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GAS-DYNAMIC PROCESSES AFFECTING COAL MINE RADON HAZARD

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The paper focuses on vertical migration of radon in surrounding rocks described by Fick's first law as well as by the continuity equation for diffusion flow, with allowance for sorption and radioactive decay processes. Taking into account special characteristics of vertical radon diffusion, the process can be considered stable. It is demonstrated that for productive areas it is feasible to consider one-dimensional convective diffusion, as diffusive transport of radon by the air of productive areas occurs at steady-state conditions. Normally the factor of radon emissions prevails if atmospheric pressure is constant. Amount of air, calculated using this factor, by 20-30 % exceeds the one needed to dilute carbon dioxide to maximum allowed concentration (MAC).

***Key words*:** radon, Knudsen diffusion, mineral rocks, sorption, radioactive decay, convective-turbulent diffusion, air amount, mathematical model

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Physical model and mathematical description of radon migration in overworked rock mass. Calculation model of radon vertical migration from uranium body to the mine working is presented in Fig.1 In accordance with Fick's law, diffusion flow from radon source can be described as follows:

$$\vec{j}_{\mathrm{Rn}} = -D_{\mathrm{Rn}}\ \mathrm{grad}[C_{\mathrm{Rn}}(z,t)]\ , \tag{1}$$

where $\vec{j}_{\mathrm{Rn}}$ – vector of filtration rate; D_{Rn} – coefficient of effective radon diffusion; C_{Rn} – radon concentration in the rock mass situated above uranium body.

Consider a random rock volume V, limited by outer surface F, containing radon. Amount of radon passing through surface F can be calculated as follows:

$$-\oiint_F \vec{j}_{\mathrm{Rn}}\, dF\ . \tag{2}$$

Then a change in radon mass in volume V per time unit will be:

$$\frac{\partial}{\partial t}\iiint_V (M+q)dV, \tag{3}$$

where M, q – masses of non-associated and fixed radon per unit of rock volume.

Mass conservation law implies that:

$$-\oiint_F \vec{j}_{\mathrm{Rn}}\, dF + \iiint_V \frac{\partial}{\partial t}(M+q)dV = 0\ . \tag{4}$$

Transforming the first component of equation (4) using Ostrogradsky-Gauss theorem, the following result is obtained:

$$-\iiint_V \mathrm{div}(\vec{j}_{\mathrm{Rn}})dV + \iiint_V \frac{\partial}{\partial t}(M+q)dV = 0\ . \tag{5}$$

As volume V has been chosen randomly, condition (5) is fulfilled, among other things, when the sum of integration elements equals zero. Then the equation of mass balance for gas diffusion in porous sorbent media can be expressed as follows [3,4]:

$$\frac{\partial M}{\partial t} + \frac{\partial q}{\partial t} = \mathrm{div}\{D_{\mathrm{Rn}}\ \mathrm{grad}[C_{\mathrm{Rn}}(z,t)]\}\ . \tag{6}$$

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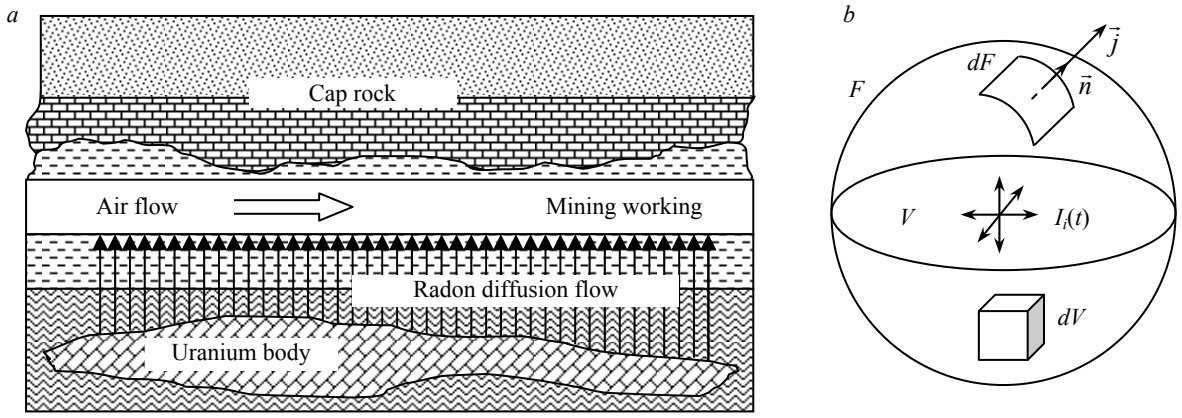


