INDOOR AIR QUALITY ASSESSMENT IN A CLASSROOM USING A HEAT RECOVERY VENTILATION UNIT

T. CATALINA[1,2], M. A. ISTRATE[1,2], A. DAMIAN[1], A. VARTIRES[1], T. DICU[2], A. CUCOŞ[2]

[1] Technical University of Civil Engineering, Faculty of Engineering for Building Services, Bucharest, 66, Pache Protopopescu Blvd. Bucharest, 021414, Romania
E-mail: tiberiu.catalina@gmail.com, andrei.istrate85@gmail.com, adamian7@yahoo.com, vartires2@gmail.com
[2] "Babeş-Bolyai" University, Faculty of Environmental Science and Engineering, "Constantin Cosma" Radon Laboratory (LiRaCC), Cluj-Napoca, Romania
E-mail: tiberius.dicu@ubbcluj.ro, dinualexandra2007@gmail.com

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Abstract. The air quality inside buildings is a major problem in EU countries because of lack of any source of fresh air. The situation is even more dramatic in schools were many individuals breathe the same air for multiple hours a day increasing the risk of illness and reduced mental performances. Finding a solution for existing buildings is a challenging task as numerous factors must be considered: noise, weight of the system, required air flow, energy efficiency, costs, maintenance, etc. The present study reports on the analysis of a novel heat recovery ventilation unit inside a high school classroom. The analysis consists of measurement of the indoor environment quality especially on the radon concentrations and CO_2 level for one week. The polluted air is evacuated while a heat recovery ventilator introduces the fresh non-polluted air. This decentralized system is for the first time studied in the literature as most of the studies were focused on centralized systems for new buildings. If before the system installation the CO_2 levels were very high (>2500 ppm) and the radon concentrations medium (>150 Bq·m^{-3}) at the end of the measurements it has been proven to be a perfect solution to reduce the indoor pollution.

Key words: decentralized ventilation system, indoor air quality, radon, school environment.

1. INTRODUCTION

We often talk about air pollution in the city, especially around roads. But several studies have measured air pollution in schools. It is not good to breathe the air of our EU schools – this is revealed in the European SINPHONIE project, which analysed indoor air in 114 schools from 23 European countries [1]. According to SINPHONIE project, every day, children breathe a cocktail of harmful pollutants, such as: benzene, radon and formaldehyde, in concentrations that exceed by far the limits set by *World Health Organization* (WHO) and National Agency for Food Safety, Environment and Labor – France (ANSES). For benzene, a substance resulting from combustion (including exhaust gases), 25% of schools exceed the threshold of

5 μg/m^3. For radon, a radioactive, but colourless and odourless natural gas, about 50% of the classes are above the limit of 100 Bq·m^{-3}. And more than 60% of establishments exceed 10 μg·m^{-3} for formaldehyde concentration.

The study also reveals a rate of CO_2 that is too high, reaching up to 1257 ppm in certain classes, when WHO recommends a threshold value of 1000 ppm. These excessively high levels of CO_2 lead to decreased attention, poor learning ability and even drowsiness. In addition, the ventilation rate is below the recommended value of 4 l·s^{-1} for 86% of children. This phenomenon is aggravated in over-crowded classes.

Under the same frame is the pollution of the outside air supplied to scholar facilities for ventilation purposes. For example, 85% of students would be exposed to air where the PM2.5 (the most harmful) fine particles once again exceed the WHO recommended limits for long-term exposure.

Very few studies have examined the relationship between ventilation and student performance in schools. Most of the data in the literature concern the productivity of adult subjects working in offices [2]. A study applied on 22 classes (550 students) in 5 refurbished schools in Norway [2–4] found that student performance assessed by the Swedish Performance Assessment System was lower when students were exposed to high CO_2 levels (between 1500–4000 ppm compared to <1500 ppm).

Other authors have addressed this subject of interest [5]. The results of the studies have two interesting conclusions: for an airflow rate below 4 l·s^{-1} pers. (15 m^3·h^{-1} pers.), the school performance decreases considerably, and for a higher airflow of 10 l·s^{-1} pers. (36 m^3·h^{-1} pers.), the academic performance was stabilized at an acceptable level. This last value of the airflow corresponds to that indicated by the Romanian I5 norm for the category I of indoor air quality atmosphere IDA 1.

