EXPERIMENTAL RESEARCH OF MITIGATION SYSTEMS FOR CONTROLLING AND REDUCING RADON EXPOSURE IN RESIDENTIAL BUILDINGS

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Abstract. This article presents the results of implementing a series of methods to mitigate the increased level of radon in multiple existing homes. The subject of this study is represented by techniques and systems to be implemented in pilot houses. From the 1000 house 100 houses from Cluj, Iași, Sibiu, Timiș and Bucharest were selected for monitoring purposes. From these, only 10 were chosen for mitigation. The remediation techniques applied to these pilot houses were active / passive depressurization, local ventilation with heat recovery, centralized ventilation system with heat recovery and installation of a membrane resistant to radon dispersion. In this article one house from Timisoara, and another one from Cluj, were deeply described. The mitigation of the radon level was up to 90% compared to the level measured a year ago.

Keywords: Indoor air quality, Mitigation systems, Experimental campaign.

1. Introduction

Gaseous pollutants migration from subsurface systems (soils and groundwater) into indoor air represents an important exposure way for human health. These pollutants can become from the natural sources or from spills contaminating the soil or groundwater. Radon gas is by far the most important natural source of ionizing radiation [1, 2]. Radon is a natural radioactive gas, odorless, colorless and flavorless, with a lifecycle of 3.8 days, which arises from the natural decay of uranium in the soil and water. Other important sources would be building materials by exposure to gamma radiation from radionuclides 226Ra and 232Th and their descendants. In 2010, approximately 100.000 deaths and 2,1
million diseases can be attributed to prolonged exposure to high radon values [3]. This gas can easily infiltrate from the soil into the air. Being inhaled, it can cause mutations in human DNA, leading to lung cancer. After smoking, radon is the leading cause of lung cancer. It is reported that between 3-14% of lung cancer cases are due to radon. The possibility to develop lung cancer increases by approximately 16% each time the level is exceeded by 100 Bq/m$^3$ in case of prolonged exposure. For most of the people, the highest exposure to radon is in their own homes. The level of radon depends on a number of factors such as: the concentration of uranium found in rock and soil substrates; the places which radon can infiltrate homes; the number of air exchanges per hour, between the inside and the outside of the house (depending on the permeability of the building envelope, the ventilation habits of its occupants [4, 5]. Radon penetration into home can occur through cracks, pores in the floors, leaks, etc [3]. The path of radon atoms from the ground to the air is is exactly represented in the following figure:

![Fig 1- Representation of processes leading to radon discharge to atmosphere [6]](image)

Cosma, Papp [7] have made some radon diagnostic investigation in a radon prone area of Romania to show that the soil is the origin of radon. In order to reduce the radon concentration in the analyzed house, they applied techniques based on the pressurization and depressurization of the building sub soil using an electrical and eolian fan. The results proved that the biggest obtained mitigation efficiency was about 85% [7]. A one year survey study was conducted by Fuente, Rabago [8] in a experimental house from Spain with seriously alarming radon levels to investigate the effectiveness of radon reduction by soil active and passive depressurization. The results showed the permeability characteristics of the house and a link connecting wind velocity and the extraction airflow during passive SD (depressurization system) operation by means of a rotating cowl. A radon reduction efficiency of 85% was achieved [8]. Other many studies showed a good mitigation efficiency for active and passive depressurization systems [9-12]. Another mitigation method for controlling the radon level from the dwellings may be the
installation of a radon-proof membrane, especially in new homes. Coskeran, Denman [13] developed a study that demonstrates that, for low radon level, installing a radon proof membrane may be cost-effective in addressing the dangers to health [13]. In many cases, this method is applied with other remedial technique, as a secondary method [14, 15].

An experimental study on ventilation system in suburban buildings is presented by Merzkirch, Maas [16]. The system overall revealed strong interdependancies among all measured pollutants leading to a highly improved air features and a good comfort [15-17].

