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Numerical modeling of the distribution of radionuclides in porous media for strong damage to underground nuclear power station

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Abstract

The distribution of radionuclides in the ground during the hypothetical serious damage to an underground nuclear power station is considered. A set of filtration gas equations and convective diffusion equations are used to describe the transport of radionuclides. Processes of nuclear decay and nonequilibrium adsorption are taken into account. The results of mathematical modeling of the distribution of 90 and 137 isobaric radionuclide chains, and zones of probable pollution of the environment by these radionuclides, are presented.

1. Introduction

The actual problem of nuclear power at the moment is the creation of a safe nuclear power station. One of the possible ways to overcome this problem is to create an underground nuclear power station, where the radionuclides can be located in the environmental media near to station's site, in case of serious damage.

The purpose of this work is to estimate the probable radioactive pollution to the environmental porous media during serious damage to an underground nuclear power station.

The study of distribution of radionuclides in porous media was carried out in a number of studies [1–5]. The one-dimensional problem of distribution of an isobaric radionuclide chain in porous media under the influence of pressure of products from an underground explosion was solved by Basanskii et al. [1]. The numerical solution of the two-dimensional problem of distribution of radionuclides without nuclear decay was given in Ref. [2]. The solution to the problem of ground pollution by radionuclides during serious damage to an underground nuclear power station was presented in Ref. [3] which took into account gas filtration and nuclear decay processes. However, the processes of adsorption and the influence of convective diffusion was not taken into account in this work. The analytical solutions of the one-dimensional problems of the movement of radioactive gas transported in half-infinite porous media by a flow of the inert gas-carrier with constant velocity are presented in Refs. [4,5]. Later we considered the transport of radionuclide chains in porous media after serious damage to an underground atomic pile, taking advantage of all the above listed processes.

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Nomenclature

P	pressure of gas mix
$\vec{u}$	velocity of gas mix movement
$\vec{r}$	coordinate vector
r	radial component of coordinate vector
z	axial component of coordinate vector
t	time
m	porosity of medium
k	permeability of porous medium
A	constant equal sound velocity in degree two
N	number of radionuclides
c	concentration of radionuclide in the gas flow
a	amount of adsorbed radionuclide in unit of volume of porous media
D	coefficient of convective diffusion
D_0	coefficient of molecular diffusion
d	the middle diameter of grains of porous medium
E	the sinuosity coefficient for the medium
n	coefficient depending on character of porous medium
t_0	characteristic time of process
k_0	characteristic value of permeability of porous medium
u_0	characteristic value of velocity of flowing gas mix
$P_{i,j}$	grid function of pressure of gas mix
$u_{i,j}$	grid function of velocity of gas mix movement
$C_{i,j}$	grid function of concentration of radionuclide in flowing gas
$A_{i,j}$	grid function of amount of adsorbed radionuclide in unit of volume of porous media
T	calculation time
z_i	grid analog of axial component of coordinate vector
r_j	grid analog of radial component of coordinate vector
h	grid step at spatial coordinate
S_0	surface of damage part of containment
Q	integrated flow [relative mass unit/sec]
W	total mass output [relative mass unit]

Greek symbols

ρ	density of gas mix
μ	average viscosity of a gas mix
γ	reciprocal of the Henry isotherm
λ	constant of nuclear decay
β	kinetic coefficient of adsorption of radionuclide
φ	coefficient that depend on character of porous medium (9)
η	kinematic viscosity of gas mix
$\chi_{i,j}$	grid function defined in (22)
$\beta_{i,j}$	grid function of kinetic coefficient of adsorption
$\Omega_{i,j}$	grid function of coefficient of convective diffusion
τ	time step

Subscripts

k	serial number of radionuclide at mass chain
r	radial component
z	axial component
i	index of grid function (axial direction)
j	index of grid function (radial direction)

2. Formulation of a problem

Let us formulate the physico-mathematical model for the description of the ground pollution process by the products of radioactive transformations formed during serious damage to an underground nuclear power station. We assume that the pressure of gas mix $P_1 > P_0$ (P_0 is the gas mix pressure in the porous media at the initial time) was formed at the initial moment of time in the cylindrical area which appropriate to the form of pile. This problem can be considered in the cylindrical system of coordinates (r, z) where the axis $r=0$ coincides with an axis of station. We take the environmental media as porous media with given properties of permeability k and porosity m.

The following set of equations describe the movement of a gas mix in porous media and consists of the continuity equation, the movement equation and the state of gas equation [2].

$$m\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho \vec{u}) = 0 \tag{1}$$

$$\vec{u} = -\frac{k}{\mu}\operatorname{grad} P \tag{2}$$

$$P = A\rho \tag{3}$$

Here $\rho(\vec{r}, t)$ is the density of a gas mix, $\vec{u}(\vec{r}, t)$ is the vector of velocity of a movement, $P(\vec{r}, t)$ is the gas pressure, m is the porosity of media, k is the permeability, and μ is the average viscosity of a gas mix.

It is accepted in Eqs. (1)–(3) that the movement of gas in porous media submits to Darcy's law.

Eqs. (1)–(3) take the form:

$$m\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\rho u_r) + \frac{\partial}{\partial z}(\rho u_z) = 0, \quad P = A\rho \tag{4}$$

$$u_r = -\frac{k}{\mu}\frac{\partial P}{\partial r}, \quad u_z = -\frac{k}{\mu}\frac{\partial P}{\partial z} \tag{5}$$

in the cylindrical system of coordinates.