In 2012, a study measuring air quality in 108 schools in six French cities had already shown that 30% of students were exposed "to levels of major air pollutants above" according to WHO recommendations [6].

In the European literature, the official document related to the indoor environment problems in educational buildings is the REHVA guidebook no. 13: *Indoor Environment and Energy Efficiency in Schools* [5]. This guidebook provides valuable information concerning the thermal comfort and indoor air quality (IAQ) issues related to educational buildings, considering the major role of the HVAC (Heating, ventilation, and air conditioning) systems implemented to solve them. Some optimization methods to save primary energy are also discussed, providing several best practice examples. A centralization of the recommended HVAC systems is also achieved for the main typical school areas, considering their specificities.

Further studies, based on REHVA guidebook no. 13, were conducted. One of these shows a strong dependence between the ventilation rate of classrooms and pupils' work performance, for a case study performed on 8 primary schools in England *via* an experimental campaign [7].

Jovanovic *et al.* [8] performed an experimental study carried on an elementary school form the Zajecar town, Republic of Serbia. The study investigated the indoor air concentrations for several air pollutants, showing that for some of them, the threshold limit values had been exceeded due to improper boiler operation and inadequate ventilation.

Gao *et al.* [9] revealed interesting findings concerning the influence of different ventilation systems on the indoor air conditions observed in a Danish elementary school, taking into account the window opening behaviour by children and teachers, the pupils perception of the classrooms environment and their health symptoms.

By using a CFD (*Computational Fluid Dynamics*) simulation method of investigation, Song and Mang [10] performed a comparative analysis between four different ventilation systems equipping a classroom. The results showed that this type of method could be an efficient tool to judge the ventilation performance of school buildings.

Madureira *et al.* [11] accomplished a cross-sectional survey to characterize the indoor air quality in schools and its relationship with children's respiratory symptoms. The investigated pollutants: VOC's (volatile organic compounds), PM (particulate matters) such as PM10 and PM2.5, carbon dioxide, bacteria and fungi were evaluated in 73 classrooms from 20 public primary schools located in the city of Porto (Portugal). The research work showed that it as a need to develop appropriate ventilation control strategies to minimize the adverse health effects induced by these pollutants on children, teachers and other school staff.

Cavaleiro Rufo *et al.* [12] conducted a follow-up experimental campaign during 2014–2015 in 20 primary schools in Porto (Portugal), to assess the indoor air quality and its influence on the children atopic sensitization. The results of this study have shown that the implementation of some ventilation strategies within these schools, relatively to a previous period of investigation (2011–2012) contributed to the important reduction of coarse particulate matters concentrations (PM10 and PM2.5), but had no impact on other indoor pollutants, as well as on the prevalence of atopic diseases, like asthma.

Schibuola *et al.* [13] demonstrated the benefit of the natural ventilation in classrooms, achieved by the voluntary windows opening by the classroom pupils. This led to a big reduction of the CO_2 concentration after the short periods of airing, but the random behaviour of the occupants linked to this type of ventilation couldn't be considered a valid solution. Authors suggested the users should promote conscious ventilation in each classroom by involving the teaching staff to monitor the CO_2 concentration measured by a CO_2 sensor, in order to act on the windows opening accordingly. This type of self-management could lead to maximum energy savings, keeping a proper air quality indoors.

A more recent study [14] presents the development of an automatic system for windows opening, based on the thermal comfort and indoor air quality issues. The study was performed on two adjacent classrooms from a typical secondary Italian school built in 2010. It demonstrates the utility of an optimized mechanical ventilation system on the reduction of indoor CO_2 concentration, leading to a healthier environment and a higher scholar performance.

