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Original Article

The effect of geometrical parameters on the radon emanation coefficient and different radon parameters

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ABSTRACT

Radon is a radioactive gas produced from the uranium-238 series. Radon gas affects public health and is the second cause of lung cancer. The study samples were collected from one area of the city of Jazan, southwest of the Kingdom of Saudi Arabia. The influence of engineering and physical parameters on the emanation coefficient of gas and other gas parameters was studied. Parameters for radon were measured using a CR-39 Solid-State Nuclear Track Detector (SSNTD) through a sealed emission container. The results showed that the emanation coefficient was affected directly by the change in the grain size of the soil. All parameters of measured radon gas have the same behavior as the emanation coefficient. The relationship between particle size and emanation coefficient showed a good correlation. The values of the emanation coefficient were inversely affected by the mass of the sample, and the rest of the parameters showed an inverse behavior. The results showed that increasing the volume of the container increases the accumulation of radon sons on the wall of the container, which increases the emission factor. The rest of the parameters of radon gas showed an inverse behavior with increasing container size. The results concluded that changing the engineering and physical parameters has a significant impact on both the emanation coefficient and all radon parameters. The emanation coefficient affects the values of the radiation dose of an alpha particle.

1. Introduction

Radon is a noble gas produced from the uranium-238 series and is found in soil, air, and homes of all kinds. Radon and its offspring are dangerous and carcinogenic substances, which are one of the causes of lung cancer [1–4]. To protect against radon, it is necessary to study the factors that help in its spread, the way it migrates, and the processes of its generation [5–7]. Radon has a rebounding energy of up to 86 kV which helps it in the process of emanation, which is the process of radon releasing from solid rocks into pores filled with fluids. Part of the released radon can escape to the outside air with a half-life of 3.8 days, which is called radon emission. The number of atoms of radon gas that are released into the air to the number of atoms generated in rocks is known as the gas emission factor. The emission coefficient is affected by different parameters related to grain size, pores, and mass.

There is some research that showed that the amount of gas released depends on the conditions and characteristics of the materials from which it is released, as it increases with the increase in the size of soil grains [8–13]. Another group showed that grain size has the opposite effect on the emission if it increased by more than 0.5 mm [14,15]. The United Nations Scientific Committee on the Effects of Radiation UNSCEAR (2000) indicated that the coefficients of radon emission from rocks ranged from 5% to 70% with an average of 20% [16]. Therefore, it is important to study the influence of various factors such as rock size, soil mass, and container size on the emanation coefficient of gas. Additional experimental validation is also required to confirm the results and to develop an experimental model that validates the results of theoretical models.

Many prediction models have examined the effect of grain size on the emission factor, but the results are not reliable since they focused on the effect of emanation from only two grains and the pore space between them [17–20]. The macroscopic model was used, which includes the concept of grain size was unable to express the proportion of fractions resulting from radon under dry or water-saturated pore conditions. Radon emission may be expected to increase with increasing humidity because water increases the probability of capturing radon emanating from rocks [21].

The research uses the experimental method to validate the previous

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theories and assumptions. One of the most important ways to measure radon and track its path is to use the CR39 solid-state detector. Where the alpha pathway resulting from radon decay is followed by monitoring the latent pathways inside the detector. The effect of all different parameters such as particle size, pores, emission container size, and mass on the radon emission coefficient are studied. Potential hazards can also be evaluated by examining exhalation rates and emission factors.