Fig.1. Calculation model of radon vertical migration from uranium body to the mining working: *a* – radon diffusion from the underworked uranium body to the mining working; *b* – calculation model to mathematical description of radon diffusion transport

The second equation that characterizes radon transport in cap rocks is kinetic equation of gas interaction with the solid phase. The key process of gas interaction with the solid phase is sorption [5,10]. Generally the process rate depends on the amount of fixed radon in the gas flow, diffusion coefficient and gas flow velocity. Implicitly this relation can be expressed as follows:

$$\frac{\partial q}{\partial t} = f\left[M\left(C_{\mathrm{Rn}}\right), q\left(C_{\mathrm{Rn}}\right), \vec{V}\left(C_{\mathrm{Rn}}\right), D_{\mathrm{Rn}}\right]. \tag{7}$$

Expression (7) implies that sorption rate is defined both by sorbing characteristics of the rock and external impact, changing diffusion resistance of the solid phase and influencing the intensity of diffusion gas flow. Gas state equation is presented below:

$$\rho = f\left(C_{\mathrm{Rn}}\right). \tag{8}$$

A complex closed set of equations (1)-(8) can be simplified without any significant distortions to the physical model of radon transport in porous media. Experimental research of kinetic gas sorption show that the rate of the process is defined by solid phase diffusion to the gas flow. In this case two situations are possible [1,7]:

• desorption rate is limited by radon diffusion to the walls of micro pores (process at microdiffusion level);

• desorption rate is limited by intensity of gas drain from macro pores (process at outer-diffusion level).

Equation of diffusion kinetics of desorption is given as follows:

$$\frac{\partial q}{\partial t} = \beta_{\mathrm{Rn}}\left[M\left(C_{\mathrm{Rn}}\right) - q'\left(C_{\mathrm{Rn}}\right)\right], \tag{9}$$

where β_{Rn} – constant of diffusion rate; $q'(C_{\mathrm{Rn}})$ – mass of fixed gas corresponding to equilibrium value at given radon concentration C_{Rn}.

Values $M(C_{\mathrm{Rn}})$, $q'(C_{\mathrm{Rn}})$ can explicitly be defined as follows:

$$M\left(C_{\mathrm{Rn}}\right) = m\rho\left(C_{\mathrm{Rn}}\right) = m\rho_{\mathrm{Rn}|_0}\left(\frac{C_{\mathrm{Rn}}}{C_{\mathrm{Rn}|_0}}\right)^{1/n};$$

$$q'\left(C_{\mathrm{Rn}}\right) = \frac{abC_{\mathrm{Rn}}}{1 + aC_{\mathrm{Rn}}},$$

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where m – average porosity of the rock mass; $C_{\mathrm{Rn}|_0}$, $\rho_{\mathrm{Rn}|_0}$ – respectively, initial concentration and density of radon; a, b – experimental constants of Langmuir isotherm; n – polytropic coefficient (at $n = 1$ an isotherm; at $n = 1.41$ an adiabat).

Values of diffusion rate constant β_{Rn} will be different for processes at outer- and inner-diffusion levels. If the process takes place at a mixed diffusion level, then:

$$\frac{1}{\beta_{\mathrm{Rn}}} \approx \frac{1}{\beta_{\mathrm{Rn1}}} + \frac{1}{\beta_{\mathrm{Rn2}}},$$

where β_{Rn1}, β_{Rn2} – constants of outer- and intra-diffusion levels, respectively.