Other authors had focused their research on the effect of natural ventilation strategies on the indoor air quality in schools [15]. By means of experimental campaigns carried on in the Central Italy, they made a comparison between the pollutant concentration levels measured during the “heating season” and “non-heating season”, to outline the effect of a typical airing strategy usually applied in schools. In addition, the authors achieved a detailed analysis of pollutant concentration levels according to the prescribed airing procedures designed to ensure good indoor air quality in classrooms.

Another experimental campaign for IAQ assessment was conducted in 12 elementary schools located in Oklahoma City metropolitan area [16]. The authors investigated several pollutants: CO, CO_2, NO_2, VOCs, formaldehyde and PMs, as well as indoor thermal comfort parameters (air temperature and relative humidity). The results of the study indicated a generally adequate temperature control, extremely low concentrations during non-occupied periods of time and little to no incursion of outdoor vehicle-related pollutants. In addition, a lack of adequate fresh air ventilation was observed for many of the studied cases.

Finally, an experimental research conducted in two primary school classrooms located in New Zealand judged on the effect of a mechanical ventilation system on the particulate matters concentrations measured indoors [17]. The results showed higher PM concentrations in the two classrooms during school hours (8:45–15:00), as well as significant infiltration of marine and traffic PMs from outdoors. However, the paper outlined that indoor PM sources (carpets, soil coverings, chalk) were greatly responsible of the increased PM concentrations and there is a need to control them more efficiently, along with the fresh air strategies.

In the case of historical buildings, the renovation strategies are generally very challenging, because keeping the existing ventilation system or replacing it with a new modern mechanical ventilation system shouldn’t affect the building architectural concept. Concerning the indoor air pollution due to radon daughters, it should be known the local concentrations of this pollutant within the soil and it is necessary to correlate the ventilation strategies according to these values.

The purpose of this article is to investigate indoor air quality in a historical building and to propose a new innovative solution to reduce the indoor pollution. The chosen solution is a decentralized ventilation unit with air heat recovery for better energy efficiency and it is a valuable study at international level as it is for the first time when such system is tested for a historical building.

2. THE EXPERIMENTAL CAMPAIGN

2.1. DESCRIPTION OF THE HISTORICAL BUILDING

The location for the experimental measurements is a classroom located in a historic building. The Mihai Viteazul National College building in Bucharest is almost 100 years old and shelters many classes, laboratories, a library, a showroom with over 1000 seats, a chapel (endowed with one of the few chapels in a school unit from Romania), an amphitheatre and a sports hall (Fig. 1). The building has been registered since 2010 on the List of Historical Monuments of Bucharest – IMI code B-II-m-B-19484 and was renovated in 2011.

Fig. 1 – Mihai Viteazul National College and a typical classroom.

This historical building had been operated as a college, not high-school, until 1892, when his director received the approval to transform its functionality. According to the technical regulations concerning the educational facilities as-built conditions, several criteria were imposed for the new-designed building:

– Classrooms windows of about 6 m height to assure the best natural lighting visual comfort;

– Classrooms heights between 4 and 5 m, corresponding to 2/3 of the classroom's widths (limited to 7 m), for architectural equilibrium reasons;

– Air volumes between 6.4 and 7.1 m^3 per pupil, to assure the minimum level of oxygen for respiration.

Moreover, the built-up strategy for the new high-school stipulated that it should contain five specialized educational spaces, such as: a natural sciences cabinet, physics and chemistry laboratories, a drawing classroom and a gymnastics hall with the minimum dimensions: 20 m (length), 10 m (width) and 10 m (height). Also, the new building should incorporate a large festivity hall to shelter simultaneously professors, pupils and guests, as well as an ample library for the pupils' use.

During year 1928, the whole building was terminated. The building walls are made of bricks, having variable thicknesses between 55 and 60 cm. The old wooden-framed windows have been recently replaced with modern double-glazing with PVC joinery, thus minimizing the winter cold outdoor air infiltration air rates and contributing to important energy savings for heating during winter time. However, this good energy measure worsened the indoor air quality in classrooms and corridors, while lacking mechanical ventilation for the occupants fresh air supply.

