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The influence of air conditioning changes on the effective dose due to radon and its short-lived decay products

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Abstract. Most people spend the majority of their time in indoor environments where the level of harmful pollutants is often significantly higher than outdoors. Radon (^{222}Rn) and its decay products are the example of radioactive pollutants. These radioisotopes are the main source of ionizing radiation in non-industrial buildings. The aim of the study was to determine the impact of air-conditioning system on radon and its progeny concentrations and thus on the effective dose. The measurements were carried out in the auditorium at the Environmental Engineering Faculty (Lublin University of Technology, Poland). Measurements of radon and its progeny (in attached and unattached fractions) as well as measurements of the following indoor air parameters were performed in two air-conditioning (AC) operation modes: AC ON and AC ON/OFF. The air supply rate and air recirculation were taken into consideration. The separation of radon progeny into attached and unattached fractions allowed for determining, respectively, the dose conversion factor (DCF) and the inhalation dose for teachers and students in the auditorium. A considerable increase of the mean radon progeny concentrations from 1.2 Bq/m^3 to 5.0 Bq/m^3 was observed in the AC ON/OFF mode compared to the AC ON mode. This also resulted in the increase of the inhalation dose from 0.005 mSv/y to 0.016 mSv/y (for 200 h/year). Furthermore, the change of the air recirculation rate from 0% to 80% resulted in a decrease of the mean radon concentration from 30 Bq/m^3 to 12 Bq/m^3 and the reduction of the mean radon progeny concentration from 1.4 Bq/m^3 to 0.8 Bq/m^3. This resulted in the reduction of the inhalation dose from 0.006 mSv/y to 0.003 mSv/y.

Key words: radon • radon progeny • attached and unattached fraction of radon progeny • dose conversion factor

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Introduction

Radon and its decay products are the main source of ionizing radiation in non-industrial buildings. They are responsible for about half of the radiation dose people in Poland are exposed to [1].

Radon is a naturally occurring radioactive gas that originates from the decay of radium (^{226}Ra) in the primordial uranium (^{238}U) decay series. Radon concentrations in buildings are usually higher than outdoors and largely depend on geological structure of the bedrock where the building is situated, as well as the construction and building materials used [2–4]. Radon concentrations indoors are also impacted by the air exchange rates [5].

Concentrations of radon and its progeny indoors are characterized by a daily and seasonal variability, which is the result of the difference between indoor and outdoor air thermal parameters, air pressure and ventilation conditions [6]. Aerosol particle concentrations and their size distribution can also be relevant for radon progeny concentration [7–9].

The highly energetic alpha radiation emitted by radon and its progeny can be harmful, as high doses and long-term exposure to such radiation can lead to cancerous processes [10].

The correct assessment of effective dose due to radon inhalation in indoor conditions is possible if reliable information on the equilibrium factor *F* between radon and its decay products is provided [11, 12]. The most common method of dose estimation is the measurement of indoor radon concentration and the application of the assumed value of *F*, that is 0.4 [13]. However, this value of *F* sometimes may not be representative for the current condition in a room and the estimated dose can be inaccurate, as has been found in the previous study [14].

The paper presents the results of measurements carried out in the auditorium of the Environmental Engineering Faculty (Lublin University of Technology, Poland) during spring and autumn 2013. The study encompassed the measurements of radon and its progeny (in attached and unattached fractions).

The aim of the study was to determine the impact of air-conditioning system on the radon and its progeny concentrations and thus on the effective dose due to radon and its progeny inhalation.

Materials and methods

The measurements have been carried out in the air-conditioned auditorium at the Lublin University of Technology in Lublin, Poland. The auditorium has a volume of about 1200 m^3 and 186 seats. It was irregularly occupied from Monday through Friday, usually from 8 a.m. to 8 p.m., according to the schedule of the students' courses. A detailed description of the auditorium, the scheme and the location of sampling instrument has been presented elsewhere [14]. The measurements were carried out during two periods in the year 2013: April and May (spring campaign) and November and December (autumn campaign). Air conditioning (AC) in these cycles was working in two modes: AC ON (working all the time) and AC ON/OFF (switched on during days and switched off during nights). There were also changes in recirculation of exhausted air (i.e. amount of fresh air in the total exhausted air) and the air flow rate (that resulted in a number of air exchanges per time unit). The description of working modes of AC during both campaigns is presented in Tables 1 and 2.