2. Methods

2.1. Sampling and analysis

The research samples were collected from Al-Safa in Jazan City, located in the southwest of the Kingdom of Saudi Arabia. To avoid the effect of the difference in soil composition, the samples were collected with large granules (coarse soil). The soil was excavated to take the sample from the internal soil away from the external soil to avoid the effect of erosion factors. The sample was placed in a container to avoid the effect of any external factors on the sample during transportation. The soil was dried in an oven at a temperature of 123 ± 1 °C for 6 h, then the granules with equal diameter were separated using sieving. The samples were divided into three groups. The first group consisted of six samples (depending on the type of sieving and the available numbers in which they were separated) of different granules with diameters ranging from 85 to 900 μm. Each sample was placed in a cylindrical container of polystyrene with a size of 8.51×10^{-4} m^3. The rest of the samples were crushed and divided into two other groups. The second group had eleven samples weighing 800 gm. They were placed in containers of different volumes ranging from 1.51×10^{-4} m^3 to 18.0×10^{-4} m^3. The third group is twelve samples with different masses ranging from 200 to 1200 gm, placed in containers for emission with a size of 8.51×10^{-4} m^3. The Solid-State Nuclear Track Detector SSNTD (CR39) is composed of strips that have been cut into squares of 1.5 cm x 1.5 and then placed in the lid of the container. The containers are covered with foil to prevent gas leakage or any external radiation from entering the container. The containers were stored in a dry place for 60 days to reach the radioactive balance between radon and its daughters. The detectors are collected and etched with NaOH with 6.25 N and a temperature of 70 °C for 6 h. The detectors are washed and dried, and the radioactive traces are measured using an optical microscope [1–4]. A full scan of the detector is done and 100 fields are read to avoid any errors in the measurement. An average of 100 values is taken and uncertainty is calculated for each point.

2.2. Theoretical sides

Calculating the radon equilibrium concentration is an essential step in emission calculation. The radon concentration in the emission chamber after the equilibrium period is the amount of radon accumulated between the pore space of the soil. Radon equilibrium concentration C_{eq} (Bq/m^3) can be calculated using the following equation (1) [4,22].

$$C_{eq} = \frac{\rho}{Kt_e} \tag{1}$$

where: $t_e = t - \frac{1-e^{-\lambda t}}{\lambda}$ is the effective exposure time in hours, t is exposure time, λ is the decay constant of radon, K is the factor of calibration of the SSNTDs detector and ρ is the track density.

The radon emanation coefficient f (%) is the ratio of the amount of radon escaping from soil pores to the amount of radon generated within the soil. The emanation from the radon-radium concentration of the studied samples can be calculated using the following equation (2) [23,24].

$$f = \frac{C_{eq} V}{C_{Ra}\, m} \tag{2}$$

where C_{Ra} is the Concentration of radium (Bq/kg), V is the effective volume of the can and m is the mass of the sample (kg).

The radon exhalation rate for surface E_a (Bqm^{-2}/h) for the radon and the mass exhalation rate E_m (Bq/kg.h) can be determined according to radon concentration using the relation 3 [1–4,25]:

$$E_a = \frac{C \times V \times \lambda}{At_e} \; \& \; E_m = \frac{C \times V \times \lambda}{mt_e} \tag{3}$$

where A (m^2) is the cross-section area, λ is the decay constant of radon.

The annual effective dose AED (mSv/y) was calculated using equation (4):

$$AED = C \times D \times F \times T = 25.2C \left(\frac{mSv}{y}\right) \tag{4}$$

where C (Bq/m^3), F, D (nSv per Bq/m^3.h), and T (hy^{-1}) are the concentration of radon, the factor of indoor equilibrium between radon and its progeny ($F = 0.4$), the dose conversion factor ($D = 9$ nSv per Bq/m^3.h), and time ($T = 7008$ hy^{-1} indoors for a person) respectively [4,14].

The radioactive dose D_{eq} (mSv/y) of an alpha particle from soil can be calculated using the radium values and the emanation coefficient f using the following relationship 5 [26].

$$D_{eq} = 0.003\, f \times C_{Ra} \left(\frac{\mathrm{mSv}}{\mathrm{y}}\right) \tag{5}$$

3. Results

3.1. Effect of grain size on different parameters

Radon concentration and emanation coefficient are affected by different soil properties. Soil samples were studied with several different characteristics (grain size, mass, and volume of the emission bin). Fig. 1 shows the relationship between the radon emanation coefficient and the grain size of soil. The results showed that the emanation coefficient was affected clearly by changing the grain size. The lowest value of the emanation coefficient was 5.130 ± 1.029% with the lowest grain size of 85 μm, and the highest value was 22.101 ± 1.631% with the highest grain size of 900 μm. The extrusion factor increased sharply with grain sizes from 85 to 500 μm. The significant increase in radon emission is due to the increase in the grain surface, which indicates that much more emission is produced from the grain surface than from the inner atoms of the grain. Also, the extrusion coefficient starts to increase slightly with larger grain sizes. This is because when the grain size increases further, the outer grains cover each other as a result of increasing their size, which leads to a decrease in the outer surface responsible for the gas release, which leads to a decrease in emissions instead of increasing.

