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Nucené odvětrání radonu z podloží stávajících staveb

Sub-slab depressurization systems in existing buildings

SUMMARY

Part A summarizes very briefly health effects of radon on human beings, mentions some historical events and describes the level of irradiation caused by radon to the Czech population. A particular attention is paid to the description of methods that were developed for protection of houses against radon. Differences between the former Czech approach to the solution of the radon problem and approach that was chosen in countries, which first began to deal with radon in dwellings, are explained. Various forms of sub-slab depressurization systems used in other countries are presented.

Part B summarizes the author's contribution to the development of sub slab depressurization systems. The work is based on the research projects solved for the State Office for Nuclear Safety and on the detailed and unique database of data from 70 houses remediated by sub-slab depressurization according to the author's design. Analysis of data from this database was completed with numerical modelling of temperature, pressure and radon concentration fields and with long-term monitoring of temperature, pressure and relative humidity of air in the soil under chosen houses. The synthesis of theoretical and experimental results was the base for the evaluation of the effectiveness and the applicability of soil ventilation systems. Results revealed that the effectiveness depends mainly on the airtightness of floors and on the ratio of sub-slab layer and soil permeabilities. Discovered effectiveness between 64 % and 98 % is very high, which leads to the conclusion that soil ventilation systems are the most effective radon remedial measure. The study confirms that negative side effects such as the decrease of sub-floor temperatures, drying of the soil or increase of heat losses can appear only under certain conditions, i.e. if the highly permeable subsoil is ventilated by continuously operating fans. Attention was also given to the verification of the reliability of numerical models that are used for optimisation of sub-slab depressurization systems design.

Part C summarizes the experience obtained from both research and practical investigations and actions. Some tasks of possible future research areas and university education are mentioned.

SOUHRN

Část A stručně shrnuje zdravotní účinky radonu na člověka, zmiňuje se o historických událostech, které tuto problematiku ovlivnily a popisuje situaci v České republice z hlediska úrovně ozáření obyvatelstva radonem. Zvláštní pozornost je věnována popisu metod, které byly vyvinuty pro ochranu staveb proti radonu. Dále je vysvětlen rozdíl mezi dřívějším přístupem k řešení radonové problematiky v Čechách a v ostatních státech, které jako první začaly podnikat zásahy proti radonu v budovách. Popsány jsou zde rovněž různé formy větracích systémů podloží používané v ostatních státech.

Část B sumarizuje příspěvky autora k rozvoji větracích systémů podloží. Práce vychází z výzkumných projektů řešených pro státní úřad pro jadernou bezpečnost a z podrobné databáze údajů zjištěných na 70 domech, pod nimiž bylo odvětrání podloží realizováno podle autorova projektu. Analýza dat z těchto objektů byla doplněna o numerické modelování teplotních a tlakových polí a polí koncentrace radonu a o dlouhodobé sledování teploty, tlaku a vlhkosti vzduchu v podloží pod vybranými objekty. Na základě syntézy teoretických a experimentálních údajů byla stanovena účinnost a aplikovatelnost větracích systémů podloží. Ukázalo se, že účinnost závisí převážně na těsnosti podlahových konstrukcí a na vzájemném poměru propustností vrstvy ležící pod podlahou a níže situovaného podloží. Dosažené účinnosti mezi 64 % a 98 % jsou velmi vysoké, což opravňuje k závěru, že větrací systémy podloží jsou nejúčinnějším protiradonovým opatřením. Dále se potvrdilo, že výskyt některých negativních jevů (ochlazování podlah, vysychání podloží a zvýšení tepelných ztrát) přichází v úvahu jen za určitých podmínek, tj. na vysoce propustném podloží a při nepřetržitém provozu ventilátoru. Pozornost byla dále věnována ověření věrohodnosti numerických modelů, které se používají pro optimalizaci návrhu větracích systémů podloží.

Část C shrnuje zkušenosti získané z jak výzkuných projektů, tak praktických aplikací. Zmíněny jsou některé cíle možných budoucích výzkumných oblastí a univerzitního vzdělání.

Klíčová slova: radon, protiradonová opatření, odvětrání podloží, návrh, účinnost, počítač, numerické modelování, experiment

Keywords: radon, remedial and protective measures, sub-slab depressurization, soil ventilation, design, effectiveness, computer, numerical modelling, experiment

ISBN

CONTENS

A. STATE OF THE ART

1. Introduction

When in 1896 the French civil engineer Henri Becquerel discovered radioactivity and in 1900 E.F.Dorn the noble gas radon, they had surely no anticipation how important role their discoveries will play at the end of the 20th century. At the end of 1970s radon became an issue for architects and civil engineers, because of high radon levels measured in a number of single-family houses in different countries. Since then several research projects carried out in many countries revealed that radon and its decay products represent a serious medical problem. The doses of radiation received by many of us in our homes due to radon and radon daughters are higher than any other dose of radiation, which we normally encounter [21]. Inhalation of radon daughters may cause lung cancer [10]. In the Czech Republic approximately 900 new cases of lung cancer per year (i.e. 15 % of all cases) is estimated to be caused by radon daughters.

Radon-222 occurs in the decay chain, which begins with uranium-238 and ends with lead-206. Uranium-238 and its decay product radium-226, which is the immediate precursor of radon-222, occur in all rock and soil types [3]. Radon is a noble gas, which decays into radon daughters –radioactive metal ions (Po^{218}, Pb^{214}, Bi^{214} and Po^{214}).

Radon from the ground under the house is the most common source of radon in buildings. However, in some cases also building materials and the domestic water from deep wells can contribute to indoor radon concentration.

In the Czech Republic measurements of indoor radon concentrations have been carried out since 1990. Up to now more than 130 000 houses have been measured. From the result of these measurements it has been estimated that [27]:
- the mean indoor radon concentration in our country is 116 Bq/m^3 that is two times higher value than in other European countries,
- approximately 220 000 inhabitants live in houses, in which indoor radon concentration exceeds the reference level 400 Bq/m^3,
- on the territory of the Czech Republic approximately 2 000 inhabitants receive irradiation from radon that is comparable with the irradiation of inhabitants that were living in 1986 – 1989 in the vicinity of the Chernobyl nuclear power station.

2. Principals of protection against radon

At the beginning of 1980s it was clear that it would be necessary to protect houses against radon from the soil. Remedial and protective measures have been tested and developed in a number of research projects. Recent measures are based on the following principles [3, 8, 22]:

- ensuring of the airtightness of the building substructure, usually by means of a radon resisting membrane,
- exceeding the indoor – outdoor ventilation,
- creating a slight overpressure within the building,
- ventilation of the sub-floor region and creating an underpressure in the sub-floor region,
- ventilation of air gaps provided along walls and floors in contact with the soil,
- placing of houses on the ventilated crawl spaces.

Between the years 1990 and 1997 the development of radon reduction techniques in the Czech Republic was focussed mainly on ensuring of the sufficient airtightness of structures in direct contact with the soil. Soil ventilation systems were outside the interest. The first sub-slab depressurization systems were successfully applied in 1997 according to author's design and supervision.