2.2. MAIN INDOOR SOURCES OF POLLUTANTS

The main source of CO_2 is represented by the occupants and rarely the plants from that room, while the sources of radon in buildings are the soil under the building and the building materials. Radon can penetrate the building by convection and diffusion, through the cracks of the foundation and through the walls. The pressure difference between the air in the soil and the air inside the building helps the penetration of radon into the inner spaces through the convection phenomenon. The second way to penetrate inside is diffusion by the difference in concentration (this has a minor contribution). The magnitude of the phenomenon of penetration of radon in the indoor environment is influenced by the pressure difference between the air and the soil, the tightness of the surfaces in contact with the soil and the rate of removal of radon from the soil.

Radon from building materials depends not only on the radiant concentration of these materials, but also on factors such as the fraction of radon production that is released from the material, the porosity of the material, the plaster and the finishing of the walls. Construction materials such as gypsum or concrete containing cloudless alluvial rocks have increased radium concentrations. Also, radioactive material concentrations may be high if the material used in brick and concrete manufacture originates from an area with high levels of natural radioactivity.

The best methods for reducing radon concentrations in buildings are: natural and mechanical ventilation, use of crawl spaces, clogging of ground-level cracks, soil depressurisation, etc. Because children spend a lot of time in school, lowering radon levels in school can significantly reduce their potential lifetime exposure to radon. Schools are special cases for measuring radon by occupying only part of the year (about 10 months) and heating and ventilation systems can work differently at different times of the day and night [18]. All these conditions can affect radon levels measured over a period. Obtaining a representative estimate of student exposure therefore requires that measurements be taken only during school hours, *i.e.* during the week or during the scholar year. Refurbishment works in buildings are also focused to the limitation of the radon penetration through building leaks, as well as to the dilution and evacuation of radon of indoor spaces. For this purpose, it is possible to act by: increasing the ventilation airflow of the building, by sealing the ground/building interface and by treating the layer of soil contaminated with radon (base rock).

2.3. VENTILATION SYSTEM DESCRIPTION

To reduce these pollutant sources, one efficient solution is to use a ventilation system. The problem is that there is a need of a decentralized unit – locally because the building is already built, and any structural modifications are forbidden. In fact, this is the case for almost all schools in Romania. The system that will be presented in the following paragraphs is a novelty, being for the time tested and its efficiency proven under specific conditions: weather, CO_2 sources, classrooms architecture, type of soil, materials, etc.

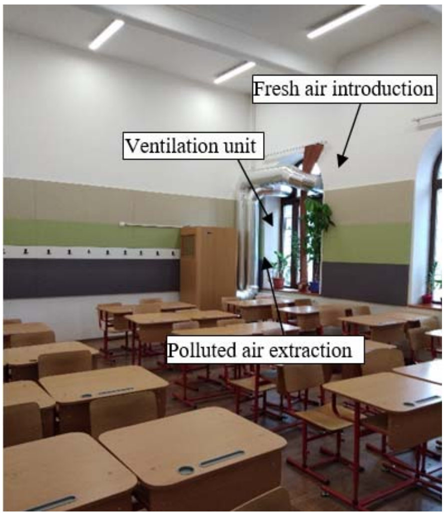

Fig. 2 – The ventilation system installed in the studied classroom.

The ventilation system (Fig. 2) is an assembly consisting of a cabinet type ventilation unit equipped with a heat recovery system. The polluted indoor air is sucked through the air grid from the side of the system, while the fresh treated and filtered air is introduced into the room at the top of the cabinet. This system is attached to fresh air inlet ducts and outside air outlet. The outer metal casing is covered with wood chipboard in the colour of the furniture of the classroom for better design integration. Its outer geometric dimensions are: 2 m height, 0.8 m wide, 0.66 mm deep. The system main components are: insulated metallic outer enclosure, inlet and outlet centrifugal fans, heat exchanger, electric heating batteries, air filters, temperature sensors, electronic control panel, polluted air extraction grid, fresh air inlet grid, anti-directional flaps.