The results of the current research showed a clear agreement with the results of other literature as shown in Table 1. In general, the size of

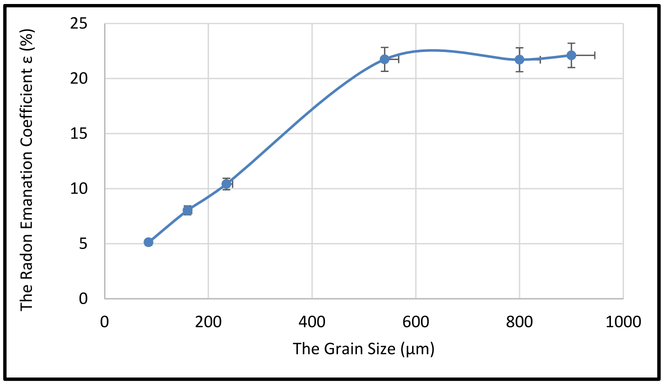

Fig. 1. The relation between grain size and the radon emanation coefficient.

Table 1
Comparison between the results of Grain size for the current research and the results of another research.

Grain Size (µm)	The Radon Emanation Coefficient %			
	Present work	Reference [12]	Reference [23]	Reference [10]
85	5.130 ± 1.029	15	3.4	—
160	8.029 ± 1.852	25	3.5	10
235	10.420 ± 0.909	26	4	14
540	21.739 ± 1.444	28	4.8	18
800	21.708 ± 1.058	34	8.3	19
900	22.101 ± 1.631	35	12	17

soil particles has a clear effect on the emanation factor. The results showed that the emanation factor increased with the increased grain size of the soil. This indicates that the emanation comes from the surface of the grains and not from the inside. The surface area of the soil particles affects the amount of emanation.

Table 2 presents the relationship between the change in grain size and the different parameters of the soil sample. The results showed that the concentration of radon gas increased with the increase in grain size. Radon concentration changes from 169.860 ± 3.263 Bq/m^3 with the lowest grain size to 226.480 ± 5.127 Bq/m^3 with the largest grain size. The change depends on the proportions of uranium atoms present on the surface of the grains. The mean concentrations of radon in the samples were 199.350 ± 3.372 Bq/m^3. Concentration values are within the internationally permitted limits of 200–600 based on the International Committee for Radiation Protection [27,28]. This indicates that the samples contain small percentages of uranium atoms that cause radioactive contamination. That is, the size of the granules increases the gaps between the soil and thus helps in the escape of gas from the inner layers of the soil.

Table 2 shows the annual effective dose and alpha dose resulting from the sample with the difference in the grain size of the soil. Also, there is a direct relationship between the size of the granules and the measured doses.

The annual effective dose and alpha dose values changed from 4.330 ± 0.083 and 0.480 ± 0.009 mSv/y to 5.775 ± 0.131 and 2.762 ± 0.015 mSv/y with an average value of 5.083 ± 0.086 and 1.701 ± 0.010 mSv/y respectively. The alpha dose is not the total value of the dose, but the dose resulting from the surface atoms of the samples. The results showed that the different radon parameters were affected clearly by the change in the grain size of the soil.

3.2. *The mass of samples and different parameters*

Fig. 2A presents the relationship between the mass and emanation coefficient of radon gas in the studied soils. It was observed from the figure that the emanation coefficient was as high as possible with a small mass of 200 g and decreased with increasing mass. The results showed that the emanation values for the gas ranged from 50.961 ± 0.096% at the mass of 200 g to 8.493 ± 0.048% at the mass of 1200 g. It is clear from the results that the emanation coefficient is affected by the masses and that the emanation coming out from the outer surface of the soil is much higher than the radon emanating from the inner soil. The results are confirmed by the study conducted by Saad et al., 2018, as the results of the current research complement the results of the previous research [23].

Table 2
The values of radon concentration, and radiation doses with different grain sizes.

