Indoor Radon Concentration Related to Different Radon Areas and Indoor Radon Prediction

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Abstract. Indoor radon has been observed in the buildings at areas with different radon risk potential. Preventive measures are based on control of main potential radon sources (soil gas, building material and supplied water) to avoid building of new houses above recommended indoor radon level 200 Bq/m³. Radon risk (index) estimation of individual building site bedrock in case of new house siting and building protection according technical building code are obligatory. Remedial actions in buildings built at high radon risk areas were carried out principally by unforced ventilation and anti-radon insulation. Significant differences were found in the level of radon concentration between rooms where radon reduction techniques were designed and those where it was not designed. The mathematical model based on radon exhalation from soil has been developed to describe the physical processes determining indoor radon concentration. The model is focused on combined radon diffusion through the slab and advection through the gap from sub-slab soil. In this model, radon emanated from building materials is considered not having a significant contribution to indoor radon concentration. Dimensional analysis and Gauss-Newton nonlinear least squares parametric regression were used to simplify the problem, identify essential input variables and find parameter values. The presented verification case study is introduced for real buildings with respect to various underground construction types. Presented paper gives picture of possible mathematical approach to indoor radon concentration prediction.

1. Introduction

The indoor radon problem is closely associated with environmental friendly indoors. Contact with radon is in most cases not harmful to human health and life. There are situations, however, in which engineers should be aware of such risks. It is assumed that the concentration of radon in the air is 10 Bq/m³, which is about half the dose of radiation which people are exposed to from natural sources. However, in buildings made in large part from concrete, cement and their derivatives, much higher natural radiation of these materials is present.

In recent years, several studies have shown that radon concentration and its decay products in buildings show large temporal and local fluctuations due to changes in temperature, pressure, humidity, building material, ventilation condition, etc. The main source of indoor radon is radon from the soil. All buildings are polluted to some extent with radon, but in certain geographical areas the rate of seepage of radon from the soil is much faster than elsewhere. The occurrence of radon in soil relates with the amount of uranium (238U) in sub-soil and with the geological structure of the area. For that, the geological sub-soil has substantial effect on amount of released radon and on the radon risk area potential. The density of radon is of 9.73 kg/m³, thus it is about eight times as heavy as air.
Accordingly, radon concentration in the lower parts of the premises, and in particular on the lower levels often greatly exceeds its mean concentration in the air. Additional effect of radiation from the subsoil is observed from the basement, especially where the substratum is made of granite containing large amounts of uranium. Most European countries have introduced limiting of the allowable concentration of radon in the buildings in which people stay for an extended period of time.

This kind of radiation is both the natural environment: air, water reservoirs, food, and from human activities: production plants emitting harmful substances, concrete engineering structures. What is natural radioactivity? Henri Becquerel, the discoverer of the phenomenon, observed the effect of blackening of the photographic plate by putting some uranium salt on it. The result of this observation was published in 1896. Two years later, Maria Sklodowska-Curie named this phenomenon radioactivity. These studies were considered groundbreaking, and both scientists were awarded the Nobel Prize in 1903. Becquerel (Bq) has become the unit of radioactivity.

The adverse health effects of exposure to radon are caused primarily by damage due to alpha-particles. The possible effects will depend on exposure level. The main danger from high radon exposure is an increased risk of lung cancer. Radon as a noble gas is rapidly exhaled after being breathed in; however, radon progeny, combine with other molecules in the air and with particles of dust, aerosols or smoke, and readily deposit in the airways of the lung. While lodged there, the progeny emits ionizing radiation in the form of alpha particles, which can damage the cells lining the airways. Experiments have confirmed that ionizing radiation affecting bronchial epithelial cells could cause cancer.