3. Sub-slab depressurization systems

Quite opposite approach was chosen in countries, which first began to deal with radon in dwellings, i.e. in USA, Great Britain, Sweden and Finland. In these countries three types of soil ventilation systems based on creating an underpressure under the house were developed – a radon sump, a radon well and a drain pipe suction. The radon sump (Fig. 1) is essentially a hole in the ground under the house, from which the soil air is sucked by means of a fan [5, 23]. The Swedish invention, radon well (Fig 2), is a dry cylindrical well with a diameter 0,4 – 1,0 m and a depth 4,0 m, which is ventilated by a relatively powerful fan [3]. The radon well is located in the vicinity of the house without the need for carrying out any work on the house itself. In case of a drain pipe suction the soil air is drawn from the drain pipes installed primarily for dewatering of the subsoil around or under the house [8, 9]. The mean effectiveness of these measures varies in the range 64 – 95 % [2, 4, 7, 24].

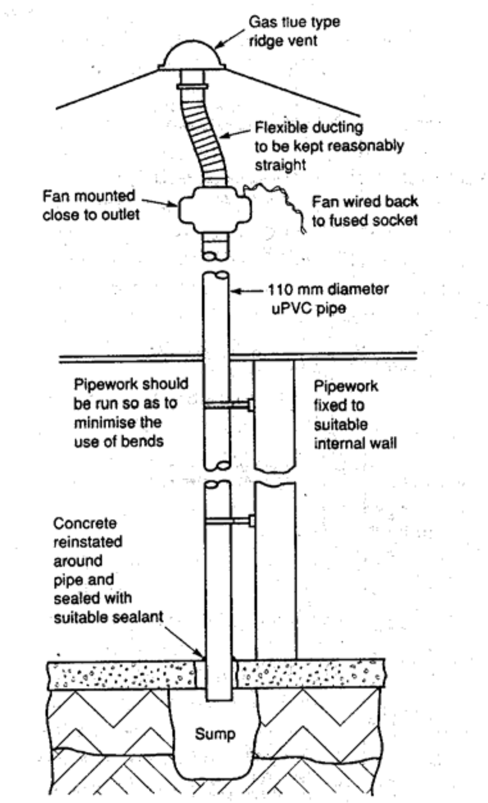


Fig. 1. Radon sump according to Building Research Establishment recommendations [23]

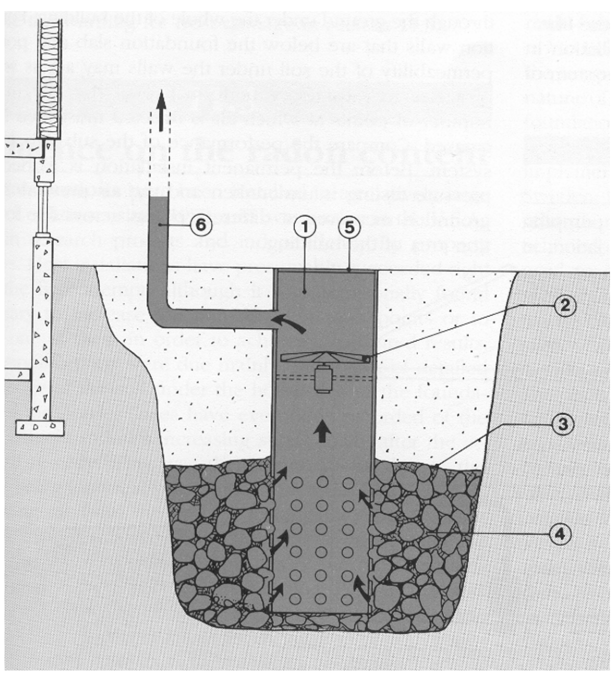


Fig. 2. Radon well [3]. 1 – pipe 0,4 – 1,0 m in diameter with holes at the bottom end, 2 – fan, 3 – sealing plastics, 4 – suction chamber, 5 – cover, 6 - outlet

B. AUTHOR'S CONTRIBUTION TO THE DEVELOPMENT AND ADVANCEMENT OF SUB-SLAB DEPRESSURIZATION SYSTEMS

1. Development of the new types of sub-slab depressurization systems

The results of the research project that was carried out in 1996 and 1997 under the author's supervision revealed that sub-slab depressurization systems known from abroad will not be so effective in the Czech conditions (houses with a number of internal foundations that divide the under-floor space into several compartments, a poor airtightness of the floor structures, in most cases no drainage layers under the concrete slabs, soil layers with usually low permeability, etc.). For ensuring of the sufficient pressure field extension under the whole area of the building it was realized that the number of suction means and their effective suction area should be greater. Therefore we proposed new types of sub-slab depressurization systems, which are formed by [12, 17]:

- one or several perforated tubes drilled beneath existing floors without their damage. The tubes can be drilled from the cellar (Fig. 3), external trench excavated along one side of the building (Fig. 4), internal trench excavated in the house (Fig. 5), or from the house exterior through the foundation wall (Fig. 6),
- the network of flexible perforated pipes inserted into the drainage layer of coarse gravel placed beneath the new floors (Fig. 7),
- combination of the above stated measures.

Several research projects that have been carried out since 1997 for the State Office for Nuclear Safety and extensive practical experience obtained from nearly 100 applications enable us to formulate several important principles for the design and application of these systems.

Beneath each habitable room at least one tube should be drilled or one suction pipe should be inserted. The total length of the drilled tubes or flexible pipes is estimated in dependence on the ratio of the sub-floor layer k_d and the soil k_s permeabilities and on the airtightness of floors [20]. If the ratio k_d/k_s is lower than 1 and the airtightness of floors is poor, 1 m of the tube has the influence over the floor area not exceeding 5 m^2. On the other hand for the ratio k_d/k_s higher than 10 and sufficient airtightness of floors, it is supposed that 1 m of the tube will have the influence over the area 10 – 15 m^2. Compared to sumps, perforated tubes ensure better pressure distribution in the sub-floor region.

Location of drainage pipes and/or drilled tubes, their number and diameter are designed again in dependence on the ratio of the sub-floor layer and the subsoil permeabilities and airtightness of floors, so that the whole sub-floor layer shall be well ventilated through the whole year. Numerical modelling is recommended for the optimisation of the design. At this time three computer models are available for this purposes in the Czech Republic [29]: TLAK3D that solves pressure and air velocity fields in three dimensions, WIND2D solving temperature fields as a result of heat transfer caused by conduction and convection of soil air and RADON2D that calculates radon concentration fields in two dimensions.

Drainage pipes and drilled tubes shall be located in a sufficient distance from perimeter walls, so that freezing of the subsoil under perimeter foundations shall not occur, unless the foundations shall be protected against freezing by thermal insulation [15]. The occurrence of the subsoil freezing shall be checked with the help of EN ISO 10211-1.