Grain Size (µm)	C_{eq} (Bq/m^3)	AED (mSv/y)	D_{eq} (mSv/y)
85	169.860 ± 3.263	4.331 ± 0.083	0.481 ± 0.009
160	184.015 ± 3.389	4.692 ± 0.086	0.816 ± 0.010
235	198.170 ± 1.938	5.053 ± 0.049	1.140 ± 0.005
540	205.248 ± 3.9215	5.234 ± 0.100	2.463 ± 0.011
800	212.325 ± 2.597	5.414 ± 0.066	2.544 ± 0.007
900	226.480 ± 5.127	5.775 ± 0.131	2.763 ± 0.015
average	199.350 ± 3.372	5.083 ± 0.086	1.701 ± 0.010

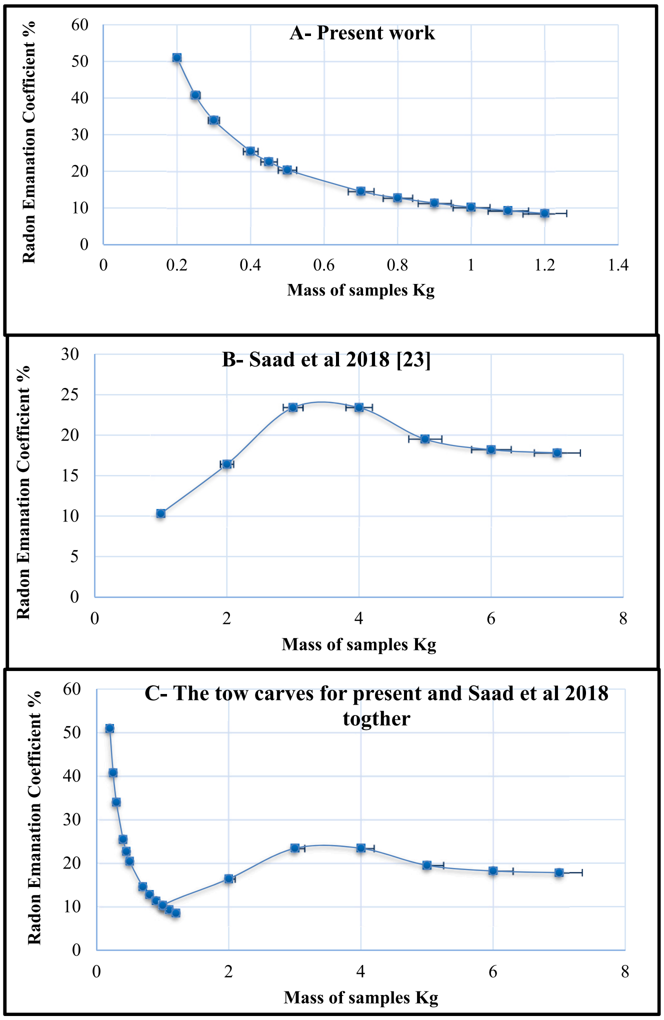

Fig. 2. a,b&c The relation between the mass and emanation coefficient% from the present study and Saad et al., 2018 [23].

Fig. 2B shows the results obtained in a previous study [23] and compares them with the current results. The comparison shows that the results of the previous study are complementary to the current results and are consistent with the results we obtained as shown in Fig. 3C. The emanation coefficient decreases with the increase in mass, which confirms that the emanation from the subsoil is much less than the emanation from the outer surface of the soil.

The results also show that the best weight for studying radon gas and its quantity in the soil is with small weights, which start from 200 g. The gas emanating from the inner layers of the soil may be absorbed from the adjacent layers, and the possibility of its exit to the outside air decreases with the distance of the extrusion layer from the outer surface.

Fig. 3A and B shows the relationship between surface and mass exhalation rate and the change in sample mass. The results showed that both the surface exhalation rate (Fig. 3A) and the mass exhalation rate (Fig. 3B) behave the same with the change in the mass of the sample. Surface and mass exhalation rates increase with increasing mass and