The areas with higher indoor radon risk correlate with known localities with high volumetric radon activity levels in the underground soil. Radon found in the underground soil influences in a large scale volumetric radon activity level indoors. It is important to realize that radon as an inert gas, on its way from origin place, where it can affect in long-term the human health, is influenced by many factors that can change resulting volumetric radon activity [1,2]. According to [3] environmental data confirm a close relationship between lung cancer and large concentrations of radon. The report states that radon is the second leading cause of lung cancer after smoking. Protection against excessive radon radiation ought to be bases on the use of materials with a relatively low level of radioactivity (e.g. slag, ash, granite aggregate, other materials derived from combustion). The rooms should be thoroughly ventilated on a regular basis. The most beneficial would be a continuous exchange of indoor air with atmospheric air. During the process of designing or adapting premises, basements must not be used for residential purposes.

The most important factors are the soil permeability, soil porosity and moistures, pressure difference between the air of soil pores and ground surface, radon diffusion coefficient, airflow rate through the gap, soil contact area, room volume and air change rate. Important factors for estimating indoor radon concentration from radon exhalation from soil are the radon concentration in the underground soil, room volume, soil contact area, airflow rate through the gap, air change rate and rate of radon exhalation from the soil. A lot of studies do exist concerning to indoor radon transportation process modelling. Final concentrations are usually influenced by emanation from building materials, exhalation from the soil and air change level as at Slovak conditions the main source of indoor radon and the main factor of influence is the underground of building. The problem of indoor radon concentration is solved as a radon entry rate leakage through underground construction [4, 5]. The model presented in this paper is based on combined radon diffusion through the slab and advection through the gap from sub-slab soil. This model is great contribution for building underground construction design on middle and high radon risk areas [6, 7]. The models and modelling substantially contributes to the problem solution and to obtaining new cognition concerning system behaviour. The mathematical description of the processes can generalize the achieved results and their
interpretation on other various processes physically similar to introduced model. Although the modelling doesn’t achieve all rules of similarity, but overall provides information concerning to systems behaviour, which is only little different from the real situation. The approximate model generally is simplifying description of the surveyed reality.

Preliminary survey of long-term effectiveness of preventive measure was carried out in 2002 including more than 200 new family houses. Radon-related risk of building site performed remedial measures and present indoor radon concentrations were studied. It was discovered that the system does not work as was expected and new houses above indoor radon guidance level are built up to now. There were found mean radon concentration above 200 Bq/m$^3$ in 17% of the new buildings and in 50% of family houses there was found at least one room above this level [8]. One of the reasons seems to be unexpectedly low air exchange rate in modern energy-saving houses and still more popular “natural damp cellars without insulation” in the last years.

2. Introduction measurements

Radon levels are usually higher in basements, cellars and ground floors. Depending on a number of factors, the concentration of radon indoors varies with the time of the year, from day to day, and from hour to hour. Because of the time-variation, reliable measurements of mean concentrations in air should be made for at least three months. The radon released from the rocks, work straight through the basement constructions into buildings or through releasing from the water. During the year, the air pressure inside of buildings is mostly lower than in the soil of surroundings. This difference in pressure draws radon, through the leaks into the building. The most important factors affecting this process are: under-pressure in the building, radon concentration in soil, permeability of sub-soil, and basement construction tightness concerning to radon leakage. Radon gas enters houses from the ground through cracks in concrete floors and walls, as well as through gaps between floor and slab, and around drains and pipes, and small pores of hollow-block walls [9]. The indoor radon concentration measurements were provided in the buildings built at different radon risk areas. The protection of new buildings is based on mentioned radon-related index of building site. Since internationally accepted definition of radon-related index and method for its evaluation is not accepted yet, three categories (low, medium and high) for radon-related index was defined and used in practice. Evaluation is based on set of radon in soil gas measurement (at least 15 probes in depth 0.8 m necessary), and permeability measurements (classification see in Table 1).

| Radon related index | Radon concentration in soil (kBq/m$^3$) |
|---------------------|----------------------------------------|
|                     | low permeability | medium permeability | high permeability |
| Low                 | < 30             | < 20               | < 10             |
| medium              | 30-100           | 20 – 70            | 10 - 30          |
| High                | >100             | > 70               | > 30             |