This set of equations can be written down as:

$$m\frac{\partial P}{\partial t} = \frac{A}{\mu}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(rkP\frac{\partial P}{\partial r}\right) + \frac{\partial}{\partial z}\left(kP\frac{\partial P}{\partial z}\right)\right], \quad k = k_0 f(r, z) \tag{6}$$

The gas mix that was formed in containment contains radioactive isotopes which were transferred to the environmental media at a further distribution of gas. The distribution of radionuclides belonging to the same isobaric chain, at the transfer by gas in the porous media in account of diffusion processes, adsorption processes and nuclear decay, is described by the following set of the equations [1]:

$$\begin{aligned} m\frac{\partial c_k}{\partial t} + \frac{\partial a_k}{\partial t} &= \frac{1}{r}\frac{\partial}{\partial r}\left(rD_{k,r}\frac{\partial c_k}{\partial r} - ru_r c_k\right) \\ &+ \frac{\partial}{\partial z}\left(D_{k,z}\frac{\partial c_k}{\partial z} - u_z c_k\right) - \lambda_k m c_k + \lambda_{k-1} m c_{k-1} \\ &- \lambda_k a_k + \lambda_{k-1} a_{k-1} \end{aligned} \tag{7}$$

$$\frac{\partial a_k}{\partial t} = \beta_k(mc_k - \gamma_k a_k) + \lambda_{k-1}a_{k-1} - \lambda_k a_k, \quad k = 1, \ldots, N \tag{8}$$

where $c_k(r, z, t)$ is the concentration of kth radionuclide at flow, $a_k(r, z, t)$ is the amount of kth adsorbed radionuclide in a unit of volume of the porous media, D_{kr} and D_{kz} are components of the coefficient of convective diffusion, $\vec{u}(\vec{r}, t)$ is the velocity of a flowing gas, λ_k is the coefficient of nuclear decay for kth radionuclide, N is the number of radionuclides in the mass chain, β_k is the kinetic coefficient of mass transfer for kth radionuclide, and γ_k is the reciprocal of the Henry isotherm kth radionuclide. It is accepted that $\lambda_0 \equiv 0$ and $\lambda_N \equiv 0$ in Eqs. (7) and (8). (At first the radionuclide of the isobaric chain is not present and the last radionuclide in the chain is not decayed.)

The coefficient of convective diffusion depends on the velocity of filtered gas and the properties of the porous media. The dependence of coefficient of convective diffusion from properties of media is presented by the following formulae:

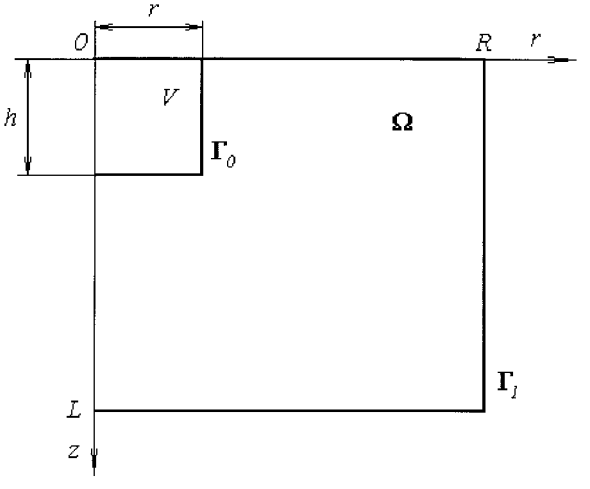


Fig. 1. Area of calculation for the problem.

Table 1
Parameters of radionuclides

Mass number of a chain	Radionuclide	Initial concentration in containment (relative mass unit/m^3)	Constant of nuclear decay (λ,1/sec)	The reciprocal of the Henry isotherm (γ)	Coefficient of molecular diffusion, (m^2/sec) $\times 10^{-4}$
137	I_2	1	0.028	0.5	0.069
	Xe	0.51	0.003	0.1	0.048
	Cs	0.03	0.0	0.9	0.76
90	Kr	1	0.021	0.1	0.05
	Rb	0.24	0.004	0.8	0.5
	Sr	0.02	0.0	0.9	0.7

