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Indoor Radon and Energy Efficiency: A "Short Blanket" Problem that Demands for Balanced Ventilation

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Abstract. A historic school building was recently retrofitted. Due to its high architectural quality, the building is listed as National Architectural Patrimony, and therefore the rehabilitation process has met very challenging requirements regarding its conservation to maintain the original layout. In view of its age, the building is done with thick stone walls which help energy conservation and enhance thermal inertia. Its primitive architecture enables natural lighting, increases solar radiation gains, and favors natural ventilation, assuring, consequently, an improved energy efficiency. The implemented rehabilitation actions tried to preserve the original architecture and the building restorations were designed to conserve as much as possible the ancient distinctive architectural style. Given the imposed constraints, matters like Indoor Air Quality (IAQ) and thermal comfort in rooms and offices for administration and staff were not met. The current situation has resulted in justifiable complaints from the building users, reporting poor rooms IAQ due to a lack of air renovation. Because of the impossibility to install mechanical ventilation ducts, the building rooms are operated through natural ventilation, which makes the adoption of constant air flow regimes difficult to implement. To evaluate the problem and promote measures to deal with it, an experimental campaign to assess IAQ and building thermal comfort was implemented during the Winter of 2022. In the framework of the campaign, two identical rooms with similar occupancy, size, volume, building typology, heating regime, and with the same equipment installed, were measured in situ for 3 months, by monitoring continuously the following variables: indoor radon concentration, air temperature and relative humidity, under distinct regimes of ventilation. By using statistical analysis of the experimental data, the results show, as expected, that the room with a permanent air renovation has an improved IAQ than the other monitored room, operated with a restricted ventilation schedule, without jeopardizing the energy efficiency. Based on the results, natural ventilation in a steady state mode is the key to balancing IAQ and energy efficiency.

INTRODUCTION

The reduction of both energy dependence and greenhouse gas emissions are the main objectives of the European Directive on the Energy Performance of Buildings (EPBD) [1], [2] and [3], by enforcing a set of new procedures and measures for improving the final building output. The new energy efficiency challenges stand not only for the thermal quality of the building´s enclosure but also for the improvement of indoor air renovation and the energy efficiency of all technical systems, in order to assure occupants' health and comfort [4]. Based on EPBD, indoor environments must manage wisely energy efficiency and Indoor Air Quality (IAQ) by assuring hygrothermal comfort, i.e., the maintenance of temperature and humidity in a range of values leading to the thermal neutrality that consequently to

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thermal comfort, and by providing the healthiness and habitability conditions of the building with adequate rates of ventilation to reduce the impact of moisture and other indoor pollutants.

In order to evaluate thermal comfort and IAQ in a recently retrofitted building, listed as National Architectural Patrimony, two offices with identical geometry (surface, volume, and ceiling height), same building options for refurbishment, similar heating and ventilation systems applied, and identical occupancy, were chosen for in situ measurement to assess indoor air temperature, relative humidity, and radon concentration. The measurements were conducted for 3 months (long-term measurements) during the winter season. The active radon sensors were placed in both rooms where occupants spend the same time per day. To evaluate the air renovation habits of both occupants, a survey was implemented to collect data concerning the routine of the window opening to promote natural ventilation.

The objective of this article is to evaluate the impact of the occupants´ ventilation habits on indoor thermal comfort and Indoor Air Quality in a retrofitted building and to correlate the effect of the monitored indoor hygrothermal parameters on radon concentration for both measured rooms.

MATERIALS AND METHODS

A 3 months monitoring campaign implemented during the Winter of 2022 was carried out to assess Indoor Air Quality (IAQ) and thermal comfort in a restored secular school building classified as a monument of public interest listed as National Architectural Patrimony. The case study building was transformed into a higher education school in the second half of the twentieth century and is still in operation today, after being recently subject to a careful retrofitting process to maintain its original form.