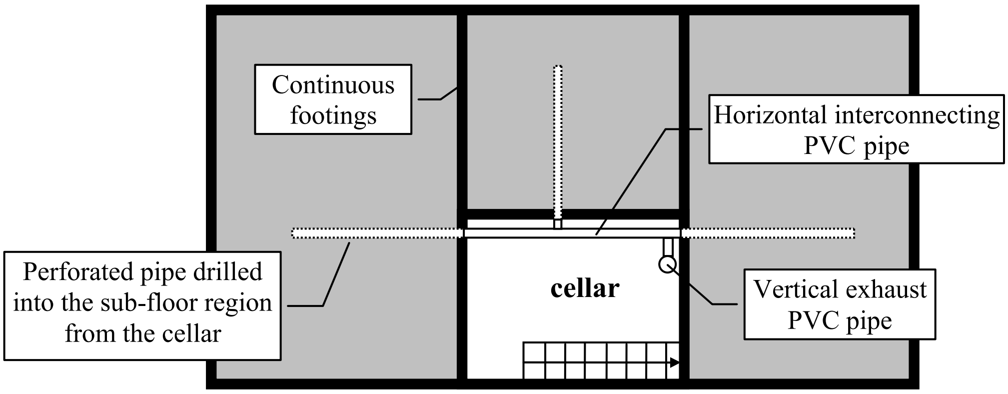


Fig. 3. Perforated tubes drilled from the cellar

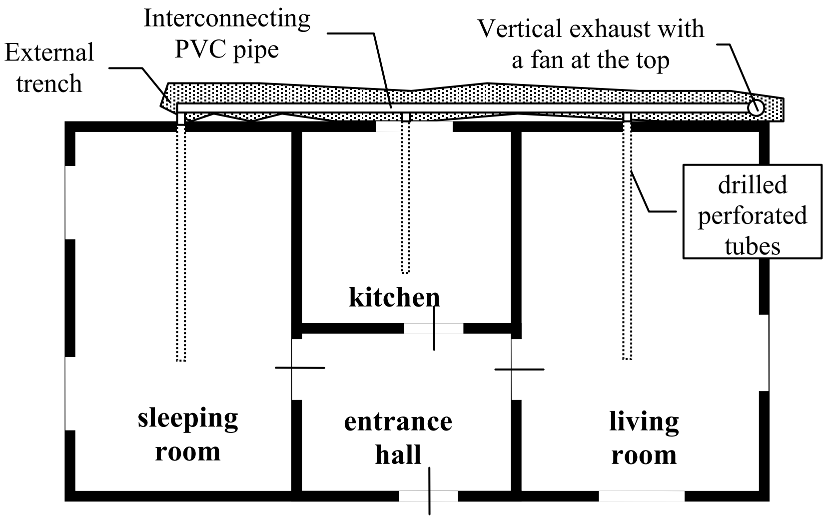


Fig. 4. Perforated tubes drilled from the external trench. The advantage of this solution is that it causes no obstructions in the living space of the house

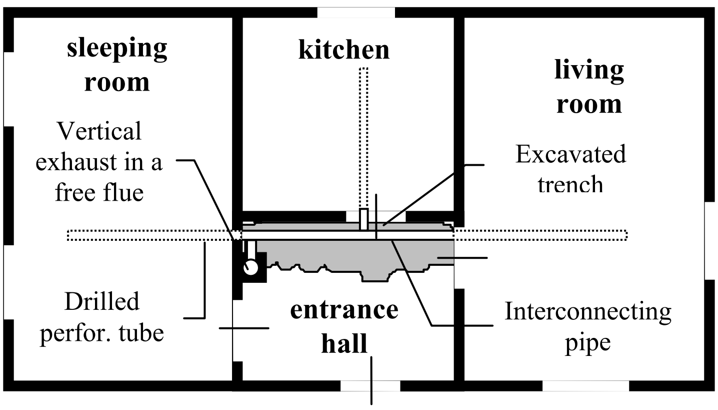
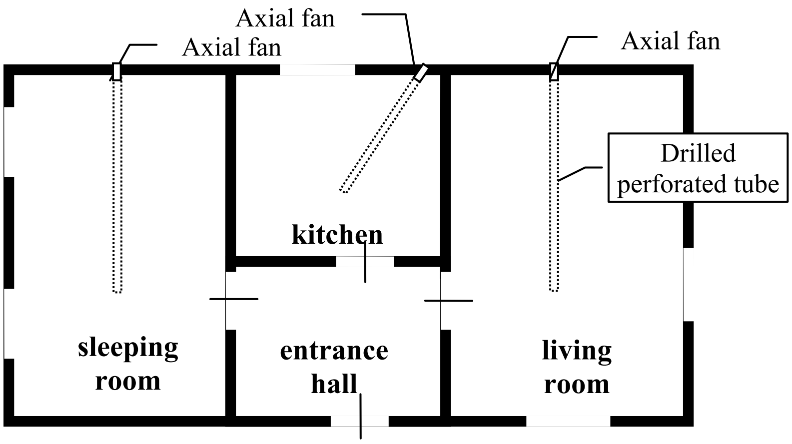


Fig. 5. Perforated tubes drilled from the internal trench. The disadvantage of this solution is the higher labour consumption due to the excavation works and obstructions in the living space of the house



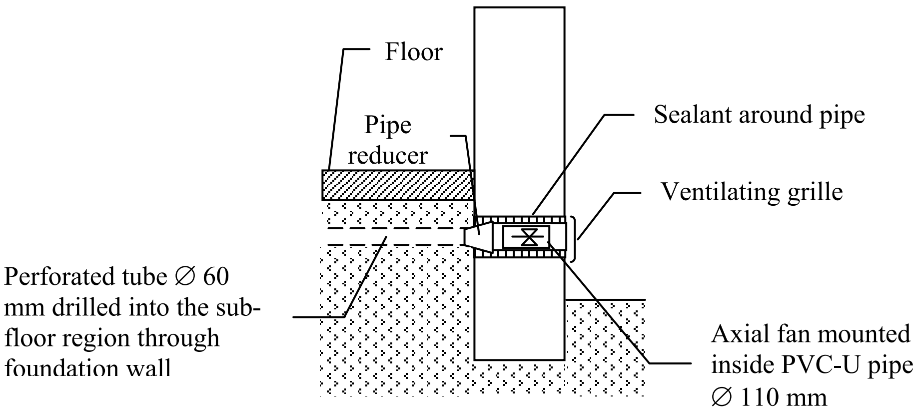


Fig. 6. Perforated tubes drilled from exterior with fans placed inside each tube. This form of sub-slab depressurization systems is convenient for houses with floors above adjacent ground. The advantage of this solution is that it is not so labour consuming, it causes no obstructions in the living space of the house and it requires less material to construct

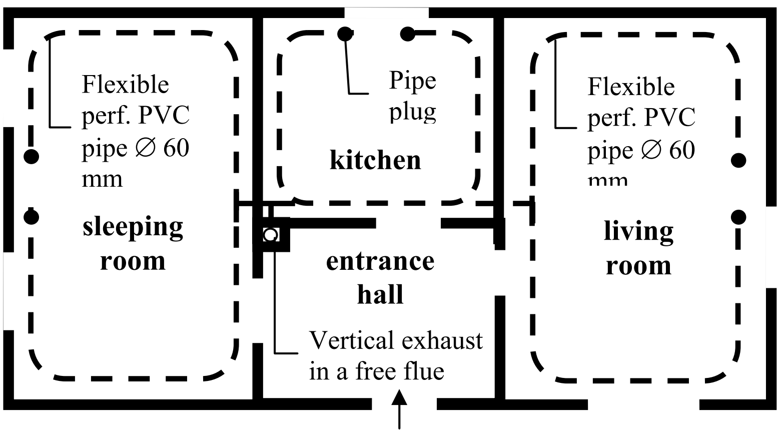


Fig. 7. Flexible perforated pipes inserted into the drainage layer during the reconstruction of floors. Pipes are laid along walls in order to stop radon from entering the dwelling through the wall-floor joint or through vertical holes and pores within the wall. This layout of pipes decreases at the same time the humidity of the soil along walls and thus protects walls from becoming wet (if the damp-proof insulation is not placed under walls)