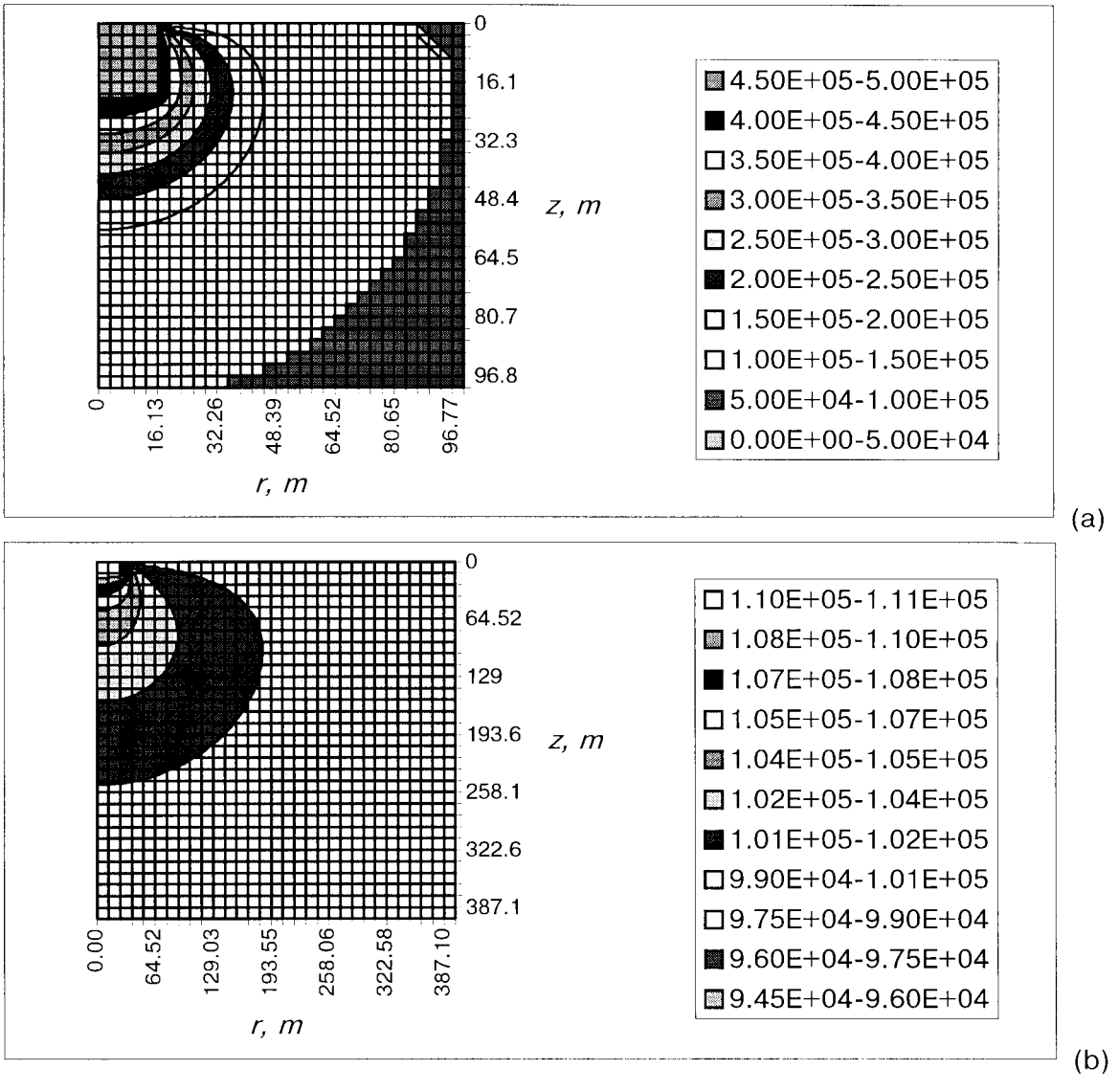
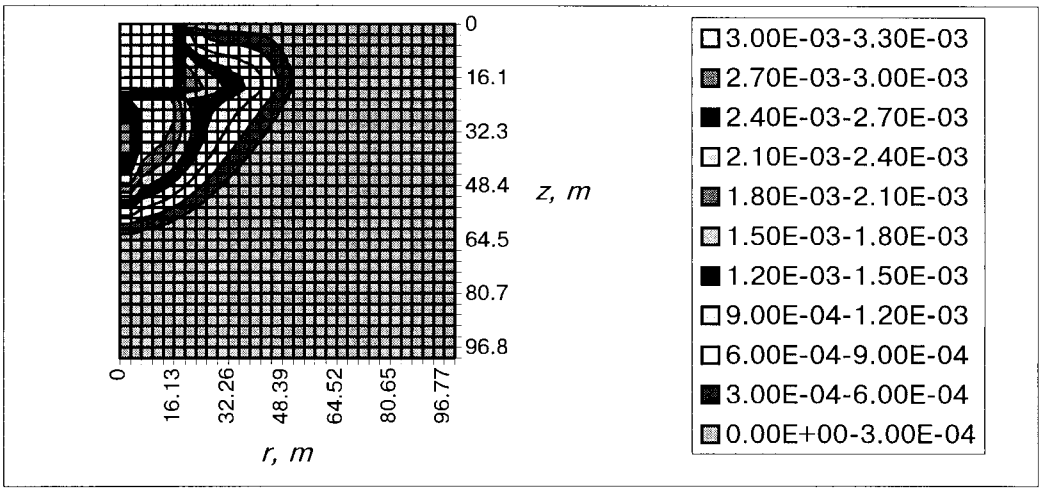
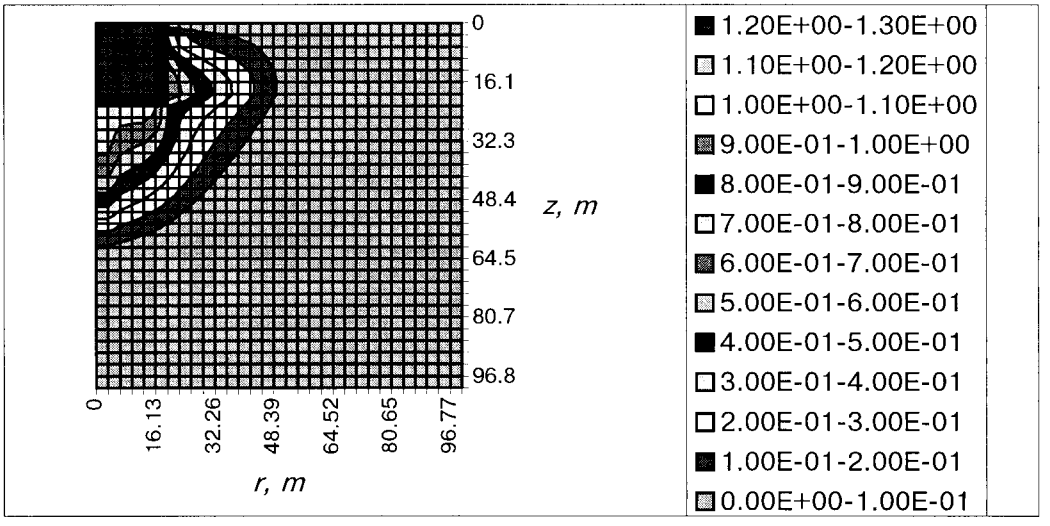


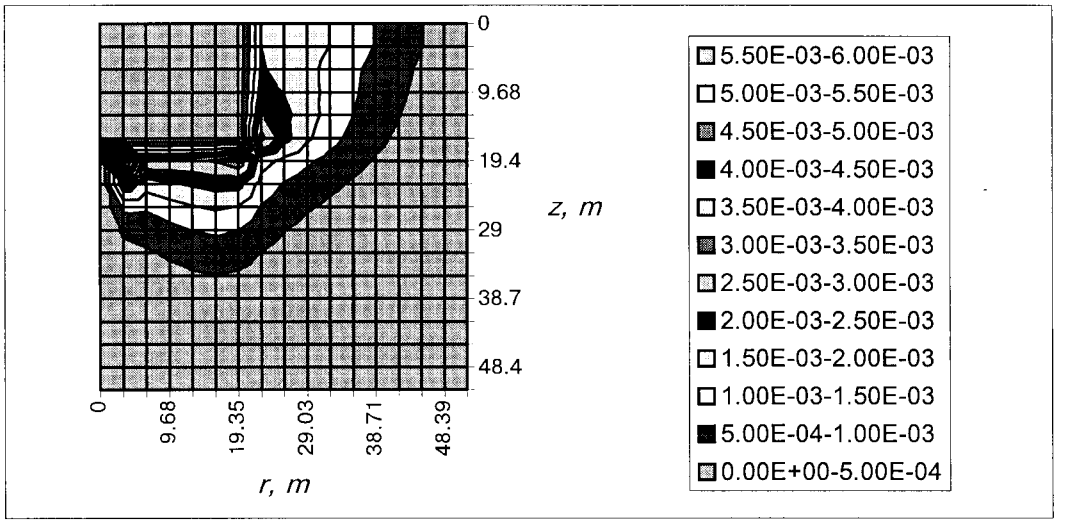
Fig. 2. Distribution of gas pressure through (a) 30 min and (b) 20 h after damage of pile.