The building retrofitting process was oriented toward energy efficiency enhancement, always bearing in mind the need to maintain some particular building elements that play a specific role in energy efficiency performance, notably the following: very dense façade wall built in stone, continuous roof lights to optimize natural lighting, a barrier covered with vegetation designed to protect the building from the sun radiation during the summer season, and hallways planned to decrease heat loss by enclosing extra airspaces whilst outdoor doors are open. Additionally, some energy efficiency enhancement was implemented by applying new thermal insulation boards to attics and roof´s garret, reinforcing the enclosure airtightness to reduce air leakage and the loss of heat, replacing the old inefficient light bulbs with new efficient LED lighting, and changing the old equipment for heating and hot water with new high-performance appliances. The major drawback of this retrofitting process lies in the lack of efficient ventilation systems. The use of mechanical ventilation equipment designed to enhance Indoor Air Quality is out of the question given the unique architectural characteristics. Given these constraints, all rooms must be operated with natural ventilation, which can compromise Indoor Air Quality and energy efficiency due to the uncontrolled air flow rates.

To study the balance between Indoor Air Quality, thermal comfort, and energy efficiency, two offices for teachers were taken for in situ measurement by using the methodology presented in FIGURE 1. The experimental campaign took place in the Winter of 2022 and was based on long-term measurements, during which mild outdoor air temperatures were recorded, thereby facilitating natural air renovation. As such, in the course of the monitoring, the heating system is centrally operated, and ventilation actions were taken by regular windows during rooms´ occupancy. The rooms were continuously monitored for 3 months since long-term measurements are suitable to identify potential IAQ hazards and to check radon risk exposure.

As referred, FIGURE 1 shows a diagram including a 5-step sequential methodology adopted to implement the experimental work.

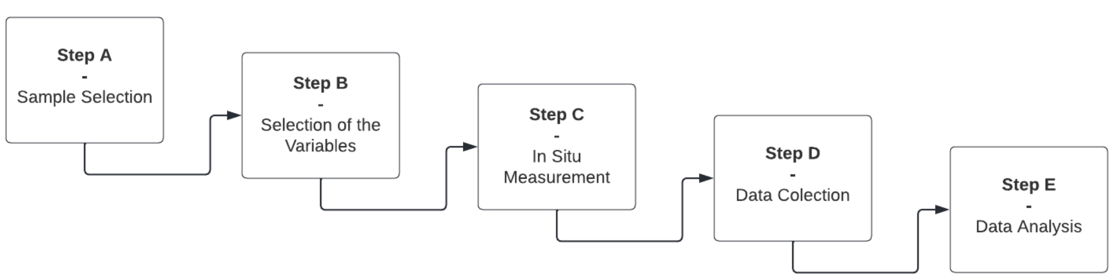

FIGURE 1. 5-step methodology adopted for the experimental work.

According to FIGURE 1, step A includes the sample selection based on a set of pre-defined characteristics, namely the following: constructed area, air volume, glazing area, equipment applied (light fittings and heating devices), and building options. Step B involves the variables selection for Indoor Air Quality and thermal comfort selection, as well as the type of detector (passive or active) to carry out in situ monitoring. Step C corresponds to the measurement implementation, involving the answers to where to measure. How to measure? How do avoid radiation exposure, sources of heat, and ventilation devices? etc. Steps D and E include the collection of measurement data, followed by a numerical and graphic analysis comparing the values with the recommendations and legal limits imposed by codes and regulations.

In step C, the variables used to assess IAQ and thermal comfort are the indoor radon concentration as well as the air temperature and relative humidity. The variables have been monitored for 3 months by using in situ measurements with 1-hour resolution collected by digital radon monitors with embedded data-logger devices of Canary Pro Series. The device specifications are found in [4] and are briefly summarized in TABLE 1.

TABLE 1. Data-logger main technical specifications.

Specification	
Radon Sensor	
Range (Bq.m^{-3})	0 to 35000 (upper measuring limit)
Accuracy	±5%
Precision	short-term < 20%, long-term < 10%
Temperature Sensor	
Range (ºC)	4 to 40
Resolution (ºC)	0.336
Accuracy (ºC)	± 0.5
Humidity Sensor	
Range (%)	5 to 95
Resolution (%)	0.5
Accuracy (%)	± 4.5

Two data loggers were positioned in strategic places in each room, to avoid exposure to direct sunlight, moisture, draught, and smoke, and both were placed at least 0.50 m above pavement level, and over 1.50 m away from any door, window, air vent, lights or other radiation source or electronic device. To allow accurate data, the data loggers were not moved during in situ measurements.