Vertical exhaust pipe running inside the living space is usually used for the extraction of the soil air. The advantage of this solution is that the pipe runs through the heated part of the house and thus it works partly as a passive system creating a slight underpressure in the subsoil without the help of a fan. To reduce visual impact vertical pipe can be inserted inside a free flue or can be boxed-in in the corner of a room. In flueways only flexible PVC, aluminium or rustless pipes are used. Due to the condensation inside pipes all pipes should be installed in a slight slope towards the perforated tubes so that water can escape (discharge) in the soil. All pipes running within the building interior shall be airtight. In cases where it is not possible to install vertical pipes inside the living space of the house the soil air can be extracted to outdoors by:

1. External vertical pipework with the terminal unit at eaves level or at a height above the ground that corresponds at least to the typical height of the snow cover,
2. Internal horizontal pipework exiting the building through the external wall at height above the ground corresponding to typical snow cover.

The diameter of pipes should correspond to the amount of air that is transported inside them. Perforated tubes have usually the diameter around 60 mm, interconnecting horizontal pipes from 60 to 110 mm and vertical exhaust pipes from 110 to 125 mm.

The most commonly used types of fans are in-line paddle-wheel fans with airtight casing or roof paddle-wheel fans. These fans should have a flow rate from 100 m^3/h to 200 m^3/h at a pressure difference from 250 Pa to 150 Pa and power consumption between 40 and 70 W. To minimise negative effects (reduced underfloor temperatures, increased air exchange rate and drying and freezing of the subsoil) the fan should be switched to intermittent mode with the frequency of operating periods depending on the rate of decrease and increase of indoor radon concentration after switching on and off the fan. Savings in operation costs and prolonged life of fans are other merits of the intermittent operation of fans. Fans should be resistant to weathering and to moisture condensation inside pipes. To avoid disturbing noise effects the fan should be installed away from the occupied rooms (within the roof space, at the top of the chimney, at eaves level, etc.).

2. Efficiency analysis of sub-slab depressurization systems

2.1. Method of verification

Factors influencing the efficiency of the systems based on drilled tubes have been studied in 70 single-family houses of different age (from 20 to 100 years) [15, 18]. In the selection there were all types of houses – with and without cellars, with timber floors or concrete slabs, with and without damp-proof insulation. Majority of houses was built on building sites classified to high radon risk category (the mean value of soil gas radon concentration was 138 kBq/m^3). The mean radon concentration before remediation in habitable rooms of all houses was 1 476 Bq/m^3.

To obtain all necessary data for the efficiency analysis, the stress was given to a detailed investigation of each house, which consists of a large number of further measurements and surveys:

- detailed building survey with a view to the floor condition and foundation type,
- indoor radon concentration measurements before and after remediation,
- radon risk classification of foundation soils based on soil gas radon concentration measurement and on permeability assessment,
- soil permeability vertical profile assessment,
- measurements of soil gas radon concentration and soil permeability in underfloor layers.

The efficiency e of soil ventilation has been calculated for each house by the formula:

$$e = \frac{C_{before} - C_{after}}{C_{before}}.100 \qquad [\%]$$

where C_{before} and C_{after} are indoor radon concentrations before and after remediation.

We have found out that the efficiency calculated for individual houses varies between 64 and 98 %, which means that indoor radon concentration decreases to 36 % up to 2 % of the initial values. The most important is that we have not discovered a house with the efficiency below 64 %. This result confirms the assumption that soil depressurization is the most effective remediation. From the chart in Fig. 8 we can estimate the probability of reaching marked intervals of efficiency.

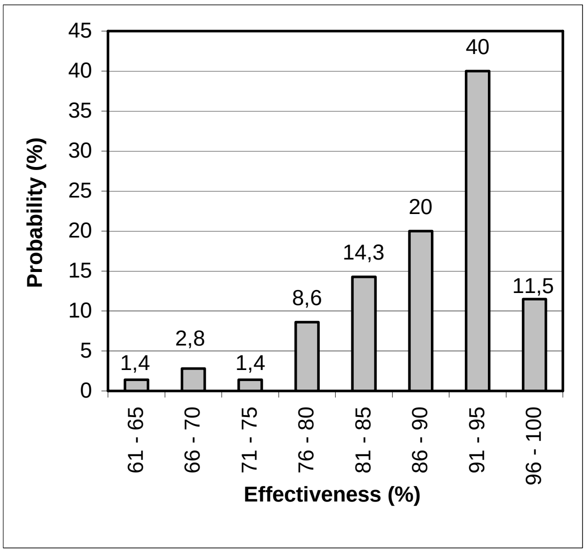


Fig. 8. Probability of reaching marked intervals of efficiency

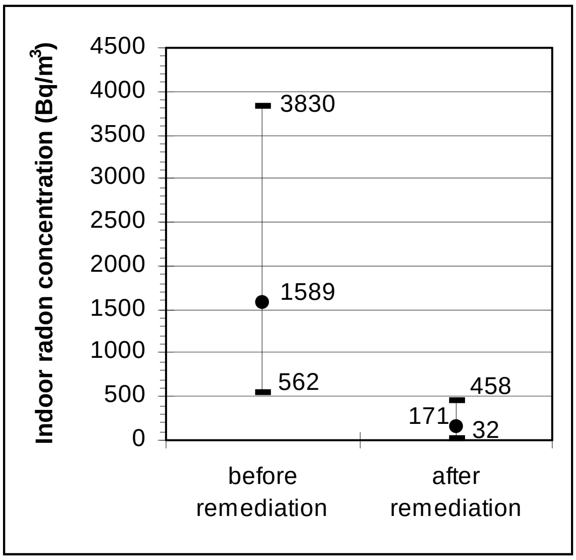


Fig. 9. Mean, minimal and maximal indoor radon concentrations in 70 houses before and after remediation

The mean indoor radon concentration decreases after installation of soil ventilation from 1589 Bq/m^3 to 171 Bq/m^3 that means to approximately 1/9 of the initial level. This decrease can be seen in Fig. 9. Indoor radon concentration after remediation remained above the reference level 400 Bq/m^3 in only two houses.

2.2. Factors influencing the efficiency

From the study it is evident that the efficiency of soil ventilation systems depends on the ratio of sub-floor layer and soil permeabilities k_d/k_s, which is apparent from Fig. 10. If the sub-floor layer has lower permeability than the soil, the mean efficiency is only 85 %. However, it increases to 90 %, if the sub-floor layer is more permeable than the subsoil. At the same time the greater is the ratio k_d/k_s, the smaller is the dispersion of values, i.e. the greater is the probability of reaching high values of efficiency.