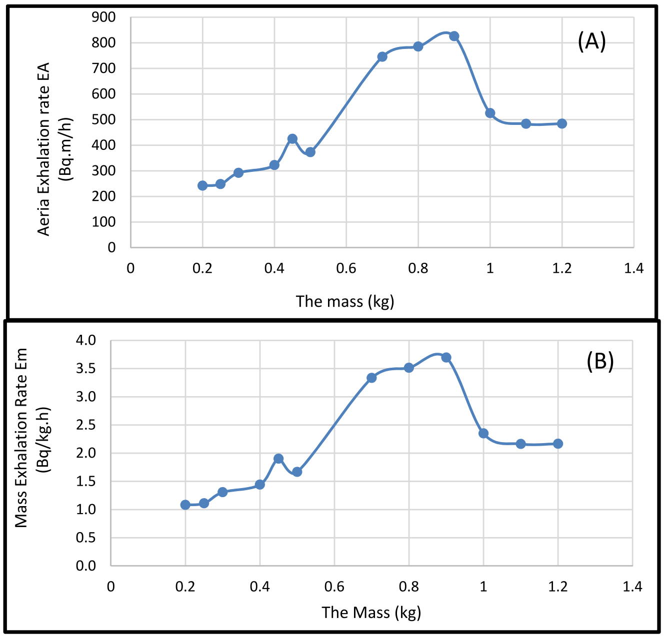

Fig. 3. a&b The relation between the mass of the sample and area and mass exhalation rate.

reach the highest value of exhalation rate at mass 0.9 kg with a value of 825.421 ± 11.987 Bq.m/h and 3.694 ± 0.078 Bq/kg.h, respectively. The exhalation rates were sudden fall occurs at the mass of 1 kg and begins to stabilize and increase when it reaches 1.2 kg.

Table 3 presents the change of different parameters of radon gas with the mass change of the sample. The results show that the highest value of radon gas concentration was 580.355 ± 12.242 Bq/m^3 at a mass of 0.9 kg, and the lowest value was 170.108 ± 22.070 Bq/m^3 at a mass of 0.2 kg, with an average value of 336.812 ± 12.645 Bq/m^3. The concentration of gas increases with the increase in mass as a result of the increase in radioactive nuclei in the sample. The increase occurs in the first part, where the increase in mass results in an increase in gas-producing surfaces. That is, the inner layers do not have high pressure, which allows gas to leak from the inside to the outside. At these points, there is a disturbance in the soil, which increases gas leakage and increases its concentration. In the second part concentration of radon decreases, as a result, the pressure of the surface layers on the inner layers, reduces the amount of gas escaping from the inside to the air of the emission container. In this part, the soil becomes in a state similar to that of soil compaction during construction, which confirms that the soil compaction process is very necessary to prevent gas leakage from the inner layers. The radium concentration also exhibits the behavior of the daughter radon concentration. The radium concentration changes from 5.975 ± 0.775 Bq/kg at mass 0.2 to 20.385 ± 0.430 Bq/kg at mass 0.9 with an average value of 11.831 ± 0.444 Bq/kg.

Table 3
The values of radon concentration, and radiation doses with different masses.

The mass of samples (kg)	C_{eq} (Bq/m^3)	AED (mSv/y)	D_{eq} (mSv/y)
0.2	170.108 ± 22.070	4.338 ± 0.563	0.913 ± 0.002
0.25	174.390 ± 12.467	4.447 ± 0.318	0.749 ± 0.001
0.3	205.248 ± 13.925	5.234 ± 0.355	0.734 ± 0.011
0.4	226.480 ± 5.563	5.775 ± 0.142	0.608 ± 0.004
0.45	298.564 ± 18.038	7.613 ± 0.460	0.713 ± 0.002
0.5	261.868 ± 14.722	6.678 ± 0.375	0.562 ± 0.009
0.7	523.735 ± 10.498	13.355 ± 0.268	0.803 ± 0.003
0.8	552.045 ± 11.500	14.077 ± 0.293	0.741 ± 0.004
0.9	580.355 ± 12.242	14.80 ± 0.312	0.693 ± 0.004
1	369.021 ± 5.752	9.410 ± 0.147	0.396 ± 0.003
1.1	339.720 ± 11.690	8.663 ± 0.298	0.396 ± 0.006
1.2	340.215 ± 13.286	8.675 ± 0.339	0.304 ± 0.002
average	336.812 ± 12.645	8.589 ± 0.322	0.629 ± 0.004

The value of the alpha dose resulting from the emission of radon gas behaves like the emanation coefficient, where the value changes from 0.304 ± 0.002 mSv/y at the mass of 1.2 kg to 0.913 ± 0.002 mSv/y at the mass of 0.2 kg. The highest value of the annual effective dose was 14.799 ± 0.312mSv/y at 0.9 kg and the lowest value was 4.338 ± 0.563 at 0.2 kg. The results show that the mass of the sample has an effect on all the different parameters of radon gas, and it can be concluded that the best mass for studying the gas is between 0.3 and 0.7 kg, where the average values of radon gas concentration. It is also clear that compacting the soil well and increasing the layers before construction reduces the escape of radon gas from the inside of the soil to the outside.