Radon and its decay products activity concentrations were measured in the middle of the seating

Table 1. Descriptive statistics for data of first (spring) period of measurements

Working modes of air conditioning (AC) Spring campaign		^{222}Rn conc. [Bq/m^3]	^{222}Rn progeny conc. (attach+unatt.) [Bq/m^3]	Effective dose [mSv/y]	Particle number conc. [1000/cm^3]
I period: 11–18.04.2013 AC ON Recirculation 80% Stream 3600 m^3/h	Mean	30	1.4	0.006	1.7
	Median	26	1.2	0.006	1.4
	SD	16	0.9	0.003	1.3
II period: 19–23.04.2013 AC ON Recirculation 0% Stream 5400 m^3/h	Mean	12	0.8	0.003	6.6
	Median	13	0.6	0.003	5.7
	SD	7	0.7	0.003	3.6
III period: 24.04.–06.05.2013 AC ON/OFF Recirculation 80% Stream 7200 m^3/h	Mean	34	5.4	0.018	4.2
	Median	33	6.0	0.018	3.7
	SD	18	2.9	0.008	2.6
IV period: 7–10.05.2013 AC ON/OFF Recirculation 0% Stream 9000 m^3/h	Mean	23	3.5	0.015	7.7
	Median	20	1.6	0.013	6.1
	SD	18	3.3	0.010	5.8
I and II period AC ON	Mean	25	1.2	0.005	4.1
	Median	20	1.0	0.005	3.2
	SD	16	0.9	0.003	3.6
III and IV period AC ON/OFF	Mean	31	5.0	0.016	5.2
	Median	26	5.5	0.017	4.4
	SD	19	3.1	0.009	4.1
III and IV period Results only from period with working AC: 6:00 a.m. – 8:00 p.m.	Mean	30	4.4	0.015	5.2
	Median	26	4.4	0.016	4.1
	SD	18	3.1	0.009	4.6
III and IV period Results only from period with not-working AC: 9:00 p.m. – 5:00 a.m.	Mean	33	6.1	0.018	5.2
	Median	26	6.1	0.018	4.8
	SD	19	2.8	0.008	3.1

Abbreviations: attach, attached; conc, concentration; SD, standard deviation; unatt, unattached.

Table 2. Descriptive statistics for the results of the second (autumn 2013) series of measurements

Working modes of air conditioning (AC) Autumn campaign		^{222}Rn conc. [Bq/m^3]	^{222}Rn progeny conc. (attach+unatt.) [Bq/m^3]	Effective dose [mSv/y]	Particle number conc. [1000/cm^3]
I period: 14–20.11.2013 AC ON Recirculation 15% Stream 5400 m^3/h	Mean	17	2.5	0.016	2.7
	Median	16	2.2	0.016	2.0
	SD	8	1.1	0.007	2.6
II period: 21–26.11.2013 AC ON Recirculation 15% Stream 7200 m^3/h	Mean	20	0.8	0.022	2.5
	Median	20	0.6	0.024	2.1
	SD	10	0.7	0.012	1.7
III period: 27.11.–7.12.2013 AC ON Recirculation 15% Stream 9000 m^3/h	Mean	12	0.9	0.008	1.8
	Median	10	0.9	0.007	1.6
	SD	6	0.6	0.005	1.1

Abbreviations: attach, attached; conc, concentration; SD, standard deviation; unatt, unattached.

area at a height of 1.2 m using the EQF3220 monitor (SARAD, Germany), which registered concentrations of radon and its unattached (<5 nm) and attached (>100 nm) decay products. The sampling interval was set to 60 min. For that sampling time and occurring radon and progeny concentrations, the uncertainty of results (for $k = 1$) is at the level of 30% for radon, between 5 and 15% for attached progeny and between 50 and 75% for unattached progeny concentrations. The detection limit of EQF3220 monitor is estimated at the level of 7 Bq/m^3 for radon and 0.1 and 0.3 Bq/m^3 for progeny concentrations in attached and unattached fractions, respectively.

