AN INNOVATIVE SYSTEM FOR MONITORING RADON AND INDOOR AIR QUALITY

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Abstract. Nowadays, a global trend towards increasing the performance of a building is the reduction in energy consumption. In this respect, for existing residential buildings the most common techniques are the application of a thermal insulation layer to the exterior wall of the building and / or window replacements. Unfortunately, their application without proper education of those involved may have a negative effect on the indoor air quality. The use of a continuous monitoring device can give the owner the ability to understand the impact of his behaviour on indoor air quality and, as such, to adjust his routine in order to maintain the indoor air quality at the desired level. This paper introduces a prototype, called ICA system, for continuous, real-time indoor air quality monitoring. The ICA system presents sensors for monitoring the concentration of radon, CO_2, CO, VOCs, as well as meteorological parameters, such as temperature, pressure, and relative humidity. Experiments were performed both in laboratory and *in situ* conditions for testing and validating the proposed system.

Key words: indoor air quality, radon exposure, sensors calibration.

1. INTRODUCTION

In the recent years, indoor air quality has drawn the attention of both academic and public sectors. Motivation is given by the time spent indoor (occupancy factor being from 0.6 up to 0.95, especially for the elder people), as well as the statistical analyses conducted by international organizations for environmental protection, which indicating that, on average, the level of indoor pollutants is 2 to 5 times higher than in the outdoors air [1, 2]. A poor indoor air quality affects human health, as well as the safety, productivity and comfort of the

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occupants [3]. Therefore, indoor air quality monitoring will allow awareness of the relationship between the behaviour of occupants and indoor air quality, leading to the improvement of the living environment. The need to monitor indoor air quality and to study the effects of new constructions, performance heating systems, insulation and ventilation on the health and life quality of residents is, therefore, paramount.

Worldwide, radon (Rn-222) is one of the most studied natural elements, classified through epidemiological studies as the second cause of lung cancer [4]. Radon is a noble, radioactive, colourless, odourless, insipid gas resulting from the radioactive decay of naturally occurring radium (Ra-226), found anywhere in soil, water and building materials. Since radon sources emit continuously, systematic measurements are required to determine areas with elevated radon potential. The resulting products from Rn-222 disintegration are solid and adhere to aerosol particles, which are called the progeny of radon or radon daughters. Inhalation of these radioactive products causes an increase in internal exposure of the human body and may result in a higher incidence of lung cancer [5]. Studies show that worldwide between 3 and 15% of all lung cancer cases may be attributable to residential radon, aspect that makes it the main environmental factor causing lung cancer [6].

Volatile organic compounds (VOCs) and carbonyls represent another class of highly toxic indoor pollutants. The main sources are the furniture lacquers, cleaning or disinfecting agents, paints, adhesives or smoking. Exposure to VOCs has been associated with carcinogenic effects and disturbances of the immune system and neurobehavioral system [7]. Another common pollutant of the indoor air is carbon monoxide (CO). This compound is one of the most frequent causes of fatal domestic accidents, due to its chemical properties, which impede the early detection of dangerous levels. It is a gas that quickly accumulates in the ambient air, thus reducing the oxygen levels that reach the body organs and tissues. Studies of exposure to low levels of CO showed that it may cause a delay in foetal development, child growth, chronic hypoxemia, cardiovascular diseases, neurobehavioral effects or abnormalities in haemoglobin [8]. *Carbon dioxide* (CO_2) on the other hand, can give rise to headaches, nausea with or without vomiting, dizziness, vision and breathing problems. Exposure to high levels of CO_2 may lead to unconsciousness and even death. Numerous studies [9, 10] have shown a strong correlation between the concentration of indoor CO_2 and ventilation rate and the general quality of the indoor air.

Monitoring indoor air quality is a challenge for researchers because the concentration of the pollutants and human activity pattern varies both spatially and temporally from one room to another [11]. The literature contains a multitude of papers on devices developed for indoor air quality monitoring [2, 12, 13]. Unlike most of them, the *indoor air quality* (ICA) system proposed in this article attempts to combine the monitoring of VOCs, CO, CO_2 with indoor radon concentrations, and metrological parameters (temperature, pressure and humidity). It also provides the possibility of setting threshold values for monitored pollutants and informing users by push notifications or SMS if these values are exceeded. The presence of the TFT display is especially useful for the elder people who prefer a direct interaction with the device and not an interface mediated by a mobile application. Last but not least, the ICA system can be connected to a mitigation system which can independently activate a mechanical ventilation system whenever the threshold values are reached, thus ensuring an increase in indoor air quality.