The new challenge in reducing energy consumption by retrofitting the existing houses. These energy efficient dwellings lead to the accumulation of many indoor pollutants. A study conducted by Sferle et. al. (2020) describe the relationship between many factors and the indoor air quality [4].

An important research direction is the implementation and experimental testing of various techniques and systems for reducing, preventing and controlling the level of radon in homes. The results of these measurements will lay the foundantions of the first guide of good practice [4]. Both beneficiaries and investors will be able to take into account the design of future new constructions, similarly as the improvement of living conditions in existing homes [15]. The main objective of this guide is to reduce the chance of developing lung cancer by establishing medium and long term applicability measures. A study conducted by Istrate, Catalina [18] showed the importance of a mechanical ventilation system to ensure the indoor air quality.

The paper presents: the method, the experimental campaign, results and the comparison of the data anterior and further the mitigation process.

Many studies have been conducted using sub-slap depressurization methods. The novelty of this study is represented by achieving a better indoor air quality simultaneously with radon reduction considering the reduction of energy consumption. The heat can be recovered using heat recovery equipments. The heat transfer into the ventilation flow, can occur in forced and mixed convencion [19].

The study comprise a very large number of measurements made in time on several dwellings, more exactly 1000 analysed dwelling. The importance of this study is shown by the health effects which radon mitigation systems brings on the exposed population.

In Romania very few studies have been performed in this branch, even though the radon potential in soil is very high in majority of areas and the exposure risk is imminent.
2. Materials and methods

2.1. Research conducted

Achieving the main objective, creating a healthy environment for occupants, in accordance with the problems related to energy consumption, can be done by implementing some equipment, depending on specifics of each house analyzed, installation possibilities and other barriers that will have to overcome throughout the project. The measurements were conducted following ISO 11665-2:2012 (guidance for measuring radon-222 activity concentration and its short-term decomposing products in air). The sensors have been placed at a height of about 1 m, at approximately 1 m distance from the walls, avoiding area near windows, or other path that can disturb the measurement. The sensors were unmoved for a better accuracy of the measurement. Research in this area has been conducted quite briefly, or only occasionally, on a single house. There are no studies conducted on a larger number of buildings using various radon reduction systems.

2.2. Radon measurement technology in the analyzed dwellings

The continuous measurement of radon level was conducted through an integrated prototype system for monitoring and controlling the interior air quality of the houses (Radon, CO, CO₂, VOC, temperature, pressure, humidity) using remote data transmission. Based on the prototype, the research team developed a number of 100 indoor air quality examination devices, which were installed in 100 houses selected to monitor environmental parameters, according to contractual planning. Of these 100 houses, 10 were selected with the highest values of radon, where energy-efficient equipment to mitigate the radon exposure and other household air pollutants were designed and implemented.

The intelligent indoor air quality examination device (Radon. CO, CO₂, VOC, temperature, pressure, humidity) with remote data transmission, includes the following hardware and software components:
- Radon sensor is using a Tesla TSR2 radon sensor with the specifications in the table below.
- Temperature, pressure, humidity sensors.
- A firmware that allows the acquisition of analog and digital data from sensors, data transmission via Wi-Fi, implementation of control loops and control execution elements.

Table 1
Tesla TSR2 sensor technical specifications

| Basic technical parameters:                        |                                      |
|--------------------------------------------------|--------------------------------------|
| Measurement sensitivity                          | 0.15 count/hour/ Bq·m⁻³ (typically)  |
| Radon scale                                      | 5 – 65535 Bq.m⁻³                     |
| Measurement unsureness                           | 15% at 300 Bq.m⁻³ per 1 hour         |
| Relative humidity scale                          | 10 – 90 %                            |
| Temperature scale                                | -20 to + 60 °C                       |
| Radio frequency range                            | up to 600 m                          |
| Records saving interval (probe)                  | 1- 255 minutes, default 1 hour       |
| Memory capacity                                  | 150 days                             |
| Probe                                            | Li-Ion battery 3.6 V, 2.6Ah           |
| Battery life                                     | >1 year                              |
| Radon concentration results display              | short-term (1 hour running average)   |
|                                                  | long-term (24 hours running average)  |