Number and mass concentrations of aerosol particles were measured using Dust Trak DRX 8533 (TSI Inc.) and Optical Particle Sizer 3330 (TSI Inc.), respectively. Number concentrations of fine and ultrafine particles were determined by P-Trak 8525 (TSI Inc.).

Indoor air parameters were measured by a multifunction instrument ALMEMO 2390 (Ahlborn) with data logger and a set of sensors to measure: the air temperature, humidity, air velocity, CO$_2$ concentration and air volume flow.

Annual effective dose was calculated using the formula [15]:

$$E = \frac{\mathrm{DCF}}{3700 \cdot 170} \cdot C_{\mathrm{Rn}} \cdot F \cdot t \tag{1}$$

where: DCF – dose conversion factor [mSv/WLM], C_{Rn} – radon concentration [Bq/m^3], F – equilibrium factor, t – time of exposure (assuming 200 h/y).

With the SARAD equipment, concentrations of both fractions of radon progeny were measured and hence the equilibrium factor F and f_{un} (unattached fraction of radon progeny) could be calculated. The value of f_{un} was determined as: $f_{un} = C_{un}/C_{un+att}$, where C_{un} and C_{un+att} are the concentrations of unattached fraction and total radon progeny, respectively.

The parameter f_{un} influences the dose conversion factor. Porstendörfer [16] proposed the following formulas for counting DCF for mouth DCF_m and nasal DCF_n breathing:

$$\mathrm{DCF}_m = 101 f_{un} + 6.7\,(1 - f_{un}) \tag{2}$$

$$\mathrm{DCF}_n = 23 f_{un} + 6.2\,(1 - f_{un}) \tag{3}$$

The total dose conversion factor (DCF) for combined style of breathing can be calculated with the assumption of 60% mouth and 40% nasal breathing [17]:

$$\mathrm{DCF} = 0.6\,\mathrm{DCF}_m + 0.4\,\mathrm{DCF}_n \tag{4}$$

In formula (1), the value of DCF was calculated according to Eq. (4) and the value of equilibrium factor F was determined according to the known formula: $F = C_{un+att}/C_{\mathrm{Rn}}$.

Descriptive statistics were used to characterize the radon and its progeny concentrations, effective dose and particle number concentration grouped according to the status of the air conditioning (AC ON and AC ON/OFF) and its characteristics: air supply rate and air recirculation. T-test analyses were conducted to determine and evaluate the impact of AC parameters on the radon and its progeny concentrations measured in the auditorium. A value of $p < 0.05$ was considered statistically significant. Correlation analyses were performed to evaluate the impact of climate parameters for effective dose.

Results and discussion

Table 1 presents the statistics for the first (spring 2013) series of measurements. The results are grouped in IV period, according to different modes of AC operation: time of operation, amount of recycled air and stream of air delivered to the auditorium. Additionally, the last two rows in Table 1 present the results for periods III and IV, which were separated due to AC operation. The values of effective dose in Table 1 (and also in Table 2) are calculated according to formula (1).

It can be seen that shutting down the AC during the night resulted in increase of radon (from