The ICA system, through the monitored parameters and by its way of rendering the results will act as a mediator between user behaviour and indoor air quality. The owner will be able to understand the effects of his household behaviour on indoor air quality and change his routine in order to increase and maintain indoor air quality to the desired level.

The purpose of this article is to describe and validate the system developed within the “Constantin Cosma” Radon Laboratory (LiRaCC) of Babeş-Bolyai University, as well as testing the accuracy of the sensors both under laboratory conditions and in real situations.

2. MATERIAL AND METHODS

2.1. GENERAL SYSTEM DESCRIPTION

Considering the construction of the device, the ICA system can be divided in three parts. As shown in Figure 1, the device has a main board, built around an ATMega microcontroller, a sensor board, containing all the internal sensors and a display board, housing the TFT display, an *Ambient Light Sensor* (ALS) and a push button with a status LED.

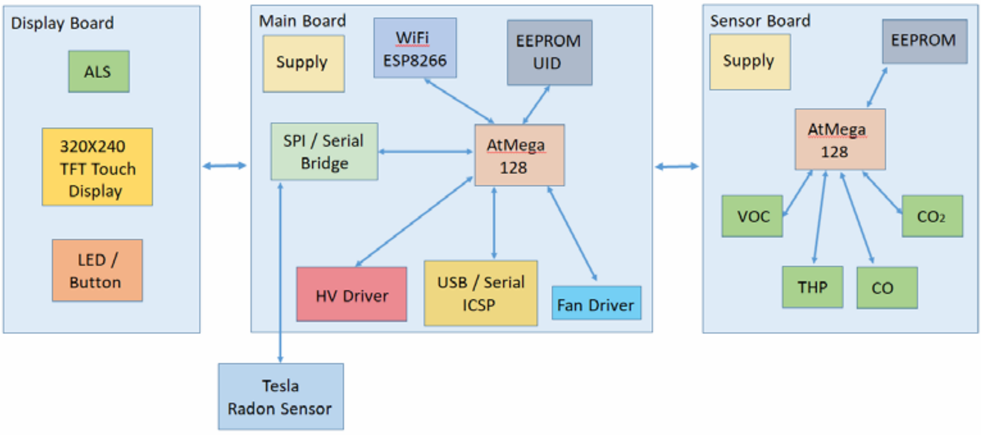

Fig. 1 – The block diagram and an external view of the ICA system.

2.2. DESCRIPTION OF THE MAIN BOARD

The main board is the central part of the ICA system containing the main microcontroller and all the necessary peripheral circuitry. The main board can be divided in several sub-modules as presented in the block diagram on Figure 1. On the next paragraphs are described the essential building blocks of the main board.

The ATmega 128 microcontroller from Microchip (Atmel) is the central element of the main board and it runs a custom firmware developed to perform the measurements, to communicate with the remote servers, to display data on the TFT Touch screen and to handle on board diagnosis of the unit.

The Wi-Fi module is built around the ESP8266 chip from Expressif. The Wi-Fi module is developed by Olimex and it uses a serial connection to communicate with the ATmega microcontroller. The ESP8266 is loaded with the default AT protocol and the microcontroller implements all the handling of the connections. At any certain time there could be up to 2 active TCP connections: one is for the data server and the other for a debug server. Both servers have reserved and fixed IP addresses. The addresses of the servers and any stored parameter can be changed either using one of the TCP connections or a local USB connection.

The SPI / Serial bridge module is used to extend the number of serial ports of the microcontroller. The microcontroller is equipped with only 2 hardware serial ports but several peripheries used in the ICA system also use serial connection. The bridge is built around two SC16IS762 chips from the NXP Company. The converter expends the number of serial ports by four and it uses the standard *Serial Peripheral Interface* (SPI) to communicate with the host microcontroller. The serial ports are used to communicate with the Radon Sensor, the TFT display, a spare RS485 and a logger not presented on the block diagram and reserved for future developments and / or integration with smart house systems.