3.3. *Effect of air volume in can on different parameters*

Fig. 4 shows the effect of changing the volume of air inside the emission vessel on the emanation coefficient values of the gas. The values of the emanation coefficient change from 4.982 ± 0.225% at the lowest volume of 1.4 × 10^{-4} m^3 to 64.057 ± 2.888% at the largest volume of 18 × 10^{-4} m^3. The results show that the emanation coefficient of radon gas increases with increasing volume. This may be due to the increase in the accumulation of radon daughters on the container wall, which increases the emission.

Table 4 shows the effect of increasing the volume of the container on the different parameters of radon gas (radon gas concentration, radium concentration, and radiation dose). The results showed that the highest concentration of radon gas was 580.355 ± 12.242 Bq/m^3 with the lowest air volume and the lowest concentration was 113.240 ± 10.069 Bq/m^3 with the largest container volume with an average value of 337.951 ± 13.469 Bq/m^3. The results show that the concentration of the gas is adversely affected by the increase in the volume of the container, and it finds that the best size of the container is between 2.8 × 10^{-4} to 8 × 10^{-4} m^3. This volume gives the average value of the gas concentration.

It was found that the emanation behaves the opposite of what was expected, as increasing the volume increases the emanation of gases.

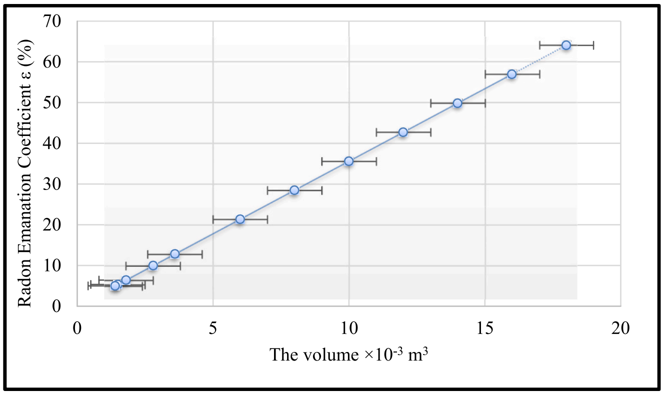

Fig. 4. The relation between the air volume in the counter and the radon emanation coefficient.

Table 4
The values of radon concentration, the concentration of radium, and radiation dose with different volumes.

Vx10^{-4} (m^3)	C_{eq} (Bq/m^3)	AED (mSv/y)	D_{eq} (mSv/y)
1.4	580.355 ± 12.242	14.799 ± 0.312	0.305 ± 0.001
1.5	552.045 ± 11.500	14.077 ± 0.293	0.311 ± 0.001
1.8	523.735 ± 10.498	13.355 ± 0.268	0.354 ± 0.001
2.8	368.030 ± 17.440	9.385 ± 0.445	0.386 ± 0.002
3.6	346.798 ± 15.143	8.843 ± 0.386	0.468 ± 0.002
6	339.720 ± 13.606	8.663 ± 0.347	0.764 ± 0.003
8	325.565 ± 12.942	8.302 ± 0.330	0.977 ± 0.004
10	304.333 ± 17.640	7.760 ± 0.450	1.141 ± 0.007
12	268.954 ± 20.995	6.858 ± 0.535	1.210 ± 0.009
14	148.628 ± 10.168	3.790 ± 0.259	0.780 ± 0.005
16	184.015 ± 9.389	4.692 ± 0.239	1.104 ± 0.006
18	113.240 ± 10.069	2.888 ± 0.257	0.764 ± 0.007
average	337.951 ± 13.469	8.618 ± 0.343	0.714 ± 0.004

Increasing the size of the emission container means increasing the surface of the sample, that is, increasing the emanation of gases, and this was confirmed by the results. The accumulation of radon daughters on the walls and the increase in the sample surface caused a significant increase in the emanation coefficient.

It was also found that the behavior between the volume of the emission container and the concentration of the gas was inverse. The results concluded that an increase in the emanation coefficient does not mean an increase in the concentration of the gas, but the volume of air in the emission container has a significant effect on the concentration of the gas.