Introduce potential Leibenson function of pressure:

$$\vec{C} = \int_0^p \rho(C_{\mathrm{Rn}}) dC_{\mathrm{Rn}} = \lambda c C_{\mathrm{Rn}}^{1+1/n}, \tag{10}$$

where $\lambda = n/(n+1); c = \rho_{\mathrm{Rn}|_0} \Big/ C_{\mathrm{Rn}|_0}^{1/n}$.

Taking into account expression (10), the rate of change in non-associated radon mass in micro pores can be defined as follows:

$$\frac{\partial M(C_{\mathrm{Rn}})}{\partial t} = m \frac{\partial \rho(C_{\mathrm{Rn}})}{\partial t} = m \frac{d\rho}{dC_{\mathrm{Rn}}} \frac{\partial C_{\mathrm{Rn}}}{\partial t} = \frac{m \rho_{\mathrm{Rn}|_0}}{C_{\mathrm{Rn}|_0}} \frac{\partial C_{\mathrm{Rn}}}{\partial t}.$$

Consider diffusion characteristics of the rock constant and radon motion in surrounding rocks vertical, then set of equations (6)-(9) can be reduced to a differential equation:

$$\frac{\partial^2 C_{\mathrm{Rn}}}{\partial z^2} = \frac{1}{\rho} \frac{d\rho}{dC_{\mathrm{Rn}}} + \frac{\partial q}{\partial t}. \tag{11}$$

Mathematical description (11) should be adapted to specific physical conditions. Thus mathematical models can be obtained for the assessment of radon intake in production and development workings.

Radon migration in overworked rock mass. Vertical radon distribution in surrounding rocks in view of continuity equation for radon diffusion flow and Fick's first law can be written as:

$$\frac{\partial M}{\partial t} + \frac{\partial q}{\partial t} = \mathrm{div}\{D_{\mathrm{Rn}} \, \mathrm{grad}[C_{\mathrm{Rn}}(z,t)]\}. \tag{12}$$

Adapting equation (12) to real conditions of vertical diffusion in overworked rock mass, the following expression can be obtained:

$$\frac{\partial C_{\mathrm{Rn}}}{\partial t} = D_{\mathrm{Rn}} \frac{\partial^2 C_{\mathrm{Rn}}}{\partial z^2} - \lambda_{\mathrm{Rn}} C_{\mathrm{Rn}} + I_{\mathrm{Rn}}, \tag{13}$$

where λ_{Rn} – effective constant of sorption and radioactive decay rates; I_{Rn} – intensity of radon generation source due to uranium radioactive decay.

Taking into account specific characteristics of radon vertical diffusion, this process can be considered stable. Then a transition to specific activity of gas mixtures allows to write equation (17) as follows:

$$D_{\mathrm{Rn}} \frac{d^2 A_{\mathrm{Rn}}^{\mathrm{s.r.}}}{dz^2} - \lambda_{\mathrm{Rn}} A_{\mathrm{Rn}}^{\mathrm{s.r.}} = 0,$$

where $A_{\mathrm{Rn}}^{\mathrm{s.r.}}$ – specific radon activity of the gas mixture in surrounding rocks.

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Boundary conditions for vertical migration are presented below:

$$-D_{\mathrm{Rn}}\left.\frac{dA_{\mathrm{Rn}}^{\mathrm{s.r.}}}{dz}\right|_{z=0} = J_{\mathrm{Rn}}^{\mathrm{s.r.}} = \mathrm{const}\,,\ \lim_{z\to\infty} A_{\mathrm{Rn}} \neq \infty\,,$$

where $J_{\mathrm{Rn}}^{\mathrm{s.r.}}$ – intensity of radon generation in underworked uranium deposit.