2.3. DESCRIPTION OF THE SENSOR BOARD

The sensor board shown in Figure 2 is a module built around an ATmega 128 microcontroller, a collection of air quality sensors, the necessary support circuitry and a non-volatile memory to store the calibration data for the on-board sensors.

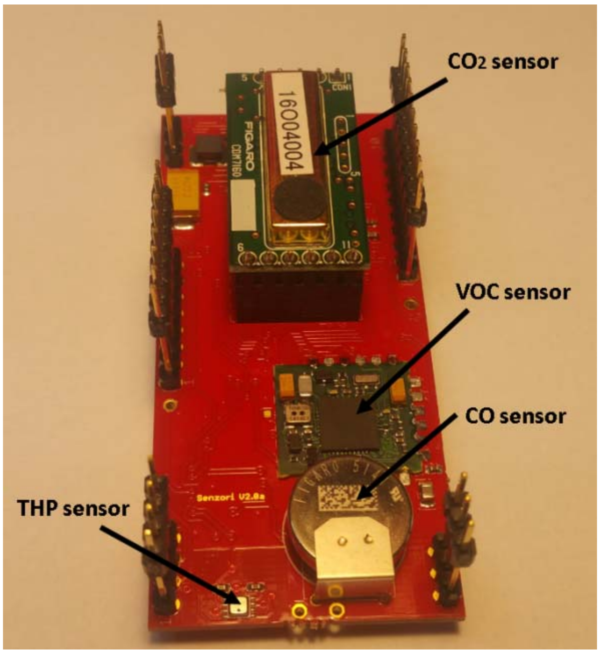

Fig. 2 – Sensor board (Bottom view).

The EEPROM memory is used to store calibration parameters for the on-board sensors and air inlet fan operation mode. All the sensors for a board contain their calibration parameter on the non-volatile memory of the same board in this case ensuring that if the sensor board is replaced there is no need for extra calibration.

The Atmega 128 microcontroller is loaded with a custom firmware developed to handle communication with the sensors, perform the calibrations using the calibration parameters from the EEPROM memory, perform the health diagnosis of the sensor board and communicate with the main board over SPI protocol.

The VOC sensor is basically an air quality sensor. It does not provide an exact measure of the VOC components in ppm or other similar units, but it provides an air quality indicator what can vary between 0% and 100% representing air quality from completely unpolluted air to polluted air. The sensor module is developed by Unitronic and the active element is the TGS8100 MEMS sensor from Figaro. Due to the on-board DSP processor, the VOC sensor acts as a completely digital sensor from this applications perspective because all the calibrations and measurements are performed by the Unitronic module.

The *Temperature, Humidity and Pressure* (THP) sensor is built around the highly accurate Bosch BME280 sensor chip. The sensor can measure atmospheric pressure in the range of 300 to 1100 hPa. The RMS noise of the pressure measurement is 0.2 Pa, which is equivalent to an absolute height difference of 1.7 cm. In our application, the temperature and humidity measurements are used only to perform corrections on the measured atmospheric pressure.

The CO sensor is measuring the carbon monoxide concentration and is developed around the TGS5141 unit produced by Figaro. The TGS5141 is an analogue sensor, being in fact a current source producing a current proportional with the CO concentration. Two measurement scales are available for the CO measurement. For low concentrations, below 460 ppm, the measurement resolution is approximately 0.5 ppm / LSB. For the high concentrations, above 460 ppm, a low-resolution scale can be used with an accuracy of 18 ppm/LSB. The EM50291 normative (30/50 ppm) is satisfied using the high-resolution scale.

The CO_2 sensor module is in fact a Non-Dissipative Infra-Red absorption (NDIR) spectrometer. The CDM7160 pre-calibrated carbon dioxide measurement module produced by Figaro has a detection range from 300 ppm to 5000 ppm interval and the accuracy is +/–50 ppm + 3% in the specified range. With a measurement interval fixed to 2 seconds it means every 2 seconds a new concentration is available from the CDM7160.

The Radon Sensor (TSR2) is the only sensor outside the device's case. The TSR2 sensor is developed by the Tesla Company and it is a junction silicon semiconductor. According to the manual, the sensor is able to measure radon activity concentration in the range 5–65535 Bq/m^3. It can perform a measurement at a pre-set time interval ranging from 4 minutes to 18.2 hours. The measurement uncertainty is less than 15% at 300 Bq/m^3 using 1-hour averaging. The relative humidity measuring range is 10 to 90% and the temperature measuring range varies from –20°C to +60°C. The power supply is discontinuous at 5V (max. 5 mA). In the current setup the sensor is configured to perform a measurement every 4 minutes and the 1 hour moving average is used as relevant value. The sensor communicates with the ICA system *via* a serial line using a custom protocol developed by Tesla.