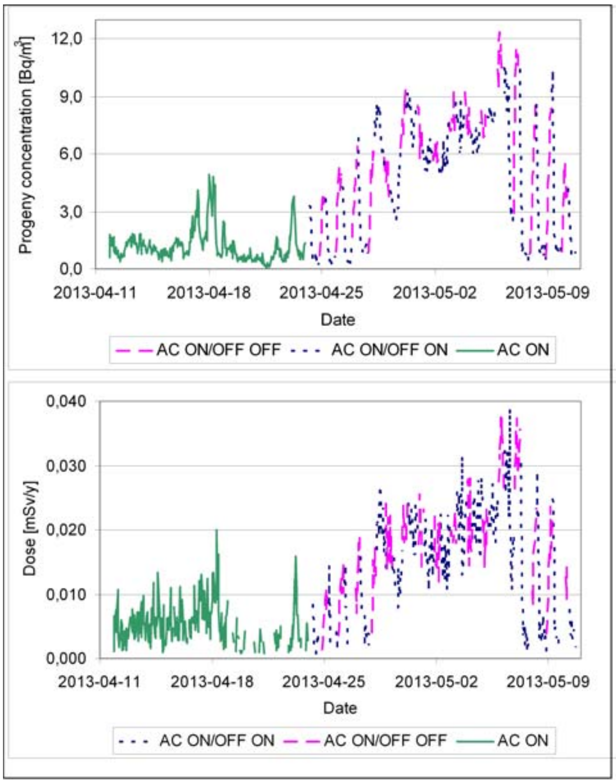

Fig. 1. Air-conditioning impact on radon progeny (attached and unattached) concentration and effective dose.

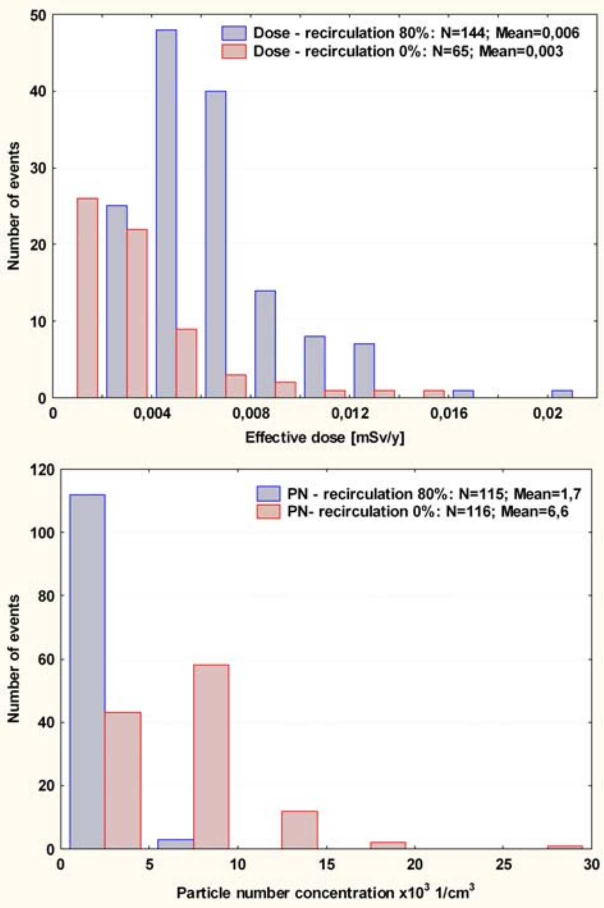

Fig. 2. Distribution of effective dose and particle number concentration PN caused by changing air recirculation.

25 to 31 Bq/m^3) and its progeny concentrations (1.2 to 5.0 Bq/m^3) and hence increase of effective dose for users of the auditorium (from 0.005 to 0.016 mSv/y). These differences are statistically significant ($p < 0.05$).

Mean values of radon and progeny concentrations in the period when AC was working (during the day) were a little bit lower than the values registered during the night, that is daily results 30 Bq/m^3 for radon and 4.4 Bq/m^3 for progeny concentrations and night results 33 Bq/m^3 for radon and 6.1 Bq/m^3 for progeny concentrations.

The variability of radon progeny concentration and effective dose due to the change of AC operation mode is shown in Fig. 1. The trend of parameters is correlated with the operation of AC. When AC was turned off during the night, increases in progeny concentration and effective dose was observed, whereas turning on the AC in the morning caused a decrease in those values.

During the periods I and II (AC ON), there were changes in the amounts of recirculated air delivered to the auditorium. It was observed that replacing of old air with fresh air in the AC system (changes of recirculation from 80% to 0%) resulted in a decrease in radon (from 30 to 12 Bq/m^3) and progeny concentrations (from 1.4 to 0.8 Bq/m^3) and hence caused the twice reduction of effective dose (0.006 to 0.003 mSv/y). These differences are statistically significant ($p < 0.05$). Contrary to radioactive elements, fresh air from outside introduced a lot of new particles suspended in air and thus resulted in increasing (almost four times) particle number concentration (from 1.7×10^3 to 6.6×10^3 l/cm^3). The histograms of effective dose and particle number (PN) concentration for changing air recirculation are shown in Fig. 2.