In general as a result of soil depressurization radon concentration in underfloor layers falls significantly, which can be seen from Fig. 11. Radon concentration after remediation decreases approximately to 1/4 of initial values and at the same time the dispersion of concentrations drops too.

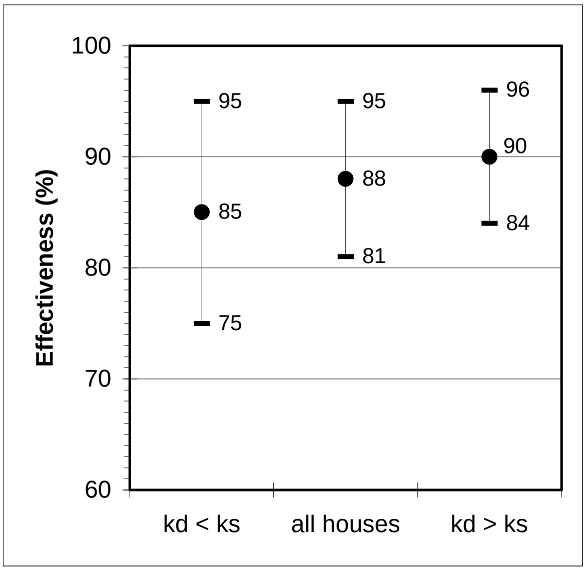


Fig. 10. Effectiveness in dependence on the ratio k_d/k_s (mean values ± standard deviations are plotted)

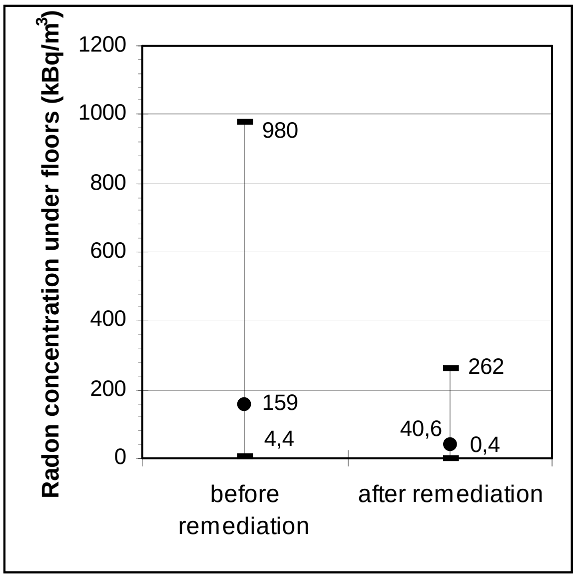


Fig. 11. Dispersion of radon concentration in underfloor layers in 70 houses (minimal, mean and maximal concentrations are plotted)

The decrease of sub-floor radon concentrations depends in the first place on the permeability of the layer laying directly under floors k_d and on the permeability of soil situated below this layer k_s. The airtightness of floors is another important and significant parameter. With respect to difficulties connected with assessment of floor tightness we have divided in our study floors into two categories – timber floors and concrete floors. The influence of both parameters (permeability of soils and airtightness of floors) on the decrease of radon concentration in the sub-floor layer is evident from Fig. 12.

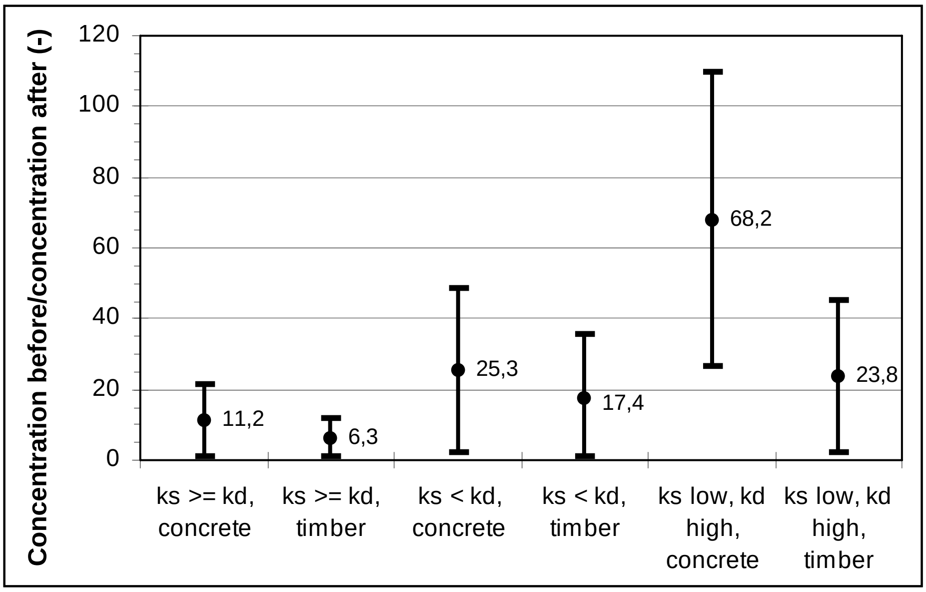


Fig. 12. Ratio of sub-floor radon concentrations before and after remediation for different floors and different combinations of underfloor layer and soil permeabilities (mean values ± standard deviations are plotted). Classification of permeabilities: high for $k > 5.10^{-12}$ m^2, low for $k < 3.10^{-13} m^2$, medium for $3.10^{-13} m^2 < k < 5.10^{-12}$ m^2

The highest drop of sub-floor radon concentrations has been observed in houses with a highly permeable sub-floor layer and with a subsoil of low permeability. Results corresponding to this situation can be seen for both types of floors from the last two vertical dispersion lines from the left hand side of Fig. 12. On the other hand the lowest decrease of sub-floor radon concentrations has been registered in houses, where the underfloor layer had the same or lower permeability than the subsoil (the first two vertical dispersion lines in Fig. 12). From the chart it is also obvious that the drop of sub-floor concentrations is lower under timber floors than under concrete slabs. However the difference between timber and concrete floors decreases with decreasing ratio of permeabilities k_d/k_s. Similar relationship, but this time plotted as a function of the ratio of permeabilities k_d/k_s can be seen in Fig. 13 (again for both types of floors).

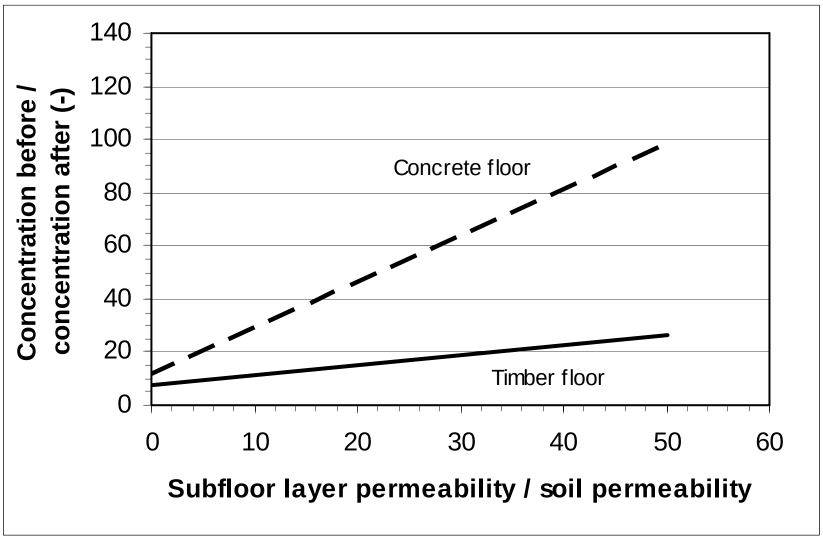


Fig. 13. Ratio of sub-floor radon concentrations before and after remediation for different floors and ratio of underfloor layer and soil permeabilities

Higher standard deviations in Fig. 12 are caused by differences among houses. Houses are built on different building sites with diverse weather and soil conditions. They have different space arrangement, internal layout, floor tightness, air exchange rate, heating system etc. In contrast to laboratory conditions all these interfering parameters vary in time continuously. In spite of this it is possible to determine the most significant factors – floor tightness and ratio of sub-floor layer and soil permeabilities.