2.3. Radon measurements

Radon measurements were performed in two stages. First measurement campaign consisted in passively monitoring for all selected houses using state nuclear track detectors. Detectors were installed into the most inhabited room. To ensure the proper results, each detector was placed and recovered. The second evaluation campaign involved a comprehensive radon detection of each building evaluating some aspects like building tightness, the soil geology, soil permeability, sources of indoor pollution, gamma dose radiation measurements of ground and building materials, the existence of HVAC system, etc. A series of information were collected from the inhabitants, as described in previous works [20]. The prototype measuring device described above was developed by a group of scientists from the Babeș-Bolyai University [21] and installed inside the analysed dwellings to record the indoor air properties (temperature, relative humidity, pressure, CO, CO₂, VOCs and radon) in real-time for up to one year, in order to select 10 pilot house for mitigation measures.

The analysed houses were from the biggest cities of Romania. Over 1000 dwellings from Iași, Timiș, Cluj, București and Sibiu counties were considered in this study. From these, 100 houses were chosen for detailed measurement as previously described. The annual mean of radon concentration has been calculated to determine the 10 pilot houses suitable for the application of mitigation measures.
Due to high values of radon measured in the analysed dwellings and the potential of radon in the soil previously investigated [22, 23], in the west of the country, exposing the population to high values of radon is a more imminent necessity. Thus, the pilot houses chosen were 4 from Timiş, 5 from Cluj and only one from Bucharest.

### 2.4. General mitigation measures

The dwellings were analysed considering a variety of facts to implement the best mitigation solution, customizing every basic system for maximum adaptability. To reach the highest efficiency level, multiple scientific and technical studies were analysed and suitable mitigation systems were designed for every pilot house. The mitigation systems installed were based on building sub-slap depressurization (SSD), radon proof membrane, simple-flow mechanical ventilation with heat recovery, double-flow mechanical ventilation with heat recovery and centralized ventilation with heat recovery.

**Active sub-slap depressurization system**

This system is based on installing a PVC perforated embossed pipe (100 mm diameter) in a granular fill material, connected to pipeline which ensure the evacuation of contaminating air from the soil by creating a low pressure under the floor. Due to this level of pressure created, the radon gas does not infiltrate into the house, being evacuated outside. To limit the intervention and thus, the cost to install the system, the workers drilled some wholes under the floor from the outside of the house and introduced the suction pipes under the floor.

**Radon proof membrane**

An efficient method to combat the high level of radon inside the buildings, when the principal provenance of radon into the house is from the soil, is to limit its entries and isolate the sources. A radon proof membrane is used to seal the contact to the soil and limit the radon diffusion inside the house. That method is used mostly in combination with another mitigation system to increase the radon reduction efficiency and a good indoor air quality.

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### Average radon level by county

| Dwellings | County   | Average values/ year Bq/m³ |
|-----------|----------|---------------------------|
| 10        | Iaşi     | 215,4                     |
| 40        | Cluj     | 428,3                     |
| 17        | Bucureşti| 282,9                     |
| 20        | Timiş    | 265,4                     |
| 13        | Sibiu    | 264,0                     |
Simple-flow mechanical ventilation with heat recovery

This system consists in drilling a hole into the exterior wall and installing the equipment. The principle used consists in driving an air flow from outside to inside from 70 seconds, whereupon the mechanical ventilation reverses its air flow exhausting air from the room for another 70 seconds. The heat recovery equipment recovers an important amount of energy. This method is a cheap and efficient way to mitigate the local rooms when the limit value is not much exceeded.

Double-flow mechanical ventilation with heat recovery

An equipment like the one presented above. The main difference derive from the continuous functioning of airflows, having different ways of intake and exhaust the air ventilated.