The radiation doses value changes with the change in volume. The highest value for an alpha dose was 1.210 ± 0.009 mSv/y at volume 12 $\times 10^{-4}$ m^3 and the lowest value was 0.305 ± 0.001 mSv/y at size 1.4 $\times 10^{-4}$ m^3 with an average value of 0.714 ± 0.004 mSv/y. The value of AED behaves like the radon concentration, where the value changes from 2.888 ± 0.257 mSv/y at the volume of 18 $\times 10^{-4}$ m^3 to 14.799 ± 0.312mSv/y at the volume of 1.4 $\times 10^{-4}$ m^3. Volume change affects different parameters of radon gas.

4. Conclusion

The samples were collected from the same soil from the city of Jizan, southwest of the Kingdom of Saudi Arabia. The CR-39 detector was used to measure the emanation factor values and all the different parameters of radon gas. The results showed that all radon parameters were affected by particle size, sample mass, and container size.

The grain size of the soil affects the values of the radon emanation factor. The relationship between particle size and emanation coefficient was direct. There was an agreement between the results of the current research and those measured in other literature. Soil particle size influenced all radon parameters. The results concluded that the emission of gases is from the surface of the granules and not from the inner layers, as the contribution decreases with the distance from the surface. The results depended strongly on the particle size of the soil studied. This method developed in the study is important as it gives a picture of the effect of soil grain change on the emission factor. The granules that were studied were from small to medium, so it is recommended to study more with granules ranging from medium to very large. More studies should be done to develop an integrated approach on the extent of emissions that occur from soils in all their forms.

Results for all parameters depend on changing the size of the emission container. The relationship between container size and emanation coefficient was direct. This is due to the increased accumulation of radon blocks on the wall of the container, which increases the emission of gases. It is concluded that increasing soil surface area significantly affects radon emanation. A technique must be developed to choose the least area of the soil surface to build on to reduce gas emissions. The conical shape with a small base will be very useful when building. Further studies are recommended with larger volumes, especially for building soil.

The relationship between sample mass and gas emanation coefficient was inversely related. All parameters were also affected by the sample mass change. The results concluded that the inner layers contribute a very small amount of the outer radon. Most of the emissions come from the surface and near-surface layers. It is recommended that the land be tamped well before using it in construction.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] H.E. Entesar, S.H. Doaa, Y. Zainab, Evaluation of radioactive exposure in soil, Int. J. Radiat. Res. 19 (2021) 719–727.

[2] H.E. Entesar, Environmental air dosimetry in some locations of gazan using passive track detectors, J. Life Sci. Technol. 1 (2013) 75–78.

[3] H.E. Entesar, Direct measurement of the radioactive radon gas activity in water in Saudi Arabia, AIP Conf. Proc. 1976 (1) (2018), 020019.

[4] Entesar H. El-Araby, A.A. El-Barbary, F.M. Tomahy, N.A. Shabir, F.J. Nahari1, Radon investigation and its progeny in ceramic cooking dishes, Int. J. Radiat. Res. 20 (1) (2022) 217–221.

[5] M. Hosoda, A. Sorimachi, Y. Yasuoka, T. Ishikawa, S.K. Sahoo, M. Furukawa, N. M. Hassan, S. Tokonami, S. Uchida, Simultaneous measurement of radon and thoron exhalation rates and comparison with values calculated by UNSCEAR equation, J. Radiat. Res. 50 (2009) 333–343.

[6] W.W. Nazaroff, Radon transport from soil to air, Rev. Geophys. 30 (1992) 137–160.

[7] J. Somlai, Z. Gorjánácz, A. Várhegyi, T. Kovács, Radon concentration in houses over a closed Hungarian uranium mine, Sci. Total Environ. 367 (2006) 653–665.

[8] W.W. Nazaroff, B.A. Moed, R.G. Sextro, Soil as a source of indoor radon: generation, migration, and entry, in: W.W. Nazaroff, A.V. Nero (Eds.), Radon and its Decay Products in Indoor Air, JohnWiley & Sons, New York, 1988, pp. 57–112.

[9] D.J. Greeman, A.W. Rose, Factors controlling the emanation of radon and thoron in soils of the eastern, U. S. A. Chem. Geol. 129 (1996) 1–14.

