Analysis on the influence of opening and closing of ventilation tunnel on radon concentration distribution

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Abstract. Meteorological ventilation conditions affect easily on radon concentration in granite tunnel. In this paper, the variation of radon concentration in the tunnel in natural and ventilation conditions is analyzed through numerical simulation method. It is found that the radon concentration in tunnel can be effectively controlled by closing the tunnel entrance under the condition of pressurized ventilation.

1. Introduction
The main factors affecting radon concentration in tunnel are not only physical properties of rock mass or the size of exposed area of surrounding rock mass, but also the meteorological conditions and ventilation models. As early as 1951, Smith O.F. found the influence of environmental meteorological conditions on radon exhalation from soil. In 1963, Schroeder G.L. et al. started experiment on the radon exhalation control by pressurized ventilation in tunnel construction [1]. Through field monitoring, F. Perrier et al. [2] conducted a study on the tunnel with length of 38m and slope of 8% in Pulchok mountain in Nepal, and concluded that the obvious natural ventilation only occurs in winter(from October to March, the temperature outside tunnel is lower than that inside tunnel), and that the radon concentration in tunnel changes with the ventilation volume. Perrier [2] pointed out that the radon concentration is very sensitive to airflow exchange, but he did not provide quantitative description. Mechanical ventilation is widely used as a radon concentration deduction method [1]. But the relationship between mechanical ventilation and radon exhalation rate is still unclear.

In this paper, the changing law of radon concentration in a granite tunnel under ventilation is studied and analyzed through numerical simulation method. By simulating the change law of radon concentration with tunnel mouth opening and closing, it is found that the closure of tunnel mouth benefit a lot on the control of radon concentration.

2. Distribution of radon concentration in mountains under natural conditions
Radon is produced from the rock body at a certain rate of continuous decay, so the process of radon generation can be regarded as a stable, long-lasting chemical reaction process. In the hypothetical chemical reaction process, radon is a reaction product generated at a steady rate which equals the gas concentration in the unit time: 0.087Bq / (m³.s) [3].

A mountain geometry model[5] is established in the COMSOL Multiphysics[4] environment. And the mountain geometry is a granite medium with a boundary condition of 100Bq/m³ and a ventilation of 9m³/s. When conducting numerical simulation of the distribution of radon concentration in the mountain, the steady-state mass transmission model in a chemical engineering module needs to be
coupled based on the Darcy seepage model. Besides, the steady state analysis under convection diffusion will be conducted when the coupling model is solved since the transport mechanism of radon inside the mountain also includes convection and diffusion[6].

The results of the model solution are shown in Figure 1 and Figure 2, showing that the concentration of radon inside the mountain under natural conditions is up to $10^8$Bq/m$^3$ magnitude. Near the surface of mountain, radon concentration gradient is very large, with rapid changes in magnitude from the atmospheric level of the surface (no more than 100 Bq/m$^3$) and reaching $1.1 \times 10^5$Bq/m$^3$ at 0.001m. These results have the same magnitude as the parsing calculation result of the numerical model[7].

![Figure 1. Radon concentration distribution on the mountain cross section in natural conditions.](image1)

![Figure 2. Contour map of radon on mountain cross section in natural conditions.](image2)
3. Distribution of radon concentration under pressurized ventilation

The pressurized ventilation of the mountain tunnel can be regarded as the flow of air one-dimensional pressure tube, and radon precipitation in rocks around can be regarded as the convection diffusion movement of materials.

A horizontal single-head tunnel geometry (as shown in Figure 2.1, where the units of coordinates are m, the same below) is established in the COMSOL multiphysics environment on the condition that: the tunnel is located in the granite medium; the length of tunnel is 100 meters and the width is 3.5 meters with tunnel end on the left; on the length of 0-60m, the height of tunnel is 4m; on the length of 60-100m, the height of tunnel is 3m with end on the right. On the condition of positive pressurized ventilation, fresh air comes from the outside of tunnel mouth, and goes to the end of tunnel through pipelines, which means that the end of tunnel(left side) is considered as the boundary of fresh air. The fresh air flows continuously along the pipeline and finally flows outside the tunnel. The boundary conditions are: the radon concentration in tunnel before ventilation is $1 \times 10^5$ Bq/m$^3$; the radon concentration in the fresh air outside the tunnel is 100 Bq/m$^3$, and ventilation volume is 9 m$^3$/s.