Solution to equation (3) for conditions (4) can be written as follows:

$$A_{\mathrm{Rn}}^{\mathrm{s.r.}}(z) = \frac{0.5J_{\mathrm{Rn}}^{\mathrm{s.r.}}}{\sqrt{D_{\mathrm{Rn}}\lambda_{\mathrm{Rn}}}}\exp\left(-z\sqrt{\frac{\lambda_{\mathrm{Rn}}}{D_{\mathrm{Rn}}}}\right).$$

Differentiating expression (5) at point $z = h$, where h – distance from uranium body to the floor of mine working in question, it is possible to find absolute radon emissions from underworked rock mass:

$$I_{\mathrm{Rn}}^{\mathrm{s.r.}} = J_{\mathrm{Rn}}^{\mathrm{s.r.}}\exp\left(-h\sqrt{\frac{\lambda_{\mathrm{Rn}}}{D_{\mathrm{Rn}}}}\right).$$

Software program RnVP has been developed in order to carry out simulation experiments using standard package MATHEMATICA 2.2. Plots of dependence between $I_{\mathrm{Rn}}^{\mathrm{s.r.}} / J_{\mathrm{Rn}}^{\mathrm{s.r.}}$ and distance h for different values of $\sqrt{\lambda_{\mathrm{Rn}} / D_{\mathrm{Rn}}}$ are presented in Fig.2. Analysis of profiles of radon diffusion flow in surrounding rocks reveals high rates of reduction in radon migration speed in case of decreasing coefficient of effective diffusion. Evidently, such modeling results are in good agreement with in-situ data on other gases, e.g. methane coming from underworked coal seams [2, 6, 8, 9].

In current situation indirect proof of the validity of mathematical model can be accepted, as up to this day there is no empirical database necessary for further investigation. This being said, modeling results demonstrate that absolute volume of radon in the rock mass is proportional to intensity of radon generation in the underworked uranium deposit.

This value has a physical significance of radon diffusion flow on the contact between overworked uranium lens and overworked rock mass. As a result, intensity of radon generation in the underworked uranium deposit can be one of the most important parameters of geophysical research for industrial coal seams in Moscow basin. Thus, new mathematical models of gas emissions can broaden the scope of problems that are being solved by geophysical research. Certainly, without simultaneous solution to these problems no reliable forecast can be made regarding the hazardousness of any gas, and in this case it refers to radon.

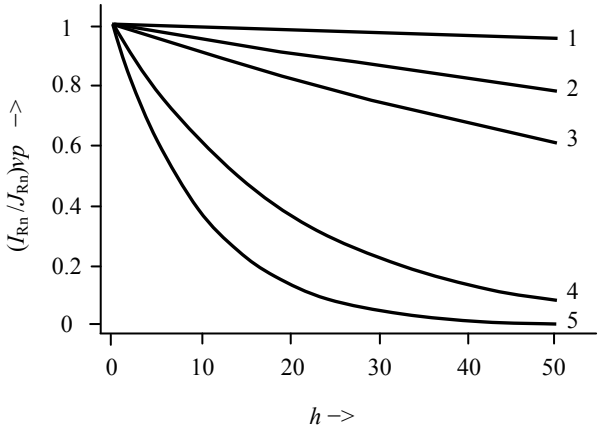


Fig.2. Plot of dependence between $I_{\mathrm{Rn}}^{\mathrm{s.r.}} / J_{\mathrm{Rn}}^{\mathrm{s.r.}}$ and distance h in meters.
Values of $\sqrt{\lambda_{\mathrm{Rn}} / D_{\mathrm{Rn}}}$ equal, respectively:
1 – 0.001; 2 – 0.005; 3 – 0.01; 4 – 0.05; 5 – 0.1

Radon transport in productive workings and calculation of air amount using radon factor. Diffusion transport of radon by the air in productive workings is a stable process. Considering ratio of cross-section area and total length of mine workings, the closest match is one-dimensional convective diffusion. In production workings (Fig.3) average air velocity is high enough to neglect turbulent diffusion; thus in general terms non-stationary convective diffusion of radon in production workings can be described by one-dimensional hyperbolic equation