(a)



(b)



(c)

Fig. 3. Distribution of concentration of radionuclides at the moment of time 30 min: (a) Xe-137, (b) Cs-137, (c) in the flow and adsorbed Cs-137.

$$D_{k,r}(r, z, t) = D_{0_k}[E^{-1} + \varphi(u_r D_{0_k}^{-1} d)^n],$$
$$D_{k,z}(r, z, t) = D_{0_k}[E^{-1} + \varphi(u_z D_{0_k}^{-1} d)^n] \quad (9)$$

if we assume the media similar and isotropic [6], where D_{0_k} is the coefficient of the molecular diffusion for the kth radionuclide, d is the middle diameter of grains of porous medium, E is the sinuosity coefficient for the medium, and φ and n are the coefficients that depend on the character of the porous medium.

The calculation of the kinetic coefficient we used experimentally received dependence [1]

$$\beta_k = 0.1 u D_{0_k} (\eta d)^{-1} \quad (10)$$

where η is the kinematic viscosity of gas.

The model of the transfer of radionuclides that results from the set of Eqs. (7) and (8) allows us to take into account both radionuclides being in a flow and radionuclides which are not transferred but adsorbed in ground. Considering the coefficients β_k and γ_k as factors describing the heat and the mass transfer of kth radionuclide between the gas and condensed phase it is possible to use Eqs. (7) and (8) together with the boundary and initial conditions for the environment pollution model.

We assume that the expiration of gas occurs from a part of the cylindrical surface S_0, and give below the appropriate boundary conditions of a problem.

The area of calculation and borders for the problem of distribution of a gas mix and radionuclides in the porous media are submitted in Fig. 1.

Here Ω is the area of calculation where the process of gas distribution is simulated, Γ_0 is the surface of containment, V is the reactor area where the pressure is increased as a result of serious damage, and Γ_1 is the external border of calculation area.

Owing to the cylindrical symmetry of a problem we carry out the modeling of process only in the area Ω.

We give the initial conditions for the gas pressure as:

$$P(r, z, t = 0) = \begin{cases} P_0,(r, z) \in \Omega \\ P_1,(r, z) \in V \end{cases} \quad (11)$$

The assumption about permanency of pressure P_0 on removed distance from containment was used as the boundary condition at $\vec{r} \in \Gamma_1$ for the problem of the gas distribution in the porous medium.

$$P(\vec{r} \in \Gamma_1, t) = P_0, \quad P(\vec{r} \in \Gamma_0, t) = \varphi(t) \quad (12)$$

We assume that gas pressure on a surface of containment $\varphi(t)$ in conditions (12) changes over time, because of the expiration of gas into the environment. This change is taken into account by the law of mass preservation.

$$\frac{\mathrm{d}\ \ln\ \varphi}{\mathrm{d}t} = -\frac{S_0}{V} u\ |_{\Gamma_0}\ , \quad \varphi(t = 0) = P_1 \quad (13)$$

Here S_0 is the area of a surface of containment through which there is the expiration of gas, and $u\ |_{\Gamma_0}$ is the velocity of the expiration of gas through the surface of a broken part of containment.

There is no radioactive impurity in the porous medium at the initial moment. The concentration of radionuclides is not equal concentration of background

$$c_k(r, z, t = 0) = a_k(r, z, t = 0) = 0 \quad (14)$$

$$c_k(\vec{r} \in \Gamma_0, t) = \phi_k(t), \quad c_k(\vec{r} \in \Gamma_1, t) = 0 \quad (15)$$

where $\phi_k(t)$ is determined from the decision of the ordinary differential equations taking into account outflow of an impurity from an area of pile in view of radioactive transformations

$$\frac{\mathrm{d}\phi_k}{\mathrm{d}t} = -\frac{S_0}{V} u\ |_{\Gamma}\ \phi_k - \lambda_k \phi_k + \lambda_{k-1}\phi_{k-1},$$
$$\phi_k(t = 0) = c_{0_k} \quad (16)$$

where c_{0_k} is the concentration of kth radionuclide in the area of containment at $t = 0$.

3. The method of the decision of problem

Dimensionless variables and parameters are given in Eqs. (5)–(8).

$$P' = \frac{P}{P_1}, \quad r' = \frac{r}{L}, \quad z' = \frac{z}{L}, \quad t' = \frac{t}{t_0},$$

$$t_0 = \frac{m\mu L^2}{k_0 P_1}, \quad u_0 = \frac{k_0 P_1}{\mu L}, \quad u'_r = \frac{u_r}{u_0}, \quad u'_z = \frac{u_z}{u_0},$$

$$\rho_1 = \frac{P_1}{A}, \quad \rho' = \frac{\rho}{\rho_1}, \quad c' = \frac{c}{\rho_1}, \quad a' = \frac{a}{\rho_1},$$

$$k' = \frac{k}{k_0}, \quad \beta' = \frac{\beta m\mu L^2}{k_0 P_1}, \quad \lambda' = \frac{\lambda m\mu L^2}{k_0 P_1},$$
$$D'_r = \frac{D_r t_0}{mL^2}, \quad D'_z = \frac{D_z t_0}{mL^2} \quad (17)$$

One can write down the set of Eqs. (5)–(8) in the dimensionless forms (the primes of the variables are omitted)

$$\frac{\partial P}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(Pkr\frac{\partial P}{\partial r}\right) + \frac{\partial}{\partial z}\left(Pk\frac{\partial P}{\partial z}\right), \quad (18)$$