2.4. DESCRIPTION OF THE DISPLAY BOARD

The display board, in fact, contains the elements the user interacts with while using the ICA system. It is the simplest board of the three and its main role is to mechanically hold the TFT display, the push button and the *ambient light sensor* (ALS) close to the top cover of the case. This board connects to the main board with a flexible ribbon cable.

The TFT Touch display module is a 3.2 inch 240 × 320 pixel, intelligent display module produced by 4D System. The Graphical User Interface (GUI) was developed with the 4D workshop IDE software. The display contains several menu pages as presented in the Figure 3. The microcontroller from the main board provides the values to be displayed on the TFT depending on the selected menu page. The display is used not just to show measured values but also provides a user interface to set the ON and OFF thresholds for each sensor in order to control the room ventilation unit.

The status LED and push button module is actually a push switch containing a bi-colour LED. The button is used to wake the system and turn on the TFT display; after the display is ON, all the rest of the user interaction can be done using the touch screen. The LED on the button is blinking green with low frequency as long as all the measured values are in normal range and there is no error detected. The LED is blinking red with a higher frequency in case of some measured sensor values are out of range or some error was detected in the ICA system.

The *Ambient Light Sensor* (ALS) is a sensor measuring the ambient light in the room and it is used to turn off the status LED during the night because the flashing of the status LED may be disturbing for some users.

2.5. DESCRIPTION OF OPERATION (THE FIRMWARE PART)

Once powered the ICA system, the microcontroller from the main board starts the diagnosis of the main power supply and, if all measured values are in the valid range, the power up sequence starts by powering one by one all the modules starting from the Wi-Fi and the sensor board and ending with the display module. After the power up sequence, the microcontroller from the main board starts the self-diagnosis thread, the communication thread, the measurement thread and the display thread. The self-diagnosis thread handles all the checking of system integrity and it decides between warnings cases which are sent over to the debug server, or the data server if the debug connection is down and the error cases with can lead up to shutting down some subsystem and reporting the error message to all active connections. The communication thread handles all the communications either through USB or through Ethernet connection. The Wi-Fi module is controlled by the Wi-Fi driver which handles the TCP connections. If the joining of the Wi-Fi router is successful, the two TCP connections are initiated to toward the radon server and the debug server. The Wi-Fi driver is responsible to restart the connecting procedures in case a connection brakes during operation or the Wi-Fi router is not reachable. The measurement thread handles the measurement starting at a pre-defined interval and it collects the data form the radon sensor and from the sensor board. It also initiates the sending of the measured data to the main server using inter-operation with the communication thread. The measurement thread also compares the measurement results with the limit parameters set for each sensor and if at least one measured data exceeds its ventilation threshold the HV driver is commanded to start the ventilation of the room. If all measured data are below the OFF threshold limit for all sensors the room, ventilation is turned off. The display thread handles the entire interface with the user. It wakes up the TFT module according to the human interaction with the push button, it controls the shown status of the display led, it takes care about the day and night mode depending on the value measured by the ALS sensor. At the same time, the display thread handles the selected menu displaying and the user input *via* the resistive touch panel.

The microcontroller from the sensor board runs also a couple of parallel tasks such as the self-diagnosis thread of the sensor board, the communication thread ensuring the communication with the microcontroller from the main board and the measurement thread itself controlling the on-board sensors and collecting the measurement results.