All measurements were taken in the ground floor rooms with approximately equal size and disposition. The windows and doors of the rooms were closed all the time during the testing measurements. Measurements were provided in winter time, by similar meteorological conditions, in order to eliminate the various physical parameters effects. The integral dosimetry system RM–1 for measurement of indoor radon concentration was used. The device consists of radon detectors, ion chambers RM–200A and reader EVR-5 model 97. The results for buildings without radon reduction techniques are given in the Figure 1.
Figure 1. EVAR for buildings without radon reduction techniques

Two different types of reduction techniques in the buildings which are located in high radon risk areas were designed: anti-radon insulation (passive measure) and ventilation (active measure). In the case of using forced ventilation as a reduction technique, readings were provided between two contrasting measurements; when running the ventilation and when the ventilation was out of operation. For comparison of efficiency of anti-radon insulation in building located in high radon risk area, contrasting measurements were made in rooms where the anti–radon insulation was not applied. The results are summarized in the Table 2.

Table 2. Ventilation and insulation effect on indoor radon concentration.

| Measurement | Operation / insulation | Radon risk | VAR \([\text{Bq/m}^3]\) | EVAR \([\text{Bq/m}^3]\) |
|-------------|------------------------|------------|-----------------|-----------------|
| No 5        | no ventilation         | High       | 718             | 259             |
|             | Ventilation            | High       | 253             | 146             |
| No 6        | bituminous asphalt     | High       | 2400            | 921             |
|             | anti-radon insulation  | High       | 353             | 134             |

In the buildings built at low and middle radon risk areas the values of under action level were found. In the case of buildings at high radon risk area with proposed forced ventilation as a radon reducing the value of 146 Bq/m³ was found. On the other hand, the indoor radon concentration 259 Bq/m³, in time of duration when the ventilation equipment was turned off, was found. This value is above the action level however; this value was effectively decreased to value 146 Bq/m³ by running ventilation. The ventilation effect is strongly affected to intensity of air change.

In the building built at high radon risk area, where the anti-radon insulation technique was realized, a value of EVAR 134 Bq/m³ was found. In contrast to measurement, in the room without anti-radon insulation technique, there was measured value of EVAR 921 Bq/m³. This value is far above the standard.
Many countries have defined an Action Level of radon concentration to guide their program to control domestic exposure to radon. The Action Level is not a boundary between safe and unsafe, but rather a level at which action on reduction of radon level will usually be justified. Some people may choose to take action when the Action Level is approached. For example, many countries consider radon concentration in the air of 200 Bq/m³ as an Action Level at which mitigation measures should be taken to reduce radon level in homes. Guideline values (action levels) of radon vary among countries. The values of average radon concentration and action levels for selected countries are evident from Table 3.

| Country          | Average indoor radon concentration | Action level |
|------------------|-----------------------------------|--------------|
| Czech Republic   | 140                               | 200          |
| Slovakia         | 135                               | 200          |
| Finland          | 123                               | 400          |
| Sweden           | 108                               | 400          |
| Germany          | 50                                | 250          |
| Canada           | *                                 | 800          |
| United Kingdom   | 20                                | 200          |
| USA              | 46                                | 150          |

*not available at the moment

3. Indoor radon modelling

In order to predict the indoor radon concentration, it is necessary to describe the dominant influencing parameters which characterize radon entry process exactly. The radon concentration in the underground soil $C_u$ [Bq/m³], room volume $V$ [m³], soil contact area $A$ [m²], airflow rate through the gap $Q_g$ [m³/s], air change rate $n$ [1/s] and radon leakage from the soil $E_a$ [Bq/m².s] can be considered as the essential input parameters.