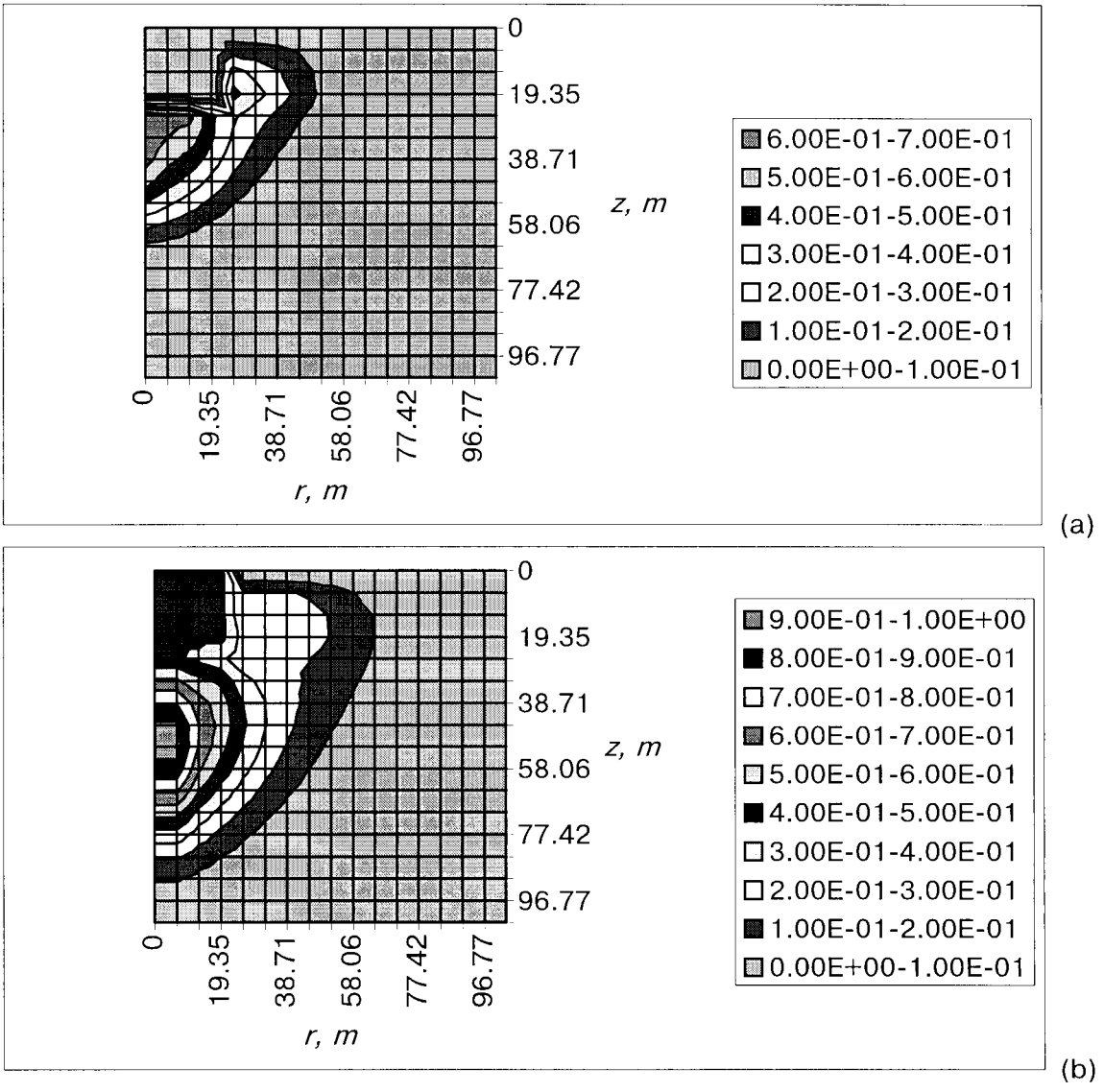


Fig. 4. Distribution of concentration of adsorbed (a) Cs-137, (b) Cs-137 in the flow at the moment of time 4 h.

$$u_r = -\frac{\partial P}{\partial r}, \quad u_z = -\frac{\partial P}{\partial z} \tag{19}$$

$$\frac{\partial c_k}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD_{k,r}\frac{\partial c_k}{\partial r}\right) + \frac{\partial}{\partial z}\left(D_{k,z}\frac{\partial c_k}{\partial z}\right) - \frac{1}{r}\frac{\partial}{\partial r}(ru_r c_k) - \frac{\partial}{\partial z}(u_z c_k) - c_k(\beta_k + \lambda_k) + a_k\frac{\beta_k\gamma_k}{m} + \lambda_{k-1}c_{k-1} \tag{20}$$

$$\frac{\partial a_k}{\partial t} = \beta_k(mc_k - \gamma_k a_k) + \lambda_{k-1}a_{k-1} - \lambda_k a_k, \quad k = 1, \ldots, N \tag{21}$$

The boundary and the initial conditions (11)–(16) are also presented with an account of dimensionless variables.

Solving Eqs. (18)–(21) with conditions (11)–(16) was carried out by the numerical method on an IBM PC. For the numerical realisation of the decisions made in Eqs. (18) and (20) the alternating method with iterations on each temporary step was used [7].

