms with more than 1500 ppm resulting in a poor air quality. On the other side, the ventilation system has proven its efficiency reducing the indoor pollution by half to a more acceptable level of 1200 ppm. The hygroscopic air vents can solve partially the introduction of fresh air this solution being recommended during winter time while for spring/autumn it is preffered to use the combination air vents and window fan. The measured data were compared to calculations and it was observed a good correlation. The numerical approach allowed us to test different fresh airflow rates (180 m3/h to 600 m3/h) and the impact on CO_2 levels or humidity.

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