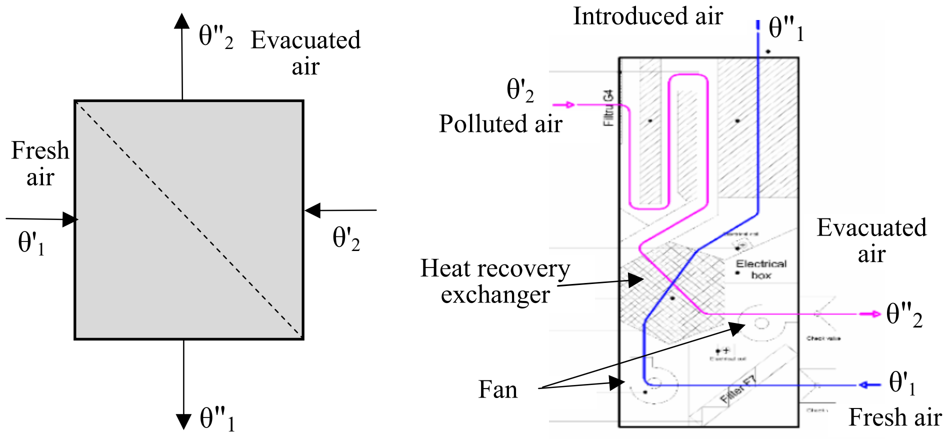

Fig. 3 – Physical principle of the decentralized ventilation system.

The general relation for the heat recovery unit efficiency ε (plate heat exchanger with sensible heat recovery only), considering equal supply and exhaust airflows, is the following:

$$\varepsilon = \frac{\theta_1^{''} - \theta_1^{'}}{\theta_2^{'} - \theta_1^{'}} \cdot 100\% \quad (1)$$

where:

θ'_1, θ''_1 – initial and final air supply air temperatures [°C]
θ'_2, θ''_2 – initial and final air exhaust air temperatures [°C]

If the supply airflow is different from the exhaust airflow, the efficiency of the heat exchanger could be expressed as follows:

– for the supply air:

$$\varepsilon_1 = \frac{\theta_1^{''} - \theta_1^{'}}{\theta_2^{'} - \theta_1^{'}} \cdot 100\% \quad (2)$$

– for the exhaust air:

$$\varepsilon_2 = \frac{\theta_2^{'} - \theta_2^{''}}{\theta_2^{'} - \theta_1^{'}} \cdot 100\% \quad (3)$$

where:

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{m_2 c_2}{m_1 c_1} \quad (4)$$

and:

- m_1 is the mass airflow [m^3/h] of the supply air with the specific mass heat c_1 [J/g°C],
- m_2 is the mass airflow [m^3/h] of the exhaust air with the specific mass heat c_2 [J/g°C].

The monitoring and control system is very complex, being equipped with electronic monitoring, control, data storage and Internet connection. The unit is equipped with temperature sensors for measurement and control at the following points in the air passage: room air extraction air, fresh air from outside, fresh air after the heat recovery. A CO_2 sensor is located at the top of the system on the extraction point to measure and control the fan speed to maintain a CO_2 limit – in this particular case the set point is 1200 ppm. The purpose of the heat exchanger is to recover a part of the indoor air heating energy before its evacuation therefore the energy efficiency of this system is very good.

2.4. MEASUREMENTS RESULTS

We carried out measurement of the radon concentration in a room with the heat recovery ventilation system and in a non-ventilated room located on the same floor and that have the same characteristics (Fig. 4). The measurement points were made in the middle of the course room at a height of about 0.8 m. Recordings were made for 5 consecutive days of normal 1-hour workout in both classrooms along with two Radon active devices (RadonScout from Sarad, Germany). The devices were calibrated by the manufacturer and checked in the LiRaCC laboratory's radon chamber by comparison with the AlphaGuard reference device.