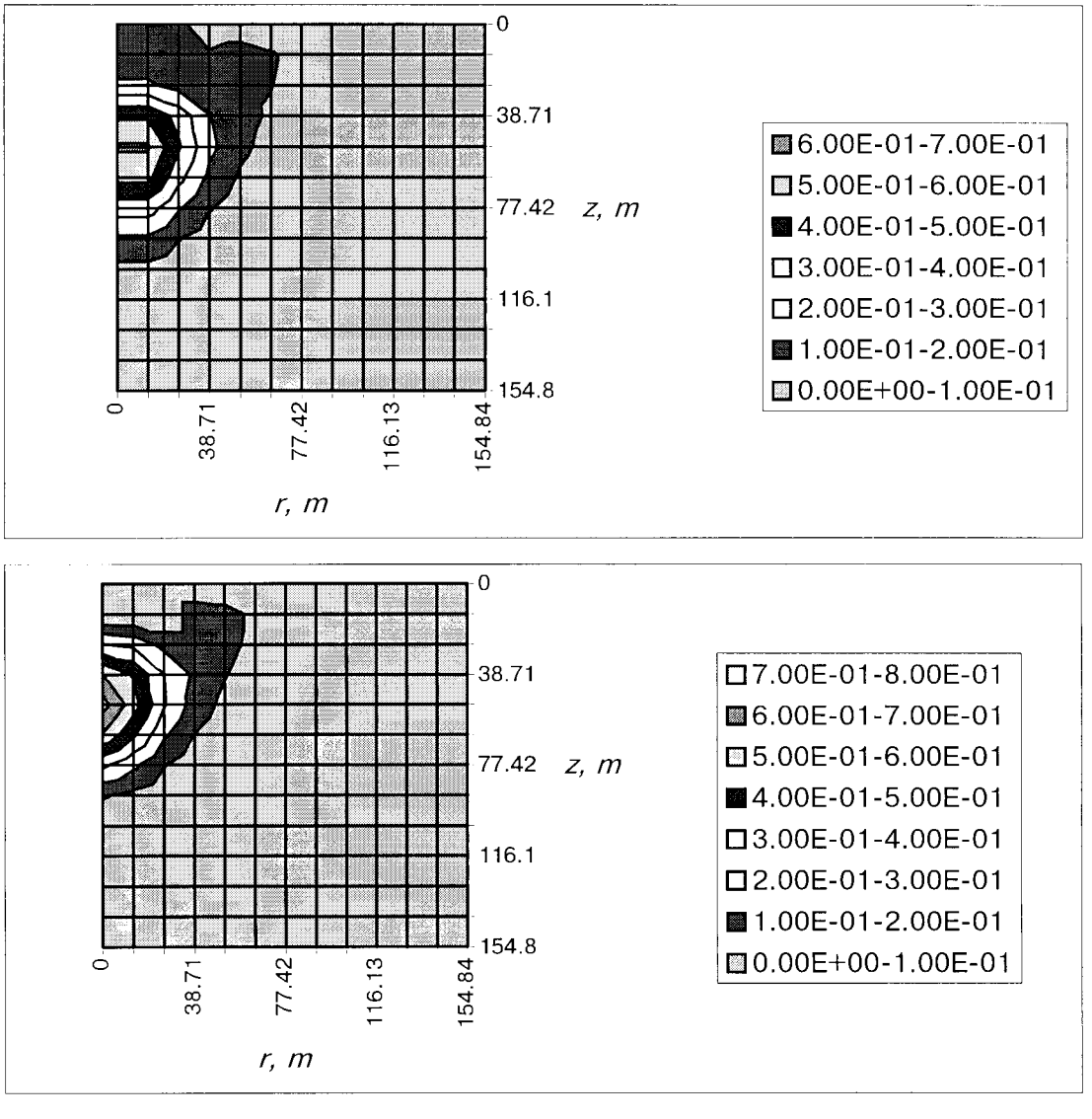


Fig. 5. Distribution of concentration of Sr-90 (a) in the flow and (b) in a adsorbed phase at the moment of time 20 h.

Grid functions are as follows:

$$
\begin{aligned}
&P_{i,j} = P(z_i, r_j, n\tau), \quad u_{\mathrm{r}_{i,j}} = u_{\mathrm{r}}(z_i, r_j, n\tau),\\
&\chi_{i,j} = P(z_i, r_j, n\tau)k(z_i, r_j, n\tau),\\
&C_{k_{i,j}} = c_k(z_i, r_j, n\tau), \quad A_{k_{i,j}} = a_k(z_i, r_j, n\tau),\\
&\beta_{k_{i,j}} = \beta_k(z_i, r_j, n\tau), \quad \Omega_{k,\mathrm{r}_{i,j}} = D_{k,\mathrm{r}}(z_i, r_j, n\tau),\\
&\Omega_{k,z_{i,j}} = D_{k,z}(z_i, r_j, n\tau)
\end{aligned}
\tag{22}
$$

where $i=\overline{1, M}$, $j=\overline{0, J}$, and n is the number of temporary steps up to a fixed moment of time $T=n\tau$. The calculations were carried out on the uniform spatial grid. Therefore,

$$z_i = h_z i, \quad r_j = h_{\mathrm{r}}\ j$$

where h_{r} is the step on coordinate r, and h_z is the step on coordinate z and τ is the step on time.

Thus the differential operators in the set of equations were approximated by the grid operators with accuracy $O(h_{\mathrm{r}}^2+h_z^2+\tau)$. The differential equations which appropriate to Eq. (18) on the first and second temporary half-steps take the forms