Obtained results can be explained by the following theory. A low permeable soil under the sub-floor permeable layer creates the bottom border of the underfloor ventilated space. The smaller is the volume of this space, the greater is the underpressure and lower radon concentration there. If underfloor layers have uniform permeability, the volume of the ventilated space is endless and therefore the underpressure and consequently the air exchange rate under the house is smaller. This explanation can be supported either by measured values of underpressure and by mathematical modelling (see Figures 14 and 15) with the help of Radon2D (2001) numerical model [29]. In the sub-floor layers with $k_d > k_s$ values of underpressure between -30 and -80 Pa are usually measured, while for $k_d \leq k_s$ values between –2 and –20 Pa are observed.

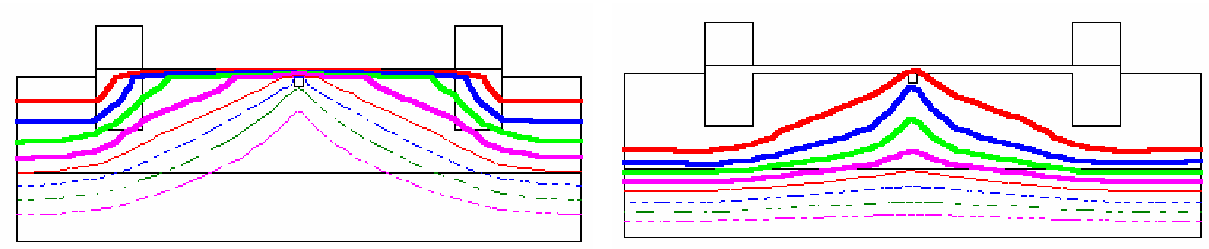
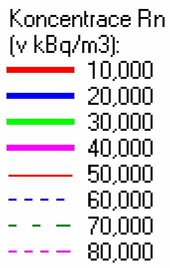


Fig. 14. Radon concentration fields in the sub-floor region when the soil air is sucked from a centrally located perforated tube. On the left hand side is the situation with $k_d < k_s$, while the right hand side represents the situation with $k_d > k_s$. Better soil ventilation and thus lower radon concentration under the house is achieved for $k_d > k_s$. Simulation made with the help of Radon2D (2001) software



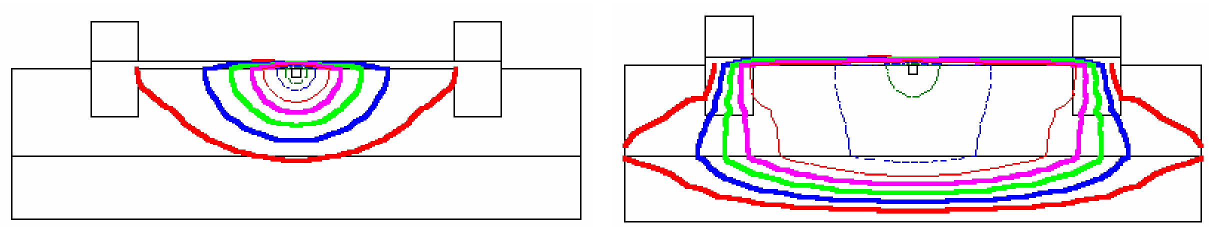
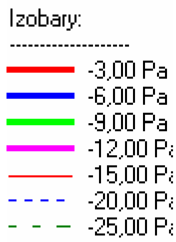


Fig. 15. Pressure fields in the sub-floor region when the soil air is sucked from a centrally located perforated tube. Inside the tube there is an underpressure –30 Pa. On the left hand side is the situation with $k_d < k_s$, while the right hand side represents the situation with $k_d > k_s$. Higher underpressure and in general better pressure extension under the house is achieved for $k_d > k_s$. Simulation made with the help of Radon2D (2001) software



3. Analysis of side effects of soil depressurization

Soil ventilation systems can cause in dependence on various conditions some negative side effects [15], among which belong decreasing of underfloor temperature, increasing of air exchange rate between indoors and outdoors and consequently increasing of heat losses or decreasing of indoor temperature. These effects were evaluated by the research project supported by the State Office for Nuclear Safety. Long-term monitoring systems were installed into three houses so that in 1-hour intervals data from several detectors could be automatically recorded. Temperature and relative humidity detectors were installed indoors, outdoors, in the sub-floor layer and inside suction pipes. Pressure sensors were used for measurement of the pressure difference between indoors and the air in the sub-floor layer or inside suction pipes. From this experiment we obtained a lot of results, which indicate that:

- Temperature in the sub-floor layer depends mainly on the indoor temperature and on the presence of thermal insulation in the floor. On the house perimeter the sub-floor temperature is also influenced by outdoor temperature. However it takes approximately two days than the change of outdoor temperature affects the sub-floor temperature.

• Soil ventilation based on fans operating in intermittent mode has no effect on sub-floor temperatures (see Fig. 16). For continuously operating fans the decrease of sub-floor temperature on the house perimeter was recorded. As can be seen from Fig. 17 for permeable layer under the floor with thermal insulation the decrease of the sub-floor perimeter temperature can be 1 or 2 °C. If there is no thermal insulation in the floor, the decrease could be as high as 3 or 4 °C. In sub-floor layers with medium or low permeability the changes of temperatures are very small and can be neglected.

• No influence of soil ventilation on indoor temperature has been observed.

• Relative humidity of the ventilated air inside suction pipes is high and varies between 80 and 100 %. Such high values of humidity result in condensation inside pipes.