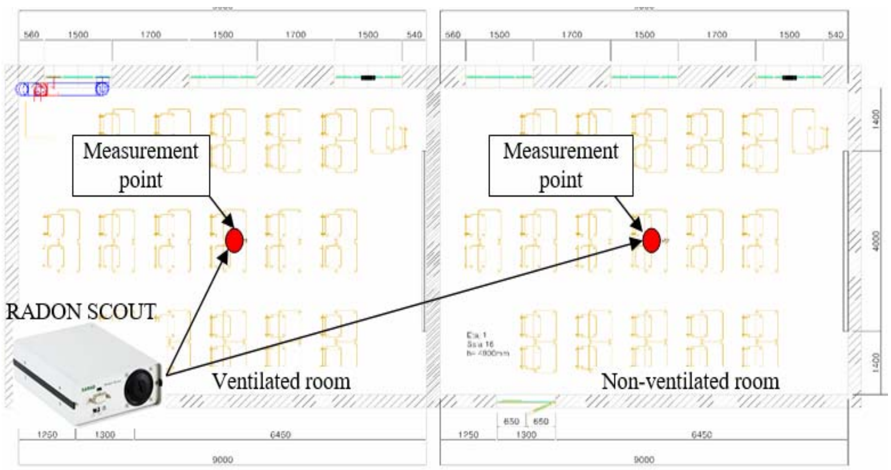

Fig. 4 – Plans of the studied classrooms and the measurements points.

The measurements analysed the CO_2 levels, the radon concentration, air temperature and relative humidity for the ventilated classroom *versus* the non-ventilated one are illustrate in Figure 5.

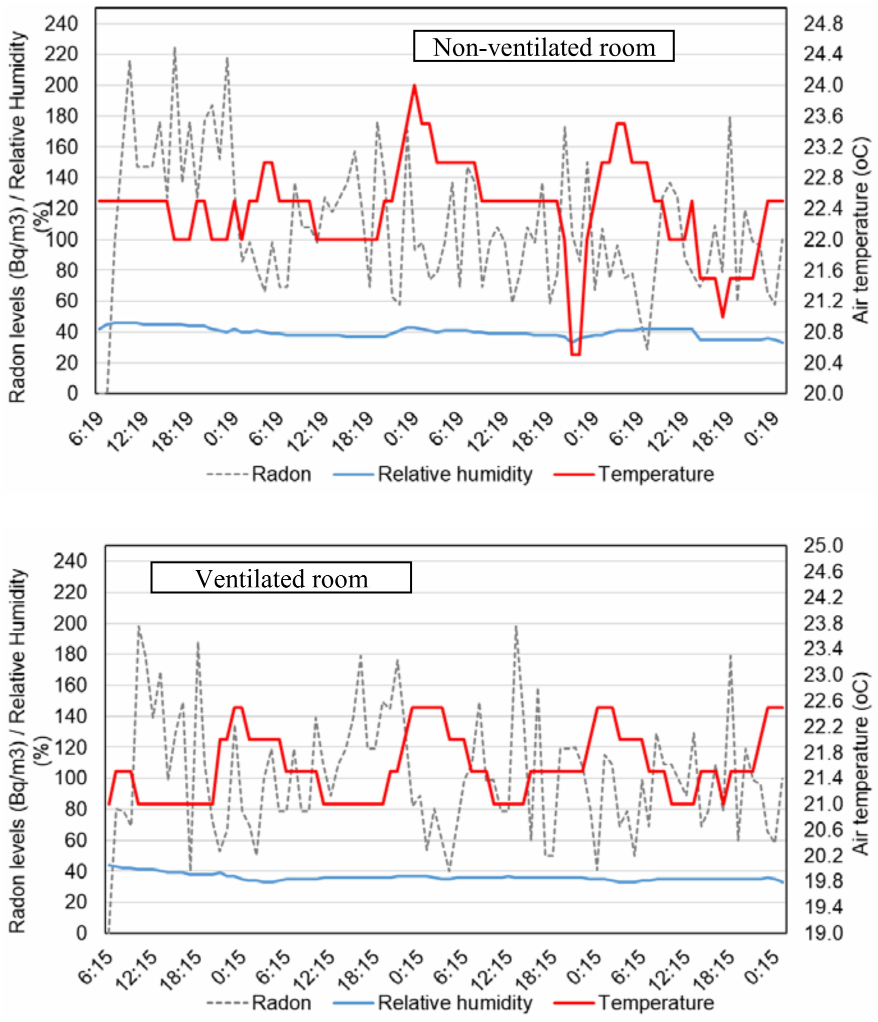

Fig. 5 – Indoor radon activity concentrations, relative humidity and air temperature for non-ventilated and ventilated classroom.