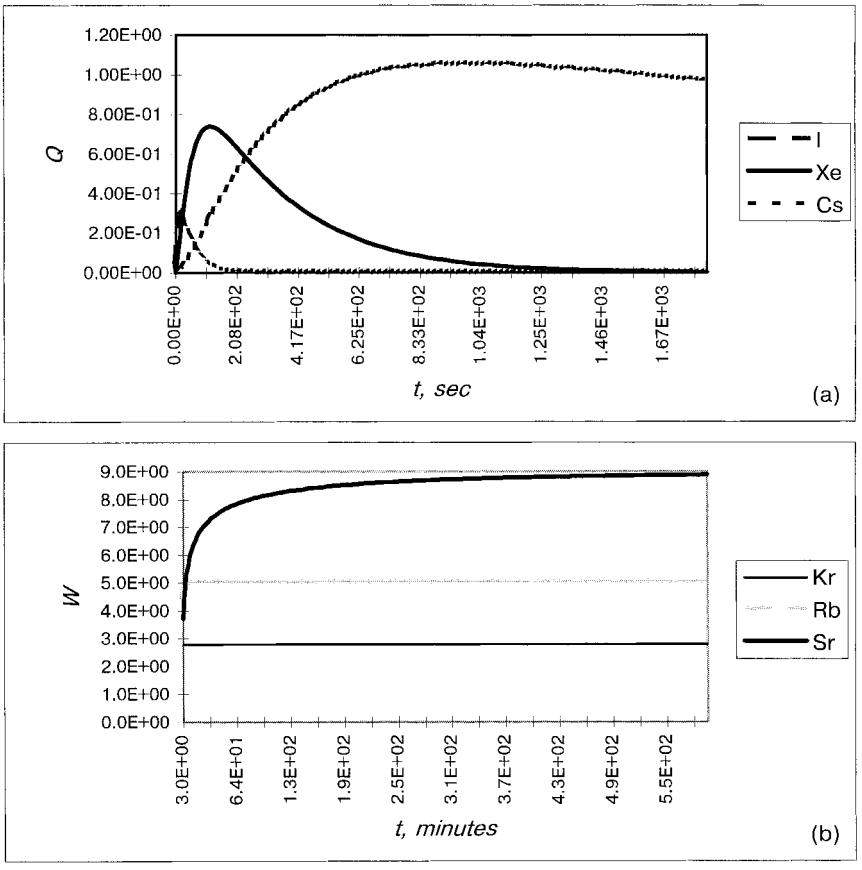


Fig. 6. Dependence for 137th chain of radionuclides of the integrated flow (a) on the surface of ground and (b) logarithmic dependence of a total mass of radionuclides of 90th isobaric chain output in atmosphere in time.

$$\frac{1}{0.5\tau}(\bar{P}_{i,j}-P_{i,j})=\frac{1}{jh_r^2}[(j-\tfrac{1}{2})\bar{\chi}_{i,j-\frac{1}{2}}(\bar{P}_{i,j-1}-\bar{P}_{i,j}) - (j+\tfrac{1}{2})\bar{\chi}_{i,j+\frac{1}{2}}(\bar{P}_{i,j}-\bar{P}_{i,j+1})] + \tfrac{1}{h_z^2}[\chi_{i-\frac{1}{2},j}(P_{i-1,j}-P_{i,j})-\chi_{i+\frac{1}{2},j}(P_{i,j}-P_{i+1,j})] \quad (23)$$

$$\frac{1}{0.5\tau}(\hat{P}_{i,j}-\bar{P}_{i,j})=\frac{1}{jh_r^2}[(j-\tfrac{1}{2})\bar{\chi}_{i,j-\frac{1}{2}}(\bar{P}_{i,j-1}-\bar{P}_{i,j}) - (j+\tfrac{1}{2})\bar{\chi}_{i,j+\frac{1}{2}}(\bar{P}_{i,j}-\bar{P}_{i,j+1})] + \tfrac{1}{h_z^2}[\hat{\chi}_{i-\frac{1}{2},j}(\hat{P}_{i-1,j}-\hat{P}_{i,j})-\hat{\chi}_{i+\frac{1}{2},j}(\hat{P}_{i,j}-\hat{P}_{i+1,j})] \quad (24)$$

The differential equations which appropriate to the Eq. (20) on the first and second temporary half-steps was used as follows:

$$\begin{aligned}\frac{1}{0.5\tau}(\bar{C}_{k_{i,j}}-C_{k_{i,j}}) &= \frac{1}{jh_r^2}[(j-\tfrac{1}{2})\bar{\Omega}_{k,r}{}_{i,j-\frac{1}{2}}(\bar{C}_{k_{i,j-1}}-\bar{C}_{k_{i,j}}) - (j+\tfrac{1}{2})\bar{\Omega}_{k,r}{}_{i,j+\frac{1}{2}}(\bar{C}_{k_{i,j}}-\bar{C}_{k_{i,j+1}})] \\ &+ \tfrac{1}{h_z^2}[\Omega_{k,z}{}_{i-\frac{1}{2},j}(C_{k_{i-1,j}}-C_{k_{i,j}})-\Omega_{k,z}{}_{i+\frac{1}{2},j}(C_{k_{i,j}} - C_{k_{i+1,j}})] - u_{r_{i,j}}\tfrac{1}{2h_r}[\bar{C}_{k_{i,j+1}}-\bar{C}_{i,i,j-1}] - u_{z_{i,j}}\tfrac{1}{h_z} \\ &\begin{cases}[C_{k_{i,j}}-C_{k_{i-1,j}}], & u_{z_{i,j}}\geq 0\\ [C_{k_{i+1,j}}-C_{k_{i,j}}], & u_{z_{i,j}}<0\end{cases} - \bar{C}_{k_{i,j}}(\bar{\beta}_{k_{i,j}}+\lambda_k) \\ &+ A_{k_{i,j}}\frac{\bar{\beta}_{k_{i,j}}\lambda_k}{m}+\lambda_{k-1}C_{k-1_{i,j}} \\ &- \bar{C}_{k_{i,j}}\left[\frac{ju_{r_{i,j}}-(j-1)u_{r_{i,j-1}}}{jh_r}+\frac{u_{z_{i,j}}-u_{z_{i-1,j}}}{h_z}\right]\end{aligned} \quad (25)$$

$$
\begin{aligned}
&\frac{1}{0.5\tau}(\hat{C}_{k_{i,j}} - \bar{C}_{k_{i,j}}) \\
&= \frac{1}{jh_r^2}[(j-\tfrac{1}{2})\bar{\Omega}_{k,r\,i,j-\frac{1}{2}}(\bar{C}_{k_{i,j-1}} - \bar{C}_{k_{i,j}}) \\
&-(j+\tfrac{1}{2})\bar{\Omega}_{k,r\,i,j+\frac{1}{2}}(\bar{C}_{k_{i,j}} - \bar{C}_{k_{i,j+1}})] \\
&+ \tfrac{1}{h_z^2}[\hat{\Omega}_{k,z\,i-\frac{1}{2},j}(\hat{C}_{k_{i-1,j}} - \hat{C}_{k_{i,j}}) - \hat{\Omega}_{k,z\,i+\frac{1}{2},j}(\hat{C}_{k_{i,j}} \\
&- \hat{C}_{k_{i+1,j}})] - u_{r_{i,j}}\tfrac{1}{2h_r}[\bar{C}_{k_{i,+1}} - \bar{C}_{k_{i,j-1}}] - u_{z_{i,j}}\tfrac{1}{h_z} \\
&\begin{cases} [\hat{C}_{k_{i+1,j}} - \hat{C}_{k_{i,j}}], & u_{z_{i,j}} \geq 0 \\ [\hat{C}_{k_{i+1,}} - \hat{C}_{k_{i,j}}], & u_{z_{i,j}} < 0 \end{cases} - \bar{C}_{k_{i,j}}(\bar{\beta}_{k_{i,j}} + \lambda_k) \\
&+ A_{k_{i,j}}\frac{\bar{\beta}_{k_{i,j}}\gamma_k}{m} + \lambda_{k-1}C_{k-1_{i,j}} \\
&- \bar{C}_{k_{i,j}}\left[\frac{ju_{r_{i,j}} - (j-1)u_{r_{i,j-1}}}{jh_r} + \frac{u_{z_{i,j}} - u_{z_{i-1,j}}}{h_z}\right]
\end{aligned}
\tag{26}
$$

The analysis of stability of the differential Eqs. (23), (24), (25) and (26) has shown that at fixed meanings [$\chi_{i,j}$ and $\Omega_{k_{i,j}}$, they are absolutely steady.