RESULTS AND DISCUSSION

A significant set of data was collected from the in-situ measurement which took place over three months on a long-term assessment campaign. The experimental work was focused on the analysis of the behavior of the variable's indoor radon concentration, air temperature and relative humidity along time, previously selected to assess the room´s IAQ and thermal comfort.

In order to evaluate the impact of natural ventilation on the indoor environment, two rooms with similar geometry, and air volume (approximately 105 m^3 each), identical doors and windows surface and accesses (both doors connect to an interior corridor and the windows to the outdoor environment), and with the same radon potential, were continuously monitored. Given the circumstances, under similar conditions of ventilation and room occupancy, the indoor radon concentration, air temperature and relative humidity would be equivalent.

However, in the so-called "standard room", the room occupant implemented ventilation actions only during the period of occupancy, by leaving the room window wide open. On the other hand, in the "test room", the window was opened 24/7, leaving a permanent 5cm perimeter gap to facilitate natural ventilation.

During the long-term evaluation, 2133 measurements were recorded (n = 2133) for the variables under analysis. The results analysis shows a significant difference between the indoor radon concentration measured in both rooms: in the "standard room", the peak value is 1275 Bq·m^{-3} and in the "test room", the top value is 867 Bq·m^{-3}. This difference is also identical to the average values: 309 ± 198 Bq·m^{-3} for the "standard room" and 230 ± 150 Bq·m^{-3} for the "test room". The results indicate that the permanent natural ventilation adopted in the "test room", seems to contribute positively to maintaining indoor radon concentration below the legal recommended value of 300 Bq·m^{-3}, according to Euronorm.

The outdoor air temperature during the monitoring period fluctuated between 1.3 ºC and 25.7 ºC, with an average value of 12.2 ± 4.4 ºC, and the relative humidity varied between 25% and 98%, with an average value of 78 ± 15%. Since all school rooms are operated with a heating system permanently on, the indoor air temperature that was measured is very similar for both measured rooms: the minimum temperature is 14.3 ºC and 14.6 ºC, for the "standard room" and the "test room", respectively, and the maximum temperatures that were recorded are 20.0 ºC and 22.0 ºC. This slight difference can also be seen in the average values, which are, respectively, 17.2 ± 1.1 ºC and 18.9 ± 1.6 ºC.

By performing the F-Snedecor and t-Student tests, the first test shows a p-value > 0.05, which points to the rejection of the null hypothesis (H_0), indicating no difference between the variances that are supposed to be the same for both scenarios. On the other hand, the t-Student test returned a $p < 0.05$, which points to the rejection of the null hypothesis and acceptance of H_1, indicating significant differences between the mean value of the two analyzed scenarios. The difference in indoor average temperature for both rooms seems to justify the differences in the indoor relative humidity, since the lower indoor average temperature for the "standard room" contributes to a higher indoor average relative humidity (64 ± 5%), with a minimum value of 46% and a maximum value of 73%. On the other hand, in the "test room" permanently ventilated, the indoor average relative humidity is 48 ± 6%, with a minimum value of 24% and a maximum value of 64%.

Concerning the relationship between the indoor radon concentration and indoor air temperature, there seems to not exist a particular correlation, as evidenced by the results of Pearson's correlation coefficient obtained for the pair [radon concentration – indoor air temperature], with a result of 0.048, very close to zero, not indicating an evident correlation. On the other hand, the correlation value for the pair [radon concentration – indoor air relative humidity] shows a value of 0.212, indicating a possible relationship between this parameter and the radon concentration, or at least some possible contribution of the indoor relative humidity to the increase of indoor radon concentration.

The same applies to the use of the decision trees methodology to evaluate the influence of the indoor temperature and relative humidity on the indoor radon concentration, which shows an interesting association between relative humidity and indoor radon concentration, which can justify the higher radon concentrations, significantly if they are also associated with high indoor air temperature.