From the measurements presented in Fig. 5, it can be observed that in the ventilated room the average value for the sample week is 103 Bq·m^{-3} while for the classroom without ventilation system the average value is around 120 Bq·m^{-3}; the average values recorded do not exceed the recommended limit of standards above 300 Bq·m^{-3} imposed by the Romanian legislation. As concerns the thermal comfort in the non-ventilated classroom the air temperature can reach values up to 24°C (thermal discomfort) while in the ventilated room due to the regulation system the air temperatures are more stable around a comfortable value of 22°C. The relative humidity is low for both cases (average value 36%) so there is a necessity to install a humidification system to reach normal values in the range 40% to 60%. If for the radon levels the reduction was 15% when using the heat recovery ventilation unit, for the CO_2 measurements the benefits are even clearer, as the initial values overpassed the actual norms by 300% (up to 3000 ppm). The system can provide the needed fresh air and therefore the CO_2 levels dropped to maximum 1200 ppm representing a considerable reduction (Fig. 6).

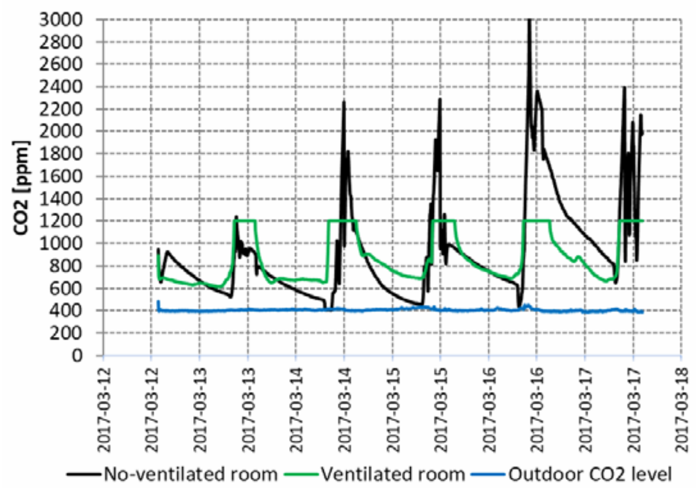

Fig. 6 – Indoor CO_2 levels for the ventilated and non-ventilated classroom.

To calculate the efficiency of the heat recovery, the intake and exhaust fan was started at the maximum (equal flow rates) and then the main parameters required to determine the efficiency of the heat recovery were monitored for 30 minutes. These are: inlet temperature, outside temperature, room air evacuation temperature and exhaust air temperature after heat recovery.

3. MODELLING STUDY

Because the educational building is a national patrimony, any wall drilling was strictly forbidden, so it was chosen to remove two window slats and remove the ducts through them (Fig. 7). The modelling was realized using the Design Builder software with Energy Plus as a calculation internal core (Fig. 8). The boundary conditions for the CFD model are based on the previous experimental measurements (Table 1). The air flow was imposed as 600 $m^3 \cdot h^{-1}$.

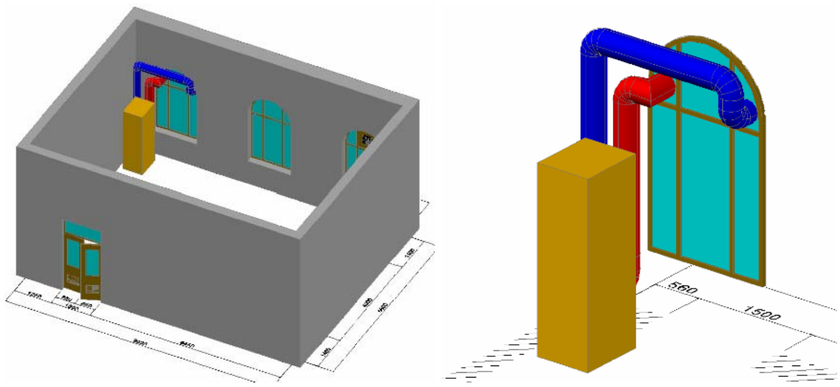

Fig. 7 – 3D Model of the air heat recovery exchanger and the air distribution system.