The components of velocity of a movement of gas were calculated on to the differential equation of the Darcy Eq. (19) at the numerical decision of Eqs. (20) and (21) with conditions (14)–(16) at each step of time.

4. Results of the mathematical modeling

The results of the mathematical modeling of the formulated problem are the zones of probable pollution by the radionuclides of the 90th and 137th isobaric chains. The radionuclides of these chains are typical at ejection of radioactive products during serious damages to a nuclear power station and biologically are dangerous to the population, because of large periods of half-decay final radionuclides of chains Sr-90 and Cs-137.

The pressure on the surface of the ground at the calculations was considered as the constant and was equal atmospheric. This condition is right as the dynamic pressure of a gas mix at the filtration velocity in the porous media is not enough in comparison with the static pressure of atmosphere. Within the framework of the model it was supposed also that the small heat capacity of gas in comparison with the heat capacity of the porous medium at the filtration of gas occurs in a field of given temperature. At realisation of calculations it was also accepted that a whole part of a containment is destroyed, i.e. the surface S_0 through which there is the expiration of gas equal to the surface of a whole part of containment. We have $S_0 = \pi r(r + 2h)$ in case of approximation of the containment by the cylinder.

The following parameters values of the problem were accepted at calculations: $P_1 = 6 \times 10^5$ Pa is the initial pressure in containment; $m = 0.1$, $k = 10^{-12}$ m^2, $d = 0.001$ m are the characteristics of medium; $\mu = 0.25 \times 10^{-4}$ kg/m $\cdot$ sec, $\eta = 13.2 \times 10^{-2}$ m^2/sec are the characteristics of a gas mix; and $L = R = 100$ m, $r = 15$ m, $h = 20$ m are the geometrical sizes of a problem. The parameters of radionuclides are submitted in Table 1.

The concentration of radionuclides was set according to data of the manual in an initial moment of time [8].

The calculations were carried out on a spatial grid of 32×32 mesh. The step on time was accepted equal to 0.001 at calculations.

The results of mathematical modeling of the distribution of radionuclides in the ground are shown in Figs. 2–6. Fig. 2 shows the distributions of gas pressure through 30 min (a) and 20 h (b) after damage of pile. Fig. 3(a, b) illustrate the distribution of concentrations Xe-137 and Cs-137 in the flow. Fig. 3 shows the distribution of concentration of adsorbed Cs-137 at 30 mins after damage.

The amount of Xe in the ground after 4 h is extremely insignificant owing to nuclear decay and the absence of adsorption Xe. Only Cs is present in the ground initially and the distribution of Cs after 4 h is submitted on Fig. 4. Fig. 5 demonstrates the distribution of Sr-90 20 h after the moment of damage. Fig. 6(a) shows dependence for the 137th chain of radionuclides of the integrated flow in time on the ground surface. The dependence of a total mass of radionuclides of 90th isobaric chain output in the atmosphere is shown in Fig. 6(b). This integrated characteristic is important for the estimation of radioactive pollution.

The marked calculations show that the distribution of radionuclides in the ground much depends on the geometry of a problem, characteristics of ground as the porous medium, and the adsorbed abilities of radionuclides.

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References

[1] E.G. Basanskii, V.M. Kolobashkin, N.A. Kudryashov, Distribution of radionuclides through shattered breed under an operation surplus pressure of yields of ex-

plosion, Izv. Acad. Nauk of USSR, Mechanics of a Liquid and Gas 2 (1980) 62–69 (in Russian).

[2] E.G. Basanskii, V.M. Kolobashkin, N.A. Kudryashov, Calculation of two-dimensional distribution of an impurity in a porous medium at a non-stationary filtration of gas, Izv. Acad. Nauk of USSR, Mechanics of a Liquid and Gas 5 (1982) 61–67 (in Russian).

[3] E.G. Basanskii, A.G. Bondarenko, A.L. Gavrilov, N.A. Kudryashov, M.N. Kul'zhik, S.M. Pokrovskii, Technique of account of zones of a penetration of an accumulated radio-activity in ground through violation of the lower part of a protective envelope at heavy accident on nuclear power station, Atomnaya Energiya 72 (1) (1992) 72–77 (in Russian).

[4] A.G. Bondarenko, V.M. Kolobashkin, N.A. Kudryashov, Diffusion and adsorption of radioactive gas in a porous medium, Izv. Acad. Nauk of USSR, Mechanics of a Liquid and Gas 5 (1976) 85–90 (in Russian).

[5] N.A. Kudryashov, E.G. Basanskii, A.G. Bondarenko, Influence of a diffusion on distribution of radioactive gas in a porous medium, Journal of Engineering Physics 1 (1978) 131–137 (in Russian).

[6] S.N. Businov, M.A. Peshkin, About factor of a variance at displacement from porous medium of gas by gas, Prikl. Mech. Teor. Phys. 4 (1975) 142–145 (in Russian).

[7] N.N. Kalitkin, Numerical Methods, Nauka, Moscow, 1978 (in Russian).

[8] V.M. Kolobashkin, P.M. Rubtzov, P.A. Ruzhanskii, V.D. Sidorenko, Radiating Performance of Irradiated Nuclear Fuel, Manual, Enargoatomizdat, Moscow, 1983 (in Russian).