The statistics for the second (autumn 2013) series of measurements are shown in Table 2.

During this campaign, the AC was working all the time (AC ON), recirculation was constant and only the stream of air delivered to the auditorium was increasing. The first modification of stream (from 5400 to 7200 m^3/h) did not bring expected changes in radon and progeny concentration and hence changes in effective dose. The stream increase to the value of 9000 m^3/h resulted in decrease in radon (from 17 to 12 Bq/m^3) and progeny (from 2.5 to 0.9 Bq/m^3) concentrations and hence double reduction of effective dose (from 0.016 to 0.008 mSv/y). These differences are statistically significant ($p < 0.05$).

Figure 3 shows the distribution of effective dose due to modification of air stream.

The results of performed measurements also served to examine the impact of indoor air parameters (temperature, CO_2 concentration and humidity) to effective dose due to radon and its progeny.

As can be seen in Fig. 4, only the correlation between the effective dose and air humidity was observed with correlation coefficient $r = 0.72$ (for data of spring campaign). It is directly associated with a respective correlation between radon progeny (in both fractions) and air humidity [14]. Correlation coefficient for attached progeny concentration is 0.71 and for unattached progeny concentration is

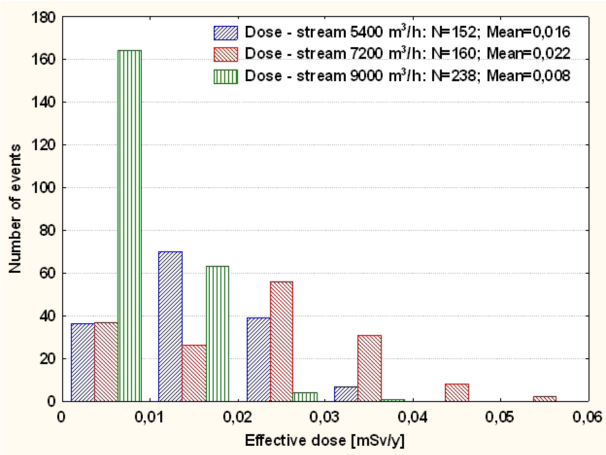

Fig. 3. Distribution of effective dose due to change in air stream.

0.43. The results for autumn campaign are similar, with correlation coefficient $r = 0.61$ for the relationship effective dose – air humidity.

Conclusions

The use of air-conditioning influences the dynamics of radon and its progeny concentrations and, hence, the dynamics of effective dose due to radon inhalation.

The change of AC system operation from mode ON to ON/OFF resulted in the significant increase of the mean concentration of summarized radon progeny (in attached and unattached fractions) from 1.2 to 5.0 Bq/m^3. This also resulted in increasing of effective dose from 0.005 to 0.016 mSv/y. The increase of radon progeny concentration and the value of effective dose during nights (AC OFF) and decrease during days (AC ON) were observed.

Change in air composition (recirculation changed from 80% to 0%) caused a decrease in the mean radon concentration values from 30 to 12 Bq/m^3 and in the mean concentration of summarized radon progeny (attached and unattached) from 1.4 to 0.8 Bq/m^3. This resulted in double reduction of effec-