Presented mathematical model for prediction of indoor radon concentration is based on formation of dimensionless arguments $\pi$ from the stated variables influencing the indoor radon concentration. Their valuable property is that in all existing systems of units they have the same numerical size and they have no dimension. The dimensional analysis is a mathematical tool used in physics and engineering to simplify a problem by reducing the number of variables to the smallest number of essential parameters. The systems which share these parameters are called similar and it is not necessary study them separately. The dimension of a physical quantity is the type of unit needed to express it. Every unit is a product of powers of the basic units. The units form a group under multiplication. The reduction of variables uses the Buckingham $\pi$-theorem as its central tool. The theorem describes how every physically meaningful equation involving n variables can be equivalently rewritten as an equation of n-m dimensionless parameters, where m is the number of basic units used. Furthermore, and the most important, it provides a method for computing these dimensionless parameters from the given variables, even if the form of the equation is still unknown. The $\pi$-theorem with linear algebra is used for suggested indoor radon prediction model. The space of all possible physical units can be seen as a vector space. A unit is presented as a set of exponents needed for the basic units (with a power of zero if the particular basic unit is not present). Multiplication of physical units is then represented by vector addition within this vector space (Buckingham $\pi$). Nonlinear models are considerably difficult to fit, requiring iterative methods that start with an initial guess of the unknown parameters. Every iteration alters the current guess using the estimated model function, until the algorithm converges to find the parameters that minimize the sum.
of the squared differences between the observed $VAR$ values and their fitted values. The Gauss-Newton algorithm with Levenberg-Marquardt modifications for global convergence was used [10].

All the given variables are presented in basic dimensions to utilize the dimensional analysis for creation of the indoor radon concentration mathematical model. The general relationship between all the chosen essential input variables which influence the radon concentration can be written in this form:

$$\varphi(VAR, Cu, Qg, n, V, Ea, A) = 0.$$

(1)

Using the calculated fundamental unit power exponents, the 5 dimensionless arguments can be written in the following form:

$$\pi_1 = \frac{VAR}{Cu}, \pi_2 = \frac{Qg}{Cu.A^3}, \pi_3 = \frac{n^2}{Cu^2.A^2}, \pi_4 = \frac{V^2}{Qg}, \pi_5 = \frac{Ea}{Cu^2.A^2}$$

General form of the functional dependence of $\pi$ arguments can be used to express the $VAR$ in the following form:

$$VAR = Cu.\Phi\left(\frac{Qg}{Cu.A^3}, \frac{Ea}{Cu^2.A^2}, \frac{n^2}{Qg}, \frac{V^2}{Cu^2.A^3}\right)$$

(2)

For construction of model function $\Phi$, general dependence of $VAR$ on input parameters was taken into account. An empirical nonlinear parametric function was estimated based on experimental data analysis and known dependencies (2):

$$VAR \approx Cu.\pi_1 + \pi_2$$

(3)

$$VAR = b.Cu.\frac{Ea}{V^2} + \frac{Qg}{Cu^2.A^3}$$

(3)

Where, $b$ is unknown parameter for nonlinear parametric model, which have to be calculated using the nonlinear least squares method.

4. Verification case study

The verification of presented mathematical model was realized by testing of predetermined values of radon volume activity for real typical family houses. The measurements were made in real buildings “in situ” with various underground construction types under model conditions. The followed buildings were chosen on the base of ground radon risk level. For calculation of determining parameters values, partial results was analysed while the calculation procedure was chosen based on known relations. The needs dimensionless arguments and regression coefficients for model verification were determined. Regression coefficients have been calculated using the Gauss-Newton nonlinear regression. Values of nonlinear regression parameters for buildings without underground floor were calculated. The final formula of predicted indoor VAR calculation will be:
The values of calculated and measured indoor radon concentrations for the buildings on the ground with low, middle and high radon risk level are in the Figure 2. The differences between measured and calculated radon concentrations can be considered acceptable. The deviation can be explained with not accurate selection of relevant parameters involved into account, which indoor radon concentration depends from. The validity of modelling approach seems to be satisfactory especially for low radon risk grounds.