Centralized ventilation with heat recovery

This is one of the most complex mitigation methods based on mechanical ventilation, consisting in the installation of a ventilation unit in the attic of the house and ensuring the interconnection of grilles through pipeline routes. The polluted air is exhausted from the bathroom, kitchen and other dirty rooms, and fresh air is introduced in the living spaces like bedroom, living-room, office, etc. The central ventilation unit is equipped with a heat recovery system. This type of equipment provides a very good indoor air quality, removing other pollutants (CO, CO₂, NOₓ, VOCs,) and maintaining the interior comfort.

3. Presentation of the dwellings analyzed with the MITIGATION methods

The analyzed house is in Timișoara, Timiș County and it is composed of two parts. The building envelope is relatively tight, the house being recently retrofitted. The values obtained for the determination of the radon potential in the soil do not exceed severely the reference level, but the radon risk category due to radon concentration does exist. The soil permeability shows a high infiltration risk of radon into the building, values which confirm that the ground is the leading source of radon. Due to exceeding the reference level in the entire dwelling, the centralized ventilation system was recommended.

For mitigation, two ventilation units with heat recovery were installed in the attic of the house to extract contaminated air from the bathroom and kitchen and to introduce fresh air into the living rooms, each one deserving a part of house. In addition to mechanical ventilation of indoor air, other measures such sealing the cover of cellar using silicone and all the visible leaks in the floor which is not sealed from the soil.
To express the impact of the improvement of the indoor air quality due to ventilation system, we analyzed two periods of time. First period of time represents the values monitorized before any measure was taken when values up to 760 Bq/m$^3$ were noticed. The variation of radon values express the time when the house occupants opened the windows for natural ventilation. Note that they have been informed with the risk they are exposed. The graph above shows an important fall of radon level from the entire house. The average radon reduction efficiency is about 53% in this case, but the other advantages for using this system are based on the other indoor air quality parameters.

As described in the graph above the indoor air quality into the analysed dwelling was very harmful for the occupants. Extremely high values of CO$_2$ were measured reaching values of up to 4000 ppm overpassing 5 times the maximum values. The only times the CO$_2$ level was lower was during the time the windows were opened. After the mitigation methods have been applied, the CO$_2$ level has been stabilized with values between 500
ppm and 700 ppm, close to the outdoor concentration. The CO₂ reduction efficiency of the system is around 67%. Due to unnecessary opening of the windows in the wintertime, the comfort level has been improved significantly. The temperature level of the room has been stabilizing to a set point, suffering no more fluctuations. As natural ventilation represented a large amount of energy loss using the heat recovery equipments, the heating costs have been reduced by half.

Another pilot house is a modern building, built in 2008, located in Cluj county. The subject of interest is a ground floor flat with three bedrooms, a living room and a kitchen. There is a small cellar under the bedroom 3 and it is permanently ventilated. During the first and second measurement campaign radon concentration in the cellar was below 70 Bq/m³ and the mean values of radon concentration in the living room varied from 300 Bq/m³ to 450 Bq/m³. Radon concentrations measured at the end of June 2019 were below 100 Bq/m³ in all rooms except of the cellar, where the values around 600 Bq/m³ were discovered. Radon concentrations in the air samples taken from possible entry routes are small; the only exception is a pipe penetration for the radiator in the living room (3,4 kBq/m³). Radon index of foundation soils is low (third quartile is 6 kBq/m³). Based on the measurements, increasing the ventilation flow through the mechanical ventilation will reduce the indoor radon concentration below the reference level. The mitigation system is based on the installation in the outer walls of the bedroom and office of two equipment for single-flow mechanical ventilation, equipped with heat recovery. The synchronization of the devices is done by ensuring the air circulation between the rooms of the house. When one equipment operates on air intake, the other should operate in air exhaust mode. Air circulation between rooms must be ensured. In addition to improve the ventilation all the visible leaks in concrete floor, which are in contact with the soil, were sealed.