2.6. THE ROLE AND THE OPERATION OF THE DATA SERVER

The data server is located at a fix IP address. A multi-client server thread is running on a dedicated TCP port accepting connection from the ICA systems distributed on the field. On the communication protocol, each message from ICA system contains the UID of the unit making easy for the data server to identify the unit sending the data and labelling automatically the TCP connection accordingly. The server can send commands to a particular unit only if the unit is connected to the server, if the unit is not connected the server will wait for that particular unit (client) to connect. *Via* the communication protocol, the data server is able to interrogate and set all the parameters from ICA system and to interrogate the internal status of the equipment. The data server is logging all the incoming data from all the units in a database. The purpose of the web application is to allow the data, statistics and national radon map to be viewed according to the user's role: admin, regular or guest. The technologies used for building this application are: JavaServer Faces with PrimeFaces components. It was developed ensuring the modularity design technique with the *Model-View-Controller* (MVC) architectural pattern. Users registered on the web platform can access the real-time sensors results through the mobile application. They can also view a series of additional data such as a map that expresses the amount of radon in the surroundings and graphs of recent values. The application is developed in the Ionic cross-platform framework that allows exporting it as native application on any mobile platform.

For storing the sensors data and to meet the scalability requirement, the TimescaleDB, one of the most popular *Time Series DB* (TSDB), was chosen. It is a PostgreSQL extension and gives transparent time/space partitioning, high data writing rate and parallelization of operations, features that make it the optimal storage option for storing the data from the 100 homes that have equipment and send values over a 2-minute period. All the data for users, roles, configurations and permissions are stored in OracleDB, a relational system, which offers advantages like portability and performance, even with large databases.

2.7. SYSTEM VALIDATION AND SENSOR VERIFICATION

The accuracy of the sensors used by ICA system was tested in a sealed stainless steel chamber, located in the LiRaCC laboratory. The chamber has a volume of 0.2 m^3 and on the top face presents two insulated holes that allow communication through polyethylene tubes with the outside air. By using different radon sources connected through these tubes, the devices inside the chamber can be exposed to a wide range of radon concentrations (200–20,000 Bq/m^3) or other pollutants. The homogeneity of the atmosphere inside the chamber is ensured by two electric fans. Even if the radon sources used in this study are not national/ international validated, the reference instrument used (AlphaGUARD PQ 2000PRO from Saphymo) is annually calibrated by the manufacturer and the accuracy of the provided results has been confirmed in many intercomparison exercises [14]. In order to evaluate the accuracy of the radon sensor, the values obtained by the tested sensor were compared with those recorded by the reference monitor (AlphaGUARD). More methods are provided in the literature in order to evaluate the accuracy of a method/device [15]. One option is the computation of the ratio (R) between the measured values and the reference value. A result between 0.8 and 1.2 is considered acceptable. Another common option is to calculate the percentage difference (PD) with the equation (1):

$$\mathrm{PD} = \frac{\left|\mathrm{C}_{\mathrm{lab}} - \mathrm{C}_{\mathrm{ref}}\right|}{\mathrm{C}_{\mathrm{ref}}} \times 100\% \qquad (1)$$

Where: C_{lab} is the mean value of the radon concentration provided by the tested device and C_{ref} is the mean value of the radon concentration provided by the reference instrument. A PD value of more than 25% involves a re-calibration of the tested device [16].

Since the carbon monoxide and dioxide sensors, pre-calibrated by the manufacturer, have been integrated into the ICA system, a test of their functionality in the new circuit was required. In this regard, three standard mixtures of different CO concentrations (25, 60 and 90 ppm – 10% error) were prepared. The measurements were made in an atmosphere with 50% relative humidity and with a mixture of standard synthetic air (78% nitrogen, 22% oxygen) and 4.8% CO concentration. In order to test the CO_2 sensor, synthetic air was introduced into the LiRaCC chamber for about two hours. Subsequently, a calculated volume of CO_2, 99.99% purity, equivalent to 750 and 3000 ppm (3% error) respectively, was introduced.

3. RESULTS AND DISCUSSION

In order to assess the accuracy of the TSR2 radon sensor, a time period has been chosen for which the radon concentration inside the chamber was stable. The average value indicated by the reference monitor was 2440 ± 120 Bq/m^3.

In Figure 3 is indicated the time series of the radon concentration of the TSR2 radon sensor expressed as R. The accepted range (0.8–1.2) is also included in the figure, while the vertical dotted line indicates the time when the tested device was recalibrated. As can be easily observed, before recalibration, the TSR2 sensor underestimates the real radon concentration, an average value of R of 0.7 being obtained. The corresponding value for PD is 28%, which suggests the need for recalibration of the device. After the recalibration of the tested device, all calculated values of R were in the range 0.8 – 1.2, the average value being 1.00.