[10] D. Breitner, T. Turtiainen, H. Arvela, P. Vesterbacka, B. Johanson, M. Lehtonen, K.-H. Hellmuth, C. Szabó, Multidisciplinary analysis of Finnish esker sediment in radon source identification, Sci. Total Environ. 405 (2008) 129–139.

[11] A. Sakoda, K. Hanamoto, Y. Ishimori, T. Nagamatsu, K. Yamaoka, Radio- activity and radon emanation fraction of the granites sampled at Misasa and Badgastein, Appl. Radiat. Isot. 66 (2008) 648–652.

[12] A. Sakoda, K. Hanamoto, Y. Ishimori, T. Kataoka, A. Kawabe, K. Yamaoka, First model of the effect of grain size on radon emanation, Appl. Radiat. Isot. 68 (2010) 1169–1172.

[13] M. Vital, S. Grondona, N. Dimova, D.E. Martinez, Factors affecting the radon (222Rn) emanation from aquifer rock materials: implications for radiological and groundwater tracer studies, Appl. Radiat. Isot. 189 (2022), 110433.

[14] R. Stefan, R. Annette, M. Florian, M. Viacheslav, B. Tanita, C. Scott, Evolution of traceable radon emanation sources from MBq to few Bq, Appl. Radiat. Isot. 196 (2023), 110726.

[15] A. Sakoda, Y. Ishimori, K. Hanamoto, T. Kataoka, A. Kawabe, K. Yamaoka, Experimental and modeling studies of grain size and moisture content effects on radon emanation, Radiat. Meas. 45 (2010) 204–210.

[16] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), Sources and effects of ionizing radiation, in: UNSCEAR (2000) Report to the General Assembly, with Scientific Annexes, United Nations, New York, 2000.

[17] T. Sasaki, Y. Gunji, T. Okuda, Radon emanation dependence on grain configuration, J. Nucl. Sci. Technol. 41 (2004) 993–1002.

[18] T. Sasaki, Y. Gunji, T. Okuda, Mathematical modeling of radon emanation, J. Nucl. Sci. Technol. 41 (2004) 142–151.

[19] H. Sun, D.J. Furbish, Moisture content effect on radon emanation in porous media, J. Contam. Hydrol. 18 (1995) 239–255.

[20] R. Barillon, A. Özgümüs, A. Chambaudet, Direct recoil radon emanation from crystalline phases. Influence of moisture content, Geochem. Cosmochim. Acta 69 (2005) 2735–2744.

[21] A. Sakoda, K. Hanamoto, I. Yuu, K. Takahiro, K. Atsushi, Y. Kiyonori, First model of the effect of grain size on radon emanation, Appl. Radiat. Isot. 68 (2010) 1169–1172.

[22] H.E. Wichmann, J. Heinrich, M. Gerken, M. Kreuzer, J. Wellmann, G. Keller, L. Kreienbrock, Domestic radon and lung cancer current status including new evidence from Germany, Int. Congr. 1225 (2002) 247–252.

[23] A.F. Saada, R.M. Abdallah, N.A. Hussein, Physical and geometrical parameters controlling measurements of radon emanation and exhalation from soil, Appl. Radiat. Isot. 137 (2018) 273–279.

[24] IAEA, Measurement of Radionuclides in Food and the Environment 2, A Guidebook, Vienna, 1989, pp. 2–5. Technical Reports Series No. 295, Section.

[25] Andreea Cristina Tataru, Aurora Stanci, Dorin Tataru, Determination of the radon concentration in homes depending on the insulation used for the floor, MATEC Web Conf. 354 (2022), 00074.

[26] Nabil M. Hassan, Tetsuo Ishikawa, Masahiro Hosoda, Kazuki Iwaoka, Atsuyuki Sorimachi, Sarata K. Sahoo, Miroslaw Janik, Chutima Kranrod, Hidenori Yonehara, Masahiro Fukushi, Shinji Tokonami, The effect of water content on the radon emanation coefficient for some building materials used in Japan, Radiat. Meas. 46 (2011) 232–237.

[27] ICRP, International commission on radiological protection statement on radon, in: International Commission on Radiological Protection Statement on Radon, 2009. Ref, 00/902/09.

[28] ICRP, International commission on radiation units, in: Publication 103 Recommendations of the International Commission on Radiological Protection Annals of the ICRP 37/2-4, 2007.