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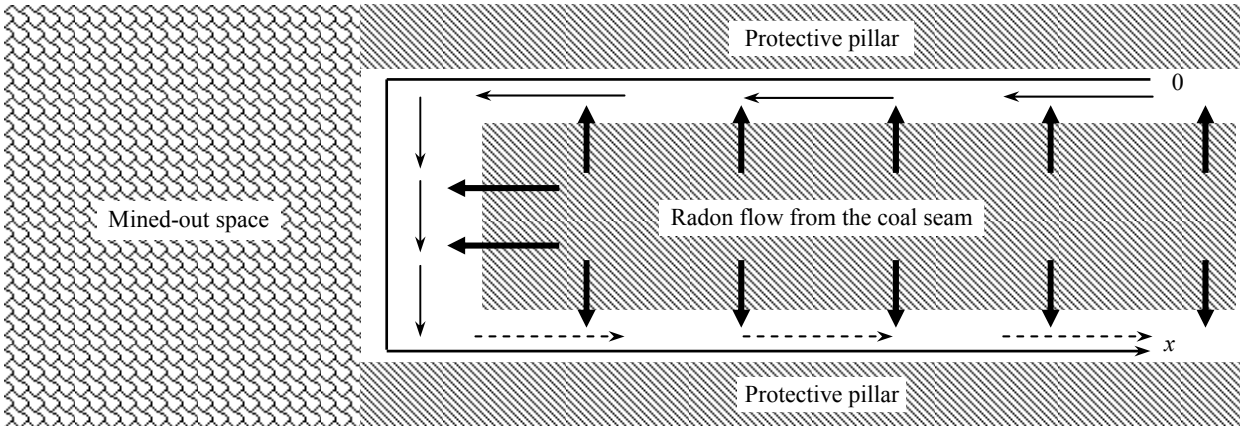


Fig.3. Calculation model of radon transport in production workings

$$\frac{\partial A_{\mathrm{Rn}}}{\partial t} + u_{\mathrm{p.w.}} \frac{\partial A_{\mathrm{Rn}}}{\partial x} = -\lambda_{\mathrm{Rn}} A_{\mathrm{Rn}} + \left(\Sigma I_{\mathrm{Rn}}\right)_{\mathrm{p.w.}}, \tag{14}$$

where $u_{\mathrm{p.w.}}$ – average velocity of air in production workings; $\left(\Sigma I_{\mathrm{Rn}}\right)_{\mathrm{p.w.}}$ – total radon emissions into production workings from different sources.

Adapting equation (14) to real physical conditions, radon transport in production workings can be formulated as follows:

$$u_{\mathrm{p.w.}} \frac{dA_{\mathrm{Rn}}}{dx} = -\lambda_{\mathrm{Rn}} A_{\mathrm{Rn}} + \left(\Sigma I_{\mathrm{Rn}}\right)_{\mathrm{p.w.}}. \tag{15}$$

Boundary conditions for production workings are expressed as follows:

$$A_{\mathrm{Rn}}(0) = 0\,;\ A_{\mathrm{Rn}}(x) = A_{\mathrm{Rn}}\,. \tag{16}$$

Solution of equation (15) for conditions (16) is presented below:

$$A_{\mathrm{Rn}}(x) = \frac{\left(\Sigma I_{\mathrm{Rn}}\right)_{\mathrm{p.w.}}}{\lambda_{\mathrm{Rn}}} \left[1 - \exp\left(-\frac{\lambda_{\mathrm{Rn}}}{u_{\mathrm{p.w.}}} x\right)\right]. \tag{17}$$

A software program ARnOU has been developed to carry out simulation experiments using standard package MATHEMATICA 2.2. Results of simulations are presented in Fig.4 as plots of dependence between $\vec{A}_{\mathrm{Rn}} = A_{\mathrm{Rn}}(x)/A_{\mathrm{Rn}\infty}$ and x coordinate, where $A_{\mathrm{Rn}\infty} = \left(\Sigma I_{\mathrm{Rn}}\right)_{\mathrm{p.w.}}/\lambda_{\mathrm{Rn}}$; $\vec{A}_{\mathrm{Rn}} = \lambda_{\mathrm{Rn}} A_{\mathrm{Rn}}(x)/\left(\Sigma I_{\mathrm{Rn}}\right)_{\mathrm{p.w.}}$. Simulation experiments have been carried out for different values of $\omega = \lambda_{Rn}/u_{\mathrm{p.w.}}$.