The computational model is built in k-ε turbulence model and convection diffusion model. Before simulation, the model is meshed. After software calculation, the velocity field and radon concentration distribution are obtained, as shown in Figure 3.

As can be seen from Figure 3, due to the influence of variable cross-section, the velocity field in the tunnel changes obviously, which also leads to uneven distribution of radon concentration. This conclusion has certain guiding significance for the design of radon concentration measurement experiment.

It shows that the lowest radon concentration is at the end of the tunnel both in Figure 3 and Figure 4, which is result of the dilution effect of fresh air. When the radon concentration in the tunnel decreases, the difference between radon concentration in the tunnel and that in the surrounding rocks increases, enhancing the diffusion effect. As the new wind flows along the tunnel, radon in the surrounding rocks spread into the tunnel. The fresh air carries the radon along the tunnel in the way of accumulation, and radon concentration in the tunnel gradually increases. If the length of the tunnel increased, the radon concentration of will increase accordingly.

Figure 3. Distribution of airflow velocity field and radon concentration in the tunnel under pressurized ventilation (100m).
Figure 4. Contour map of radon concentration in tunnel under pressurized ventilation (100m).

Figure 5. Contour map of radon concentration in tunnel under pressurized ventilation (500m).
Figure 6. Contour map of radon concentration in tunnel under pressurized ventilation (1000m).

Under the same conditions of ventilation, surrounding rocks etc., through the calculation of tunnel with length of 500m and 1000m, it shows that the longer the tunnel, the higher the radon concentration is in the tunnel mouth. The contour map of radon concentration in tunnels with two lengths is shown in Figure 5, Figure 6.

By comparing Figure 4, Figure 5 and Figure 6, it can be seen that under the pressurized ventilation state, the radon concentration in the laneway is the lowest at the air supply point (less than 100 Bq/m³), but the wind flow trend along the tunnel gradually increases, and finally reaches the maximum in the tunnel mouth. Radon concentration at the mouth of 100m-long tunnel is about $2.8 \times 10^3$ Bq/m³. It is about $1.0 \times 10^3$ Bq/m³ when the length of tunnel becomes 500m, and about $2.0 \times 10^3$ Bq/m³ when the length comes to 1000m. The numerical simulation results show that the change trend of radon concentration in tunnel under positive pressurized ventilation is the same as that of the literature [9] and [10].

From the above numerical simulation results, it is indicated that the pressurized ventilation works well only in the vicinity of the air supply point. With the flow of wind in tunnel, radon continuously into the air flow, so that the concentration of radon continuously increases, resulting in reduced effect of ventilation mode. The longer the tunnel, the worse the effect.

4. Distribution of radon concentrations under closed ventilation tunnel mouth

According to the analytical and computational results of the "numerical model of radon movement in the surrounding rocks" [7], the movement mechanism of radon in the mountain under the state of micro-positive pressurized ventilation is dominated by seepage [8].

In order to further analyze the influence of pressure change in the mountain on the distribution of internal radon concentration, a tunnel located in the longitudinal center of the mountain (see Figure 7) was added based on the above model. The cross-sectional dimension is 4m x 4m and the length is 1000m. By setting up the pressure conditions in the tunnel, the effect of pressure on the movement of radon in the mountain is analyzed using software.

The numerical simulation results of pressure changes in the surrounding rocks under the closed conditions of the ventilation in tunnel mouth are shown in Figure 8 and Figure 9. The numerical
simulation results of the effect on radon concentration are shown in Figure 10, Figure 11, and Figure 12.

Figure 7. Calculation model of transverse section of mountain along the tunnel.