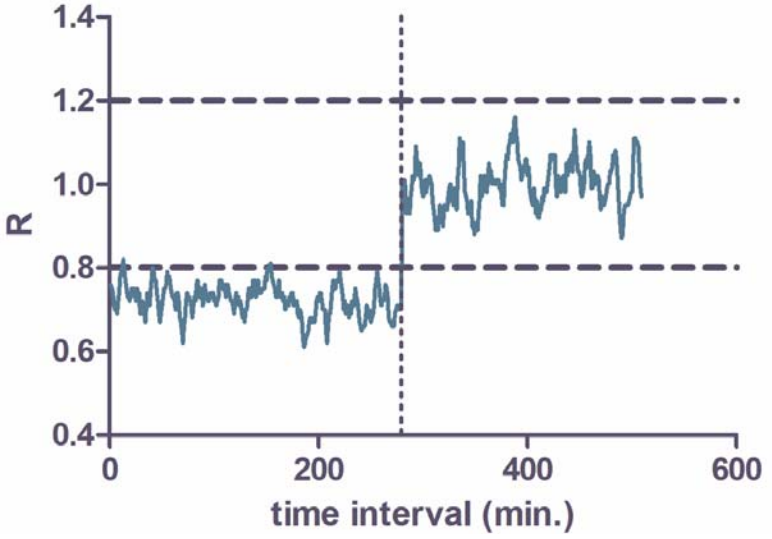

Fig. 3 – Radon concentration measured by TSR2 radon sensor expressed as ratio to the reference value for radon level of about 2500 Bq/m^3.

Prior to the *in situ* evaluation of the ICA system, the accuracy of the recalibrated radon sensor was tested at a wider range of concentrations. Thus, in addition to the above mentioned test (at approx. 2500 Bq/m^3), two additional experiments were carried out at an average radon concentration of approx. 250, respectively 1200 Bq/m^3. The results are presented in Figure 4 as box-plot, on the horizontal axis being indicated the average radon concentration at which the test was performed, while on the vertical axis the ratio between the obtained values and the reference values.

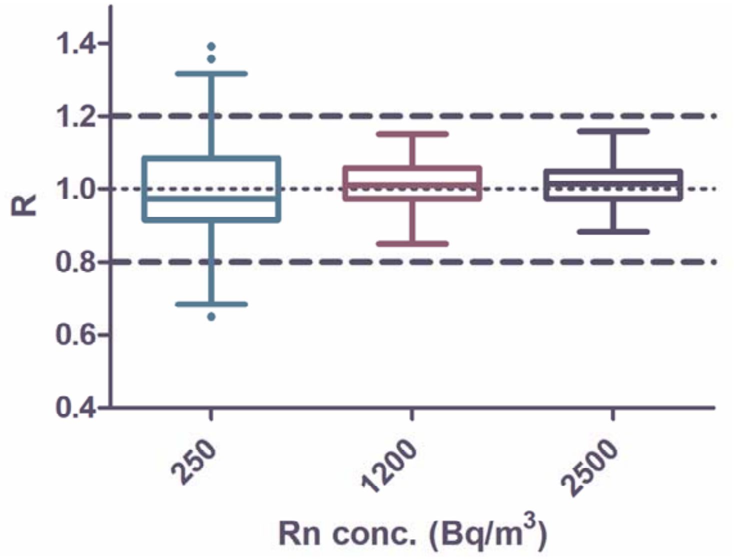

Fig. 4 – The box-plot representation of the ratios between the radon concentrations values of the tested device and the reference value for three different radon levels.

As expected, the highest variability, calculated as the coefficient of variation (15%), was recorded for the lowest radon concentration level. Even so, despite the presence of some outlier values, the mean value for R is very close to 1.00. In fact, by applying the paired t-test, the difference between the values obtained by the tested and the reference device is not statistically significant ($p > 0.05$), regardless of the radon level at which the experiment was performed.

For all three CO concentration levels, the accuracy evaluated by the equation (1) was less than 10%, while for the CO_2 sensor the maximum value of the percentage difference was 5%.

Following the laboratory tests, the ICA system was placed inside a house, where previous radon measurements indicated an average higher than the national reference level (300 Bq/m^3). The *in situ* evaluation of the ICA system, in terms of radon concentration, was carried out by monitoring this radioactive gas for one week with both the proposed prototype and Radon Scout device (SARAD GmbH, Germany), previously calibrated within LiRaCC laboratory. The results are shown in Figure 5.