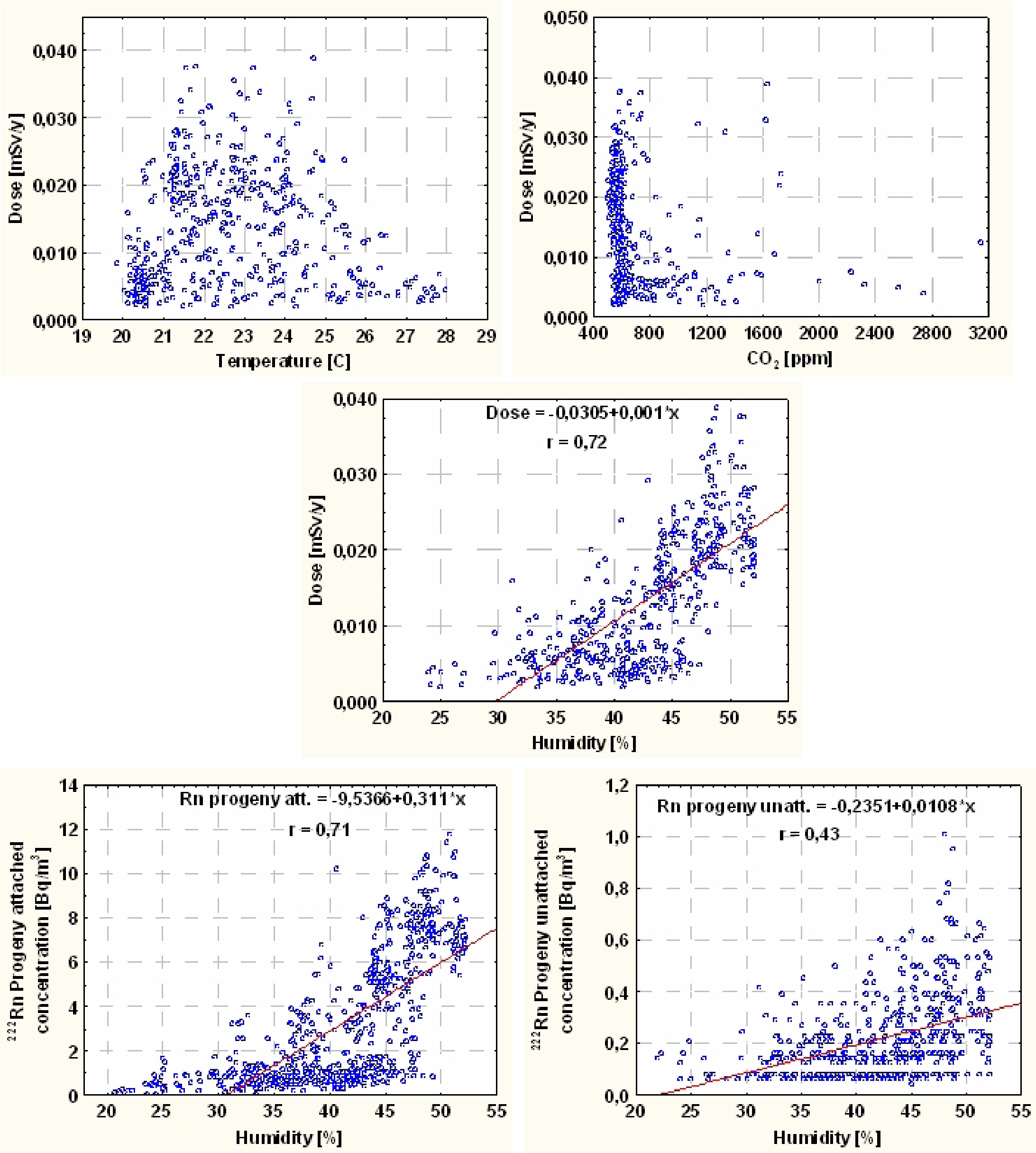

Fig. 4. Dispersion plots for correlation of effective dose to meteorological parameters.

tive dose from 0.006 to 0.003 mSv/y. Furthermore, the change of air recirculation caused a significant increase in particle number concentration from 1.7 to 6.6 × 10^3 l/cm^3.

Adjusting flow rate of the air mass being supplied to the hall (from 5400 to 9000 m^3/h) resulted in a decrease in the mean values of radon concentration (from 17 to 12 Bq/m^3), Rn progeny concentration (from 2.5 to 0.9 Bq/m^3) and effective dose (from 0.016 to 0.008 mSv/y).

The only correlation between effective dose due to radon and its progeny and indoor air parameter was observed for air humidity. The correlation coefficient amounted to $r = 0.72$ and $r = 0.61$ for spring and autumn results, respectively. It is associated with a respective correlation between radon progeny and air humidity.

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