![Fig 4 - Position of local ventilation units in the house](image)
After the equipment were installed, we started to oversee the results. The preliminary results showed a improvement of radon level, sufficient to decrease the average level of radon below the limit. The radon reduction efficiency was calculated to be 86% for the analyzed period as it is described in the graph below, maintaining the radon level very low. Due to its costs this system is suitable for mitigation in dwellings where the average radon level is not so much exceeded (≈ 450 Bq/m³). As can be observed in the graph below during the accumulation period, very high values were noticed, the limit being outdated almost every time. Due to proper utilization of the system, a better indoor air quality can be assured.

This mitigation method improves the air quality, not only decrease the radon level. Thus, the CO2 level is found in normal concentration after the mitigation solution was applied,
showing values around 530 ppm. The highest CO$_2$ value was close to 2000 ppm which is a harmful exposure. The CO$_2$ reduction efficiency is around 55% expressing a better and safe indoor air quality. The fluctuations represented in the graph shows the moment when the occupant opened the window for natural ventilation. The highest values of CO$_2$ concentrations were found in the morning after accumulation overnight.

Following the mitigation methods applied in all 10 pilot houses, a series of conclusions will determine the advantages and disadvantages for implementing every method due to dwelling characteristics and radon level in the soil and in the water.

### Table 3

| System name                        | Implemented measures                                      | Mitigation efficiency |
|------------------------------------|-----------------------------------------------------------|-----------------------|
| Sub-Slab depressurization          | Only the SDS system                                       | up to 86%             |
|                                    | Radon proof membrane                                      | up to 95%             |
|                                    | Radon proof membrane + decentralized heat recovery system  | up to 95%             |
| Centralized heat recovery ventilation | Ventilation unit installed in the attic                    | up to 55%             |
| Decentralized heat recovery ventilation | 1 reversible flow unit                                    | up to 72%             |
|                                    | 2 reversible flow units                                    | up to 86%             |
|                                    | Continuous double flow operation                           | up to 75%             |

As observed in the above table, the most efficient method to mitigate the high radon level from existent dwellings is by installing the sub-slab depressurization system, but other pollutants cannot be removed from the indoor air. The utilization of a mechanical ventilation system to mitigate the high radon level can provide an important improvement of indoor air quality and a good comfort for the home occupants. To choose the proper system for radon mitigation a detailed analysis should be conducted.

**Conclusions**

- According to the measurements made, in most areas of the country the soil has medium or high radon risk values against health of the population.
- The lack of regulations regarding health risk of radon led to this study, one of the aims being the writing of a guide for house owners and constructors.
- The project aimed at designing and implementing solutions to remedy the radon in homes, following the characteristics of buildings, radon level, construction materials, installation and operating costs, energy efficiency.
- The measured data were analysed before and after the implementation of the systems. Data analysis showed that all proposals regarding radon mitigation, had
significant positive results in increasing indoor comfort, more exactly, the radon reduction into the analysed dwellings was between 53 to 86%.

- Into those houses were ventilation mitigation system were applied the CO₂ decreased to a average level between 500 to 700 ppm.

- The average level of radon indoor concentration was reduced below the limit imposed by the national regulations of 300 Bq/m³, creating a safe indoor environment for the house occupants.

- In comparison with the traditional method (natural ventilation through the windows openings), using the energy efficient systems to mitigate the radon level, a significant reduction in energy costs was observed.

- The purpose of these studies is to increase the concern for radon exposure, to test the radon mitigation measures and to increase the radon prevention by implementing the guides into building norms.

Acknowledgement. The authors are grateful for the support provided by the local authorities and the residents who collaborated on this experimental research. The study is part of a large project, with the title “Smart Systems for Public Safety through Control and Mitigation of Residential Radon linked with Energy Efficiency Optimization of Buildings in Romanian Major Urban Agglomerations SMART-RAD-EN” of the POC Programme.

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