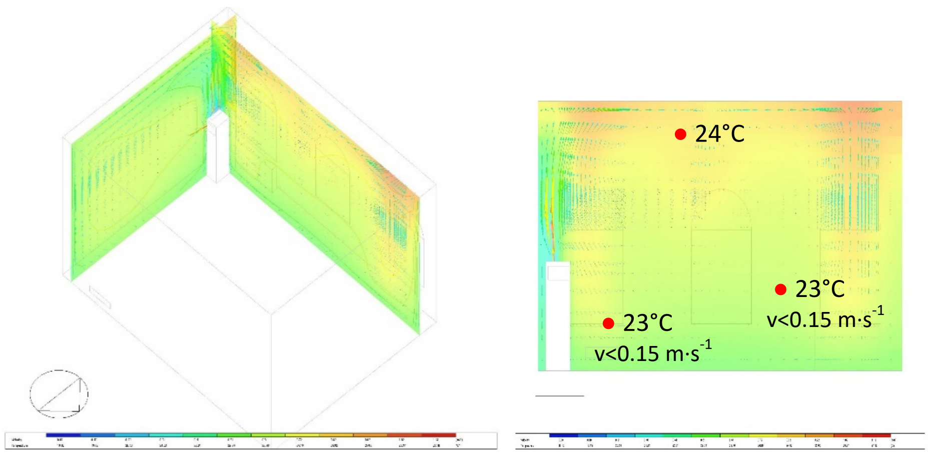

Fig. 8 – Air temperature and velocity distribution inside the classroom.

Table 1

Air Heat Exchanger energy efficiency calculation

Date, time	θ'$_1$ outdoor temperature	θ"$_1$ supply room temperature	θ"$_2$ exhaust room temperature	θ'$_2$ exhaust HR temperature	ε
	[°C]	[°C]	[°C]	[°C]	[–]
20.3. 18:36:43	6.3	18.9	24.1	12.3	0.71
20.3. 18:40:03	3	20.2	24.6	8.3	0.80
20.3. 18:45:33	2.1	20.2	24.5	6.1	0.81
20.3. 18:50:03	2	20.1	24.4	5.5	0.81
20.3. 18:50:13	2.1	20.1	24.4	5.5	0.81
20.3. 18:55:23	1.6	19.9	24.4	5	0.80
20.3. 19:00:03	1.7	19.8	24.3	4.8	0.80
20.3. 19:05:03	1.3	19.6	24.2	4.5	0.80

It can be seen from the CFD screenshots obtained from the simulations that the temperature inside the room is constant and uniform with values around 23–24°C in the whole room volume. As for the air velocity the values are low ($v < 0.15\ m\cdot s^{-1}$) and no air draft was developed in the occupational zone.

4. CONCLUSIONS

This paper aimed to determine the reduction of pollutant concentration in an educational indoor space related to the mechanical ventilation with outdoor fresh air. In this idea, two cases were studied: a classroom without any ventilation and a similar classroom in which a heat recovery air-to-air unit had been installed. The measures of the indoor concentrations were focused on the CO_2 and radon gaseous pollutants, but the experimental campaign was also applied to determine air temperature and relative humidity, as markers for the thermal comfort. The results of the experimental campaign demonstrated that the indoor comfort parameters values are within a satisfactory range during the investigation period, while the concentration peaks of radon decrease with about 15% for the "ventilated room case" at the same time step, compared to the "non-ventilated room case". As for the CO_2, the peaks decrease reveals to be much more important (over 100%) for the room ventilated by the heat recovery unit, knowing that the unit was programmed to adjust its airflow to ensure a maximum indoor concentration of CO_2 equal to 1200 ppm. The experimental results have also shown that, for mild outdoor conditions in terms of air temperature and humidity corresponding to a spring period, the mechanical ventilation is able to maintain satisfactory indoor thermal conditions.

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