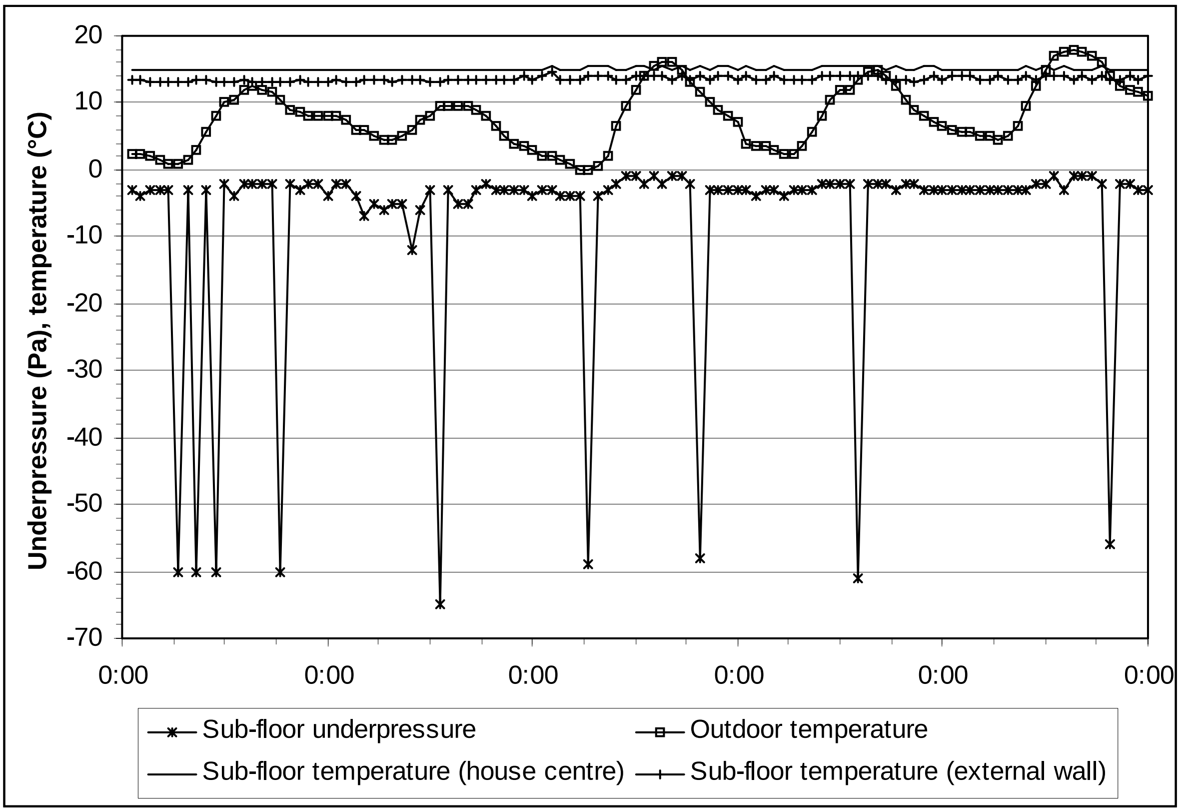


Fig. 16. Sub-floor temperatures versus outdoor temperature and underpressure in the sub-floor layer when fan operates in intermittent mode

The effect of soil ventilation on air exchange rate between indoors and outdoors was investigated by means of carbon dioxide measurements. Obtained results suggest that the increase of the air exchange rate can be relatively high as well as low. If initial values of the exchange rate are around 0,3 h^{-1} the increase is low and usually does not exceed 15 %. However in houses with very low initial values of exchange rate (below 0,1 h^{-1}), the soil ventilation can cause two times higher air exchange rate. Final conclusion is that in houses which are ventilated in appropriate way the soil ventilation cannot lead to substantial increase of air exchange rate and consequently to enormous increase of heat losses. It is important to stress that the increase of air exchange rate can appear only during the operating period of the fan. When the fan is switched to intermittent mode, the influence on the exchange rate is almost negligible.

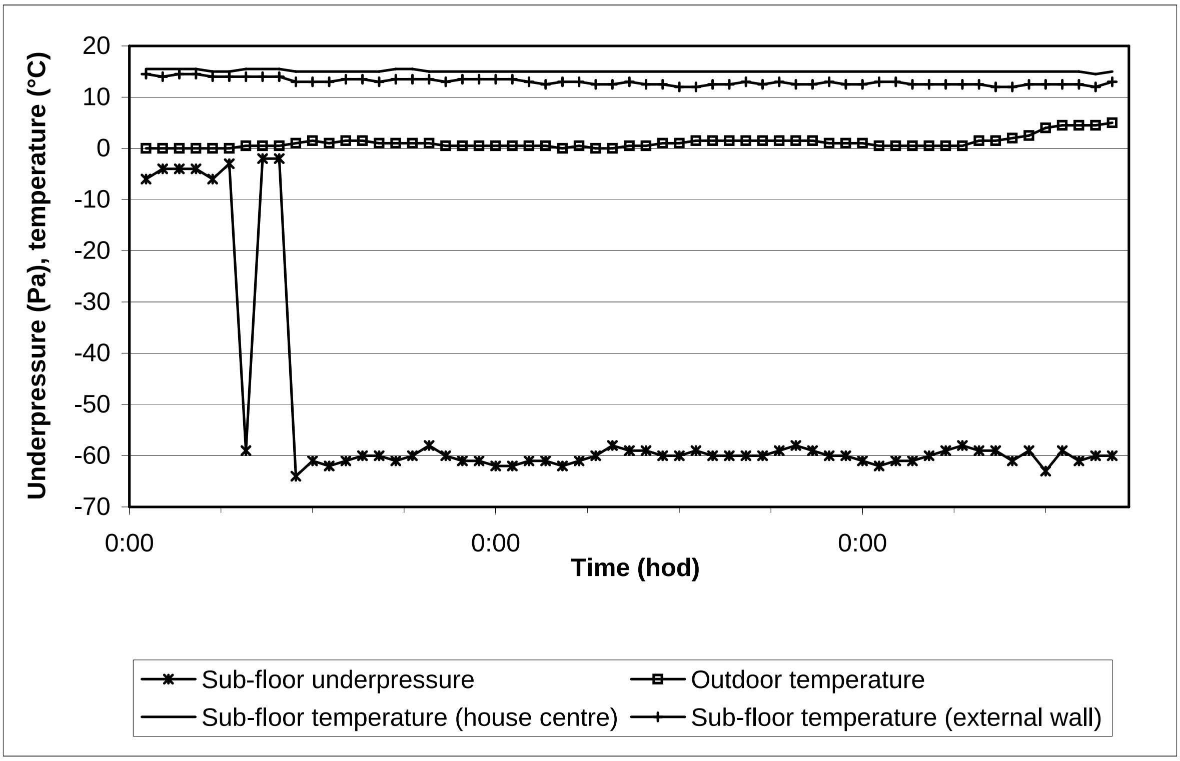


Fig. 17. Sub-floor temperatures versus outdoor temperature and underpressure in the sub-floor layer when fan operates continuously. As a result of fan operation sub-floor temperature close to the external wall decreases

Soil ventilation can cause not only negative side effects, but in some cases it can induce also positive effects. As stated above it can enhance the house ventilation to a more convenient level. Our investigation shows that owners of 47 % of remediated houses observed improvements in the quality of indoor air. Another example can be found in houses with increased moisture content in walls owing to the lack of damp-proof insulation between foundations and walls. After installation of soil ventilation into 22 houses with damp walls, in 5 houses walls completely dried out and in 11 houses the moisture content was lowered [19].

4. Verification of numerical models

Numerical modelling can be a very powerful tool in the design stage of sub-slab depressurization systems [1, 2, 13, 14]. The designer can investigate with the help of theoretical simulation how the specific arrangement and layout of the ventilation system affects its operation and effectiveness.