Figure 8. Pressure distribution on the transverse section of mountain along the tunnel under closed ventilation tunnel mouth.
Figure 9. Pressure contour map on the transverse section of mountain along the tunnel under closed ventilation tunnel mouth.

Figure 10. Radon concentration distribution in the transverse section of mountain along the tunnel under closed ventilation tunnel mouth.
Figure 11. Contour map of radon concentration in the transverse section of mountain along the tunnel under closed ventilation tunnel mouth.

Figure 12. Local magnification of radon concentration contour map in the transverse section of mountain along the tunnel under closed ventilation tunnel mouth.

From the above numerical simulation results, it indicates that the pressure field and radon concentration field of the mountain have been changed after the micro-positive pressurized ventilation is implemented in the tunnel.
Pressure field: by comparing Figure 8 and Figure 9, it can be seen that after the formation of positive pressure of 200Pa in the tunnel, the pressure distribution in the surrounding rocks is significantly affected, and the radius of influence is about 10 meters. In this range, due to significant increase of pressure gradient, the gas seepage is enhanced. This conclusion is consistent with the conclusion in literature [11]: research on the effective migration distance of radon.

Radon concentration field: due to changes in the pressure field, especially changes in the area within 10m from the tunnel wall, fresh air into the tunnel by ventilation system continuously carry radon and its progeny through the seepage, resulting in a change in the radon concentration field in the rocks around the tunnel, and a lower level of radon concentration in the tunnel (lower than 400Bq/m³). As can be seen from Figure 10 and Figure 11, the maximum radon concentration in the mountain decreased slightly after closing the ventilation tunnel mouth, and there was no change in magnitude. It was still 10⁶Bq/m³. The fresh air enters the tunnel through ventilation system by the way of seepage into surrounding rocks near the tunnel. Concentration of radon and its progeny is diluted. With the increase of surrounding rock thickness, the seepage effect is rapidly reduced. The dilution effect also weakens. So the radon concentration of surrounding rocks near the tunnel increases with the increase of rock thickness. It reaches maximum in the deep tunnel, then decreases gradually. Due to effect of gas diffusion and atmospheric diffusion in the pores of rocks, the concentration decreases most when it comes to the rock mass near the mountain surface.

In order to comprehensively reflect the change of the radon concentration distribution in the mountain under closed ventilation tunnel mouth, the numerical simulation of mountain profile in longitudinal sections is conducted as shown in Figure 13. The analysis was based on a section of the mountain along longitudinal direction, which contains a tunnel with length of 160m. Other parameters and conditions are same as before.

![Figure 13. Calculation model of longitudinal section of mountain along the tunnel.](image)

The numerical simulation results of radon concentration on the longitudinal section of mountain are shown in Figure 14 and Figure 15. As can be seen from the figure, due to the length of mountain, micro-positive pressure (200Pa) ventilation has a limited impact. The left part of the figure is consistent with the numerical simulation results under natural state, and the right part is the same as the simulation results under micro-positive pressure inflation of mountain cross-section.
Figure 14. Distribution of radon concentration on the longitudinal section of mountain along the tunnel under closed ventilation tunnel mouth.

Figure 15. Contour map of radon concentration on the longitudinal section of mountain along the tunnel under closed ventilation tunnel mouth.

5. Conclusion
The above numerical simulation results show that:

(1) General pressure-in ventilation has a certain effect of lowering radon concentration, especially at the air supply point. But with the airflow outwards along the tunnel, and the continuous diffusion and seepage of radon in surrounding rocks, the radon concentration at tunnel mouth is higher when the tunnel is longer. If the tunnel is longer than 1km, the ideal radon reduction effect can be hardly achieved using general pressure-in ventilation.
(2) The effect of lowering radon concentration is more ideal under closed ventilation tunnel mouth. And radon concentration in the entire tunnel could be less than 400Bq/m³ under this ventilation condition. The main principle of this radon reduction method is to apply micro-positive pressure to the tunnel, so that the radon inside tunnel enter the mountain through seepage along the crack. Under the micro-positive pressure, fresh air entering the tunnel continuously carries radon into the mountain, and finally realizes the goal of radon concentration control.

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