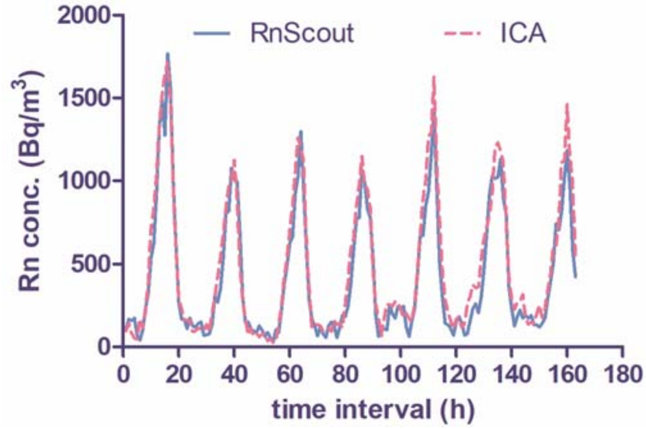

Fig. 5 – Time series of the radon concentration recorded by the ICA system and Radon Scout device over a week in the selected house.

An identical pattern can be observed for the two devices, the arithmetic mean of radon concentration monitored by the ICA system being 480 Bq/m^3, while Radon Scout indicates an average of 430 Bq/m^3, with a similar variation range (31–1765 Bq/m^3 for Radon Scout and 26–1715 Bq/m^3 for ICA system, respectively).

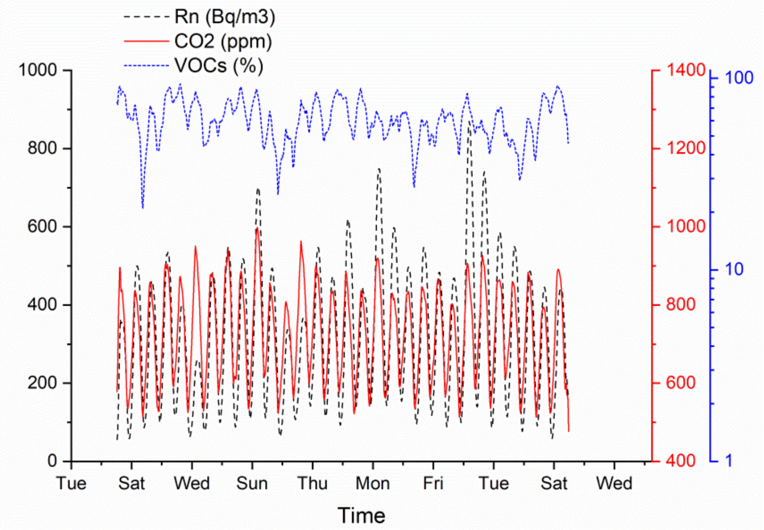

Fig. 6 – Time series of the monitored pollutants (radon, CO$_2$, VOCs) by the ICA system in the selected house for one month. The plots were constructed using a moving average of 12 hours.

The evolution of the indoor pollutants (radon, CO_2 and VOC) monitored by ICA system for a period of one month within the selected house is shown in Figure 6. By applying the Fast Fourier transform, 12-hours periodicities were observed. For this reason it was preferred to represent the data in the form of a moving average for 12 hours. Although the sources of pollutants are different, a similar pattern of evolution influenced by user's behaviour regarding the ventilation of the investigated chamber can be observed. Moreover, by applying the Pearson correlation coefficient, a good correlation ($r = 0.75$) between radon and CO_2 concentrations was observed. For the VOC sensor, as mentioned above, only a qualitative assessment of total VOCs can be made. Even so, a moderate correlation ($r = 0.55$) between CO_2 and VOCs was calculated. A weak correlation ($r = 0.25$) was found between radon concentration and VOCs.

4. CONCLUSION

The results obtained both in the laboratory and *in situ* confirm the accuracy of the tested sensors under the given conditions. However, long-term studies in a wider temperature and humidity range, along with the sensitivity time assessment of the sensors, are required to detect the limits of the sensors used by the ICA system. It should be remembered that the device was not designed as a safety device, but as one that provides a real-time screenshot of the indoor air quality. The results obtained recommend the developed system as a verified, accessible and safe way to adjust user's behaviour in order to increase indoor air quality and health.

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