The selected relevant variables for mathematical model construction do not give a real picture of the indoor radon concentration wholly and exactly. Therefore, some differences were observed among measured and calculated indoor radon concentrations. The mathematical model approach is introduced with belief in next continue work in order to precise arguments in order to achieve more complex entry database for statistical approach and fine tune the model function by increasing parameterization.

\[ VAR = 6,12472 \times 10^6 \cdot Cu \cdot \frac{Ea}{V^2} + \frac{Qg}{Cu \cdot A^3} \]

\[ \frac{1}{A^3} + \frac{n^2}{Cu^2 \cdot A^3} \]  

(4)

5. Results and discussions

These results show that generally there is evident necessity of using the anti-radon insulation technique. Unforced ventilation as solitary reducing techniques appears only preliminary and not very suitable approach of indoor radon elimination. This technique is also affected by the ventilation management and its efficiency as well as operating costs. The design of reducing techniques has to be comprehensive and has to respect interactive effects of sub-soil, the basement construction, distribution and air level change. The optimal solution is the combination of several types of reducing techniques.

Selection of the input parameters seems to be well done as the result deviation from verification is pretty low. Presented model construction offers good space for indoor radon auditing in building pre-design (re-design) process. Indoor radon concentration is influenced mainly by the effect of radon leakage from the soil and from radon transportation through the gap construction. Opening model
verification confirmed that indoor radon concentration correlates with the radon underground concentration. The most important from indoor radon loading point of view is the underground construction control and proper design.

6. Conclusions
Radon levels in room air can be lowered in a number of ways, from sealing cracks in floors and walls to changing the flow of air into the building. The five principal ways of reducing the amount of radon entering a house are: Improving the ventilation of the house; Sealing floors and walls; Increasing under-floor ventilation; Installing a radon sump system; Installing a whole house positive pressurization or positive supply ventilation system. Some of these solutions are not suitable for all types of houses, nor are they suitable for all levels of radon. In some cases, more than one solution is needed in resolving the radon problem. Radon safety needs to be considered when new houses are built. Aim of preventive measures is to build new houses with “as low natural radiation as reasonable achieved” and avoid constructing of new houses above guidance levels. In many countries, for instance in England and in the United States, including protective measures in new buildings has become a routine procedure. These measures have been proven to keep radon levels well below the recommended action level, both in the short and long term.

References
[1] I. Senitkova, M. Bucakova, “Radon and basement construction”, 24th Int. science conference Industry Toxicology, pp. 113–116, 2004.
[2] I. Senitková, A. Szabóová, “Building underground construction design focusing on radon elimination from the soil”, International Civil Engineering Conference”, Bratislava, pp.266-271, 1998.
[3] Raport EPA's Assessment of Risks from Radon in Homes (‘Estimation of risks posed by radon in homes. Made by the EPA”), 2003 prepared by Environmental Protection Agency in USA
[4] I. Cozmuta, E.R. van der Graaf, R.J. de Meijer, “Modeling radon transport in concrete”, MSC2001 Conference”, Caltech, Pasadena, 2001.
[5] I. Cozmuta, E.R. van der Graaf, “Methods for measuring diffusion coefficients of radon in building materials”, The Science of the Total Environment, vol. 272, pp.323-335, 2001
[6] C. E. Andersen, D. Albarracín, I. Csige, E.R. van der Graaf, M. Jiránek, B. Rehs, Z. Svoboda, L. Toro, ERRICCA radon model intercomparison exercise. www risoe.dk, 20 p., 1999
[7] K. Sun, Q. Guo, W. Zhuo, “Feasibility for mapping radon exhalation rate from soil in China”, Journal of Nuclear science and technology; vol.41, no. 1, pp. 86-90, 2004.
[8] M. Levinská, J. Dolejs, J. Hůlka, L. Tomášek, „Research of radon occurrence in new houses in dependence on the soil radon index“, International Workshop on the Geological Aspects of Radon Risk Mapping, Praha, 2002.
[9] I. Senitkova,” Radon“, Indoor pollutants- buildings for living. Bratislava, pp. 55-98, 1999
[10] I. Senitkova, A. Szaboova, “Prediction of indoor radon concentration”, Indoor Air 2005, Tsinghua University, Bejing, China, 6 p., 2005.