The results analysis allows concluding that natural ventilation plays a decisive role in reducing indoor radon concentration and it effectively contributes to maintaining the value below the recommended limit of 300 Bq·m^{-3}. To benefit of the effect of natural ventilation, it´s important to secure that the window is left in a partially open position, or a façade ventilation grill is installed, allowing steady air circulation and creating a permanent inflow that contributes to reducing indoor radon concentration by air renovation. This solution is decisive to preserve health and well-being without creating a negative impact on indoor air temperature and room energy balance, as shown in FIGURE 2. The graph suggests that the indoor air temperature for the "test room" which is permanently ventilated, does not seem to be strongly affected by the outdoor temperature variation. Therefore, the impact of the permanent ventilation on the room energy efficiency is under control.

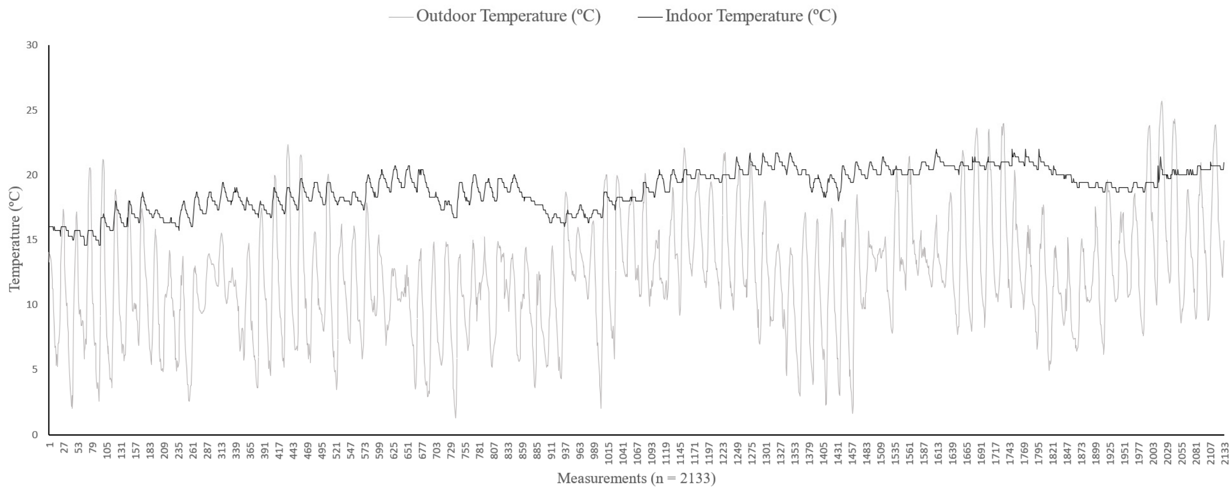

FIGURE 2. The indoor and outdoor air temperature of the “test room”.

CONCLUSIONS

To study the balance between Indoor Air Quality, thermal comfort, and energy efficiency, two offices for teachers were taken for in situ measurement in the Winter of 2022 based on long-term measurements, during which mild outdoor air temperatures were recorded, thereby facilitating natural air renovation. The measured offices are part of a restored secular school building classified as a monument of public interest listed as National Architectural Patrimony, recently subject to a careful retrofitting process to maintain its original form. Given the imposed constraints, matters like Indoor Air Quality (IAQ) and thermal comfort in rooms and offices for administration and staff were not met, resulting in justifiable complaints from the building users, reporting poor rooms IAQ due to a lack of air renovation. After in situ monitoring, the analysis of the results allows concluding that natural ventilation plays a decisive role in reducing indoor radon concentration and it effectively contributes to maintaining the value below the recommended limit of 300 $Bq\cdot m^{-3}$. The implementation of natural ventilation actions in a steady state mode is the key to balancing IAQ and energy efficiency, by allowing steady air circulation and creating a permanent inflow that contributes to reducing indoor radon concentration by air renovation. This solution is decisive to preserve health and well-being without creating a negative impact on indoor air temperature and room energy balance.

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