The author of this work has cooperated on the development of three computer models for the optimisation of the sub-slab depressurization systems. The first computer tool is called Tlak3D and can be used for calculation of three-dimensional steady-state air pressure and air velocity fields in porous materials. The second program – Wind2D – is able to solve the two-dimensional steady-state temperature field in areas exposed to combined heat transfer caused by conduction and convection. And finally, the third computer program – Radon2D – can be used for analysis of the two-dimensional steady-state field of radon concentrations in the soil under the buildings.

4.1. Description of models

Three-dimensional steady-state pressure field in a porous medium is in the model Tlak3D calculated by means of the well-known partial differential equation

$$\frac{\partial}{\partial x}\left(k\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial P}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial P}{\partial z}\right)=0\,,$$

where k is the permeability of the porous medium [m^2] and P is the air pressure [Pa].

The heat transfer in the soil under the building with the sub-slab depressurization system cannot be taken as the simple heat conduction. The heat transfer caused by convection is also very important in this case and thus the combined heat transfer must be taken into account. The partial differential equation governing this process can be for steady-state two-dimensional case stated as

$$\lambda\left(\frac{\partial^2\Theta}{\partial x^2}+\frac{\partial^2\Theta}{\partial y^2}\right)-\rho_a c_a\left(u\frac{\partial\Theta}{\partial x}+v\frac{\partial\Theta}{\partial y}\right)=0\,,$$

where λ is the thermal conductivity [W/(m.K)], Θ is the temperature [K], ρ_a is the density of the air [1,2 kg/m^3], c_a is the thermal capacity of the air [1010 J/(kg.K)] and u, v are the velocity vector components in the x-axis and y-axis direction respectively [m/s].

The first term on the left-hand side of this equation represents the heat transport due to conduction; the second term represents the heat transport due to convection.

This equation is a typical example of the convective-diffusion equation [25, 26]. The search for the numerical solution of the convective-diffusion equation is always more complicated than the search for the solution of the related diffusion equation. The main cause is the convective transport term that can introduce under certain conditions instabilities in the numerical solution. The finite element method has been used to find the solution of this equation [11, 28]. The general finite element formulation has been derived by means of the Petrov-Galerkin process.

The distribution of radon concentration in the soil under the building is governed by another type of convective-diffusion equation. This equation can be written for the two-dimensional steady-state case as

$$D_e\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right)-\frac{1}{\varepsilon}\left(u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}\right)+G-\lambda_r C=0\,,$$

where G is the radon generation rate [Bq/(m^3.s)], D_e is the effective radon diffusion coefficient [m^2/s], C is the radon concentration in the soil gas [Bq/m^3], ε is the porosity of a porous material [-] and λ_r is the radon decay constant [$2{,}1.10^{-6}$ 1/s].

The first term on the left-hand side of this equation represents the radon transport due to diffusion; the second term represents the radon transport due to convection. The third term expresses the increase of radon concentration due to radon generation rate in the soil or material pores and the last term represents the drop in radon concentration due to radioactive decay. The radon transport caused by water flow is neglected due to its minor importance.

The solution of this equation has been derived by means of the finite element method again. The general finite element formulation has been found using Petrov-Galerkin approach.

All equations can be used with the assumptions that the air is incompressible and the airflow is laminar.

4.2. Results of verification

The reliability of the presented numerical models has been verified on several soil profiles and also on six houses with different types of sub-slab depressurisation systems [20]. The verification was based on the comparison of the calculated and measured values of under-pressure, temperature and radon concentration in the soil gas.

The completed verification of numerical models shows that the highest reliability can be expected from the model for three-dimensional pressure field calculations (program Tlak3D). The maximum difference between the calculated and measured air pressure values was for this model only 10%.

On the other hand, the lowest accuracy was found out for the numerical model for the assessment of radon concentrations. Here the maximum difference between measured and calculated values reached the level of 85 %. The fact that this calculation procedure is not so precise can be caused by several factors. The first one is of course the simplifying of the calculation to the two-dimensional model. The second factor could be lower accuracy of numerical solution of the governing equation – the convective-diffusion equation is far more sensitive from the point of view of numerical stability than the standard diffusion equation governing the air pressure distribution. The third and probable the main factor can be found in a great number of various soil properties that influence the radon concentration distribution under the house. These properties include for example radium content, radon emanation coefficient, soil porosity, moisture content and presence of fractions. Even if measurements of all soil properties are done with so much care as possible, it is still almost impossible due to significant spatial heterogeneity of these parameters to prepare reliable inputs into the model. This fact is quite in contrary to the air pressure field calculation, which results depend mainly on the permeabilities of the soil layers, which can be measured more easily.

The numerical model of Radon2D software can be therefore recommended preferably for the calculations of the trends of radon concentration distribution (for example the assessment of the influence of various operation modes of SSD systems) rather than for accurate calculations. Nevertheless, this conclusion does not decrease the applicability of numerical modelling in the field of soil ventilation, because it is much better to derive the design of SSD systems from predicted under-pressures than from expected decrease of radon concentrations.

The numerical model Wind2D for the calculation of the two-dimensional temperature field gives results with the accuracy about 15 %. This degree of reliability is quite sufficient for the purposes of the heat loss calculations. Better results in comparison with the radon concentration field calculation, which is governed by the same type of equation, can be caused by the fact that the distribution of the temperature field is influenced by lower number of material properties. In addition, these properties – thermal conductivity and permeability – are either known or can be easily measured and they are usually not subjected to great spatial changes.

C. CONCLUDING REMARKS

Experience from more than 70 houses confirms that the sub-slab depressurization systems are the most effective radon remedial measure. Their effectiveness reaches up to 98 %, which is two times more than in case of additionally applied radon-proof insulation. Negative side effects, such as decrease of sub-floor temperatures and drying of the subsoil, can occur only, if highly permeable soils are ventilated by continuously operating fans. However these effects can be overcome by experienced and advanced design, which takes advantage of the numerical modelling of sub-slab depressurization systems performance.

Although the principle of sub-slab depressurization systems is well known, their development is strongly dependent on local conditions, building characteristics and soil parameters. From this point of view only national research projects can ensure high and long-term effectiveness of these systems.

Future research projects should focused on optimisation of heat losses caused by soil ventilation. In combination with mechanical ventilation of the house interior a part of the heat in the air exhausted from the soil can be transferred by means of the heat exchanger to the supply air.

The design and installation of sub-slab depressurization systems require interdisciplinary approach. The designer needs to collaborate with other professions, such as geologists and specialists dealing with various types of radon measurements. The design shall be derived with respect to building physics, structural analysis, waterproofing and requirements on reliability, effectiveness and durability.

It is highly probable that the building physics will have a substantial influence on the future development of sub-slab depressurization systems. Lectures on this subject mainly at the university level should concentrate on understanding of complex physical processes connected with the soil ventilation.

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Technical Interests:
Radon, radon remedial and protective measures, building physics, research, design, numerical modelling, optimisation and standardisation of radon countermeasures, measurement of the radon diffusion coefficient in insulating materials

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- Subcontractor to the research projects supported by the State Office for Nuclear Safety dealing with the evaluation of effectiveness and applicability of sub-slab depressurization systems (2000 – 2002)
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