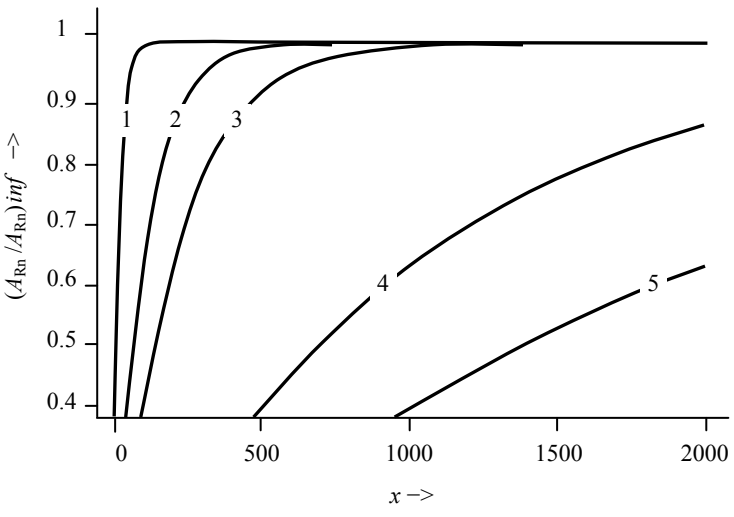


Fig.4. Plot of dependence between $\vec{A}_{\mathrm{Rn}}$ and x coordinate in meters for productive workings.
Value of ω, 1/m: 1 – $5\cdot10^{-2}$; 2 – 10^{-2}; 3 – $5\cdot10^{-3}$; 4 – 10^{-3}; 5 – $5\cdot10^{-4}$

Analysis of simulation experiment results shows that in case of great x values specific radon activity of the air tends to asymptotic value of $A_{\mathrm{Rn}\infty}$. Specific activ-

ity of air in production workings depends on absolute radon emissions, rate of radon's radioactive decay, average air velocity and coefficient of turbulent diffusion. Thus, relation (17) can be used to calculate amount of air needed in the production working from the viewpoint of radon emissions.

Relation (17) allows to calculate the amount of air with a dynamic method, in accordance with which average radon concentration for the unit of working's cross-section area should not exceed MAC_{Rn}. The result of solving equation (17) for $A_{Rn}(x) = MAC$ respectively when $x = (\Sigma L)_{p.w.}$ relative to average air velocity and making a transition to airflow rate is presented below and can be used to estimate air amount from the viewpont of radon emissions:

$$Q_{Rn}^{prod} = \lambda_{Rn}(\Sigma L)_{p.w.} S_e \Big/ \ln\left|\frac{(\Sigma I_{Rn})_{p.w.}}{(\Sigma I_{Rn})_{p.w.} - \lambda_{Rn} MAC_{Rn}}\right|,$$

where Q_{Rn}^{prod} – amount of air needed in the production working for radon concentration in the outcoming stream to stay below MAC_{Rn}; $(\Sigma L)_{p.w.}$ – total design length of extraction galleries and longwalls; S_e –cross-section area of production workings, equivalent in air supply.

Calculations of air amounts needed for production workings of Moscow basin mines

№	Combination of parameters	Calculated volume of carbon dioxide (CO_2), m^3/min		Calculated air amount, m^3/min	
		Average production area	Production area with optimal parameters	based on carbon dioxide volume	based on radon factor
1	Maximum	0.85	1.00	201-260	274
2	Minimum	0.10	0.24	36-86	156
3	Average	0.63	0.74	189-222	231

Data presented in the table clearly shows that both for average production area and for production area with optimal parameters radon factor plays a major role. Notably, this can be the case not only for Moscow basin. Radon emissions can be central to air amount calculations to Kuznetsk and East Donetsk basins as well.

Developed mathematical models of radon emissions and air amount calculations have served as a basis for algorithms and a software complex aimed at automation of solving engineering problems when using cutting-edge methods to forecast gas emissions in coal mine workings and to calculate air amounts needed for ventilation of production and development areas. Simulation experiments have been carried out for average mining, geological and technological conditions of mines with high CO_2-concentration. Their results show that normally, under steady atmospheric pressure, radon factor plays a key role in air amount calculations. This being said, air amounts based on radon emission factor by 20-30 % exceed amounts of air needed to dilute CO_2 below maximum allowance concentration.

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