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METHODOLOGY FOR MODELING THE SPREAD OF RADIOACTIVE SUBSTANCES IN CASE OF AN EMERGENCY RELEASE AT A NUCLEAR POWER PLANT

Abstract. The methodology for modeling the propagation of accidental releases of radionuclides from a power unit of a nuclear power plant has been developed. The calculation method takes into account the most critical factors propagation cloud - wind direction and speed, the intensity of the release radionuclides change: semi-continuous release, long-term release, instantaneous release. Diffuse processes and the presence of interference in the form of buildings were also taken into account. To solve the modeling equation of the aerodynamic model, the velocity potential equation is solved. The use of this equation instead of the traditional Novier-Stokes equation makes it possible to rationalize the calculation process in terms of the speed obtaining simulated data. To build a numerical model, a rectangular difference grid is used. The velocity potential and the quantities values of volumetric activity are determined at the centers of difference cells. The value of the airflow velocity vector component is determined on the sides of the difference cells. A finite-difference splitting scheme is used for numerical integration of the equation convective-diffusion transfer radionuclides. A computer code was developed on the basis of the constructed numerical model, the programming language Fortran was used. The approach used makes it possible to reduce the time for obtaining one scenario of an accident development. The cloud propagation dynamics determining is carried out almost in real time. This allows you to quickly respond to changing situations and make adequate decisions.

Keywords: nuclear accident, mathematical model, aerodynamic model, forecasting.

Introduction

Radionuclides releases in the event of an accident at a power unit of a nuclear power plant (NPP) are an event of low probability. But according to the results for the population and the environment, such an event exceeds all man-made accidents of non-nuclear origin. This is evidenced by the consequences of the Chernobyl disaster and the severe accident at the Fukushima Daiichi nuclear power plant. Despite the high reliability of modern nuclear power units, the probability of an accident with releases of radioactive substances cannot, in principle, be zero. This is especially true of deliberate terrorist acts, which also cannot be completely ruled out.

The specificity of such modeling is the impossibility of verifying the modeling results in real and laboratory conditions. In addition, a forecasting software tool should provide high efficiency in taking into account scenarios, so the maximum adequacy of the model must be ensured in the process of its development. This is achieved by taking into account all the critical factors affecting the distribution of emissions.

Efficiency of calculations can be achieved through the use of the optimal calculation method, which will ensure the minimum possible expenditure of machine time. This will make it possible to promptly respond to changes in the initial data (climatic conditions) and change the forecast data on the propagation of the radionuclide cloud.

Analysis of recent research and publications

Part of the publications and developments of accidents at nuclear power plants concerns the equipment reliability and the personnel actions adequacy. Only the possibility of failures and personnel training to reduce the probability of an accident are considered in paper [1].

The study [2] is devoted to the formation of the philosophy of nuclear safety, the requirements for safety are considered. This only applies to large pressurized water reactors. All suggestions are about accident prevention.

A risk-based approach to the prevention of an accident at a nuclear power plant is considered and improved in paper [3]. Attention is also paid to the decision-making procedure in a stressful situation. But the development of the accident is not considered.

The study [4] predicts the territory contamination and the injury of people in the event of an accident. But the model is based on historical weather data in Finland, which limits its application in other climatic zones and terrain features.

The paper [5] concerns a floating nuclear power plant. Therefore, the main way to reduce the consequences of the accident is to rotate the station platform. But the CFD computational method is very efficient.

The dynamics of pollution of the area around the Fokushima station for seven years was predicted in the study [6]. That is, radionuclides that have fallen on the surface of the earth are considered.

The problem of fuel removal at the Fukushima station is studied in paper [7, 8], which is important, but does not predict the occurrence of possible emergency situations.

To date, the existing methodologies for predicting the development of accidents with emissions of harmful substances are based on the solution of the Novier-Stokes equation, which requires the use of small cells the computational grid and increases the calculation time.

Therefore, it is advisable to break down the modeling methodology that allows calculations to be made within ten to twenty seconds.

This will allow us to quickly assess the situation and make adequate decisions to protect the population and the environment.

Problem statement. The purpose of the study is to develop a methodology for modeling the spread of radioactive substances in an emergency at a nuclear power plant.

The main task of the study is to determine an error-acceptable and convenient in the software implementation of the calculation apparatus for the operational assessment of the radiation situation.

Presentation of the main material

The forecasting of the radiological situation at the industrial site of a nuclear power plant in the event of an emergency release of radionuclides from one power unit is considered.

Prediction of the radiological situation is carried out on the basis of the developed CFD model.

The task of assessing the level of radiological air pollution on the territory of the nuclear power plant in the area where the power units is set.

To assess the level of radioactive air pollution in the event of an accidental radioactive release Q [Ki] at a nuclear power plant, the following equation for the distribution of radioactive emissions in the atmospheric air is used $u,\ v,\ w$:

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}+\frac{\partial (w-w_s)C}{\partial y}+\lambda C=$$
$$=\frac{\partial}{\partial x}(\mu_x\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(\mu_y\frac{\partial C}{\partial y})+\frac{\partial}{\partial z}(\mu_z\frac{\partial C}{\partial z})+ \qquad (1)$$
$$+\sum_{i=1}^{n} Q_i(t)\delta(x-x_i)\delta(y-y_i)\delta(z-z_i),$$

where C is the volumetric activity value, Ki/m^3;

$u,\ v,\ w$ are the components of the wind speed vector in the projection on the x, y, z coordinate axes, respectively, m/s;

w_s - is the rate of deposition of radioactive particles in the atmosphere;

$\lambda = 0,693/T_{1/2}$, 1/c,

$T_{1/2}$- half life time, years;

$x_i,\ y_i, z_i$ - cartesian coordinates of the i-th source of radioactive emission at the a nuclear power plant, m;

t - time, s;

$\mu_x,\ \mu_y,\ \mu_z$ - atmospheric turbulent diffusion coefficients, m^2/s;

$\delta\left(x_i, y_i, z_i\right)$ - the Dirac delta function, with the help of which the location of an accidental radioactive release at a nuclear power plant is specified in the model.

The intensity of the emission of radionuclides is equal Q.

This model takes into account the change in the rate of release radionuclides over time.

To carry out the simulation, it is necessary to set the dependence

$$Q\left(x_i, y_i, z_i\right)=f\left(t\right),$$

i.e. set how the intensity of the release of radionuclides changes over time.

With this approach, within the framework of the modeling equation (1), it is possible to simulate different types of emergency release: semi-continuous release, long-term release, instantaneous release.

Boundary conditions for the modeling equation (1) are next:

- at the boundary of the wind flow entry into the study area:

$$C=C\big|_{entrance} -$$

is the known background concentration of radioactive contamination in the atmosphere (accepted for pilot calculations C = 0);

- at the boundary of the wind flow exit from the study area:

$$\frac{\partial C}{\partial n}=0\ ,$$

where n is the unit vector of the outer normal to the boundary.

Initial condition

$$C\big|_{t=0}=0 \ \text{or}\ C\big|_{t=0}=C_0\,,$$

where C_0 – the background concentration of radionuclides is known.

The wind speed profile as well as atmospheric diffusion coefficients are calculated:

$$u=u_1\left(\frac{z}{z_1}\right)^p,$$
$$\mu_z=k_1\left(\frac{z}{z_1}\right)^m,$$
$$\mu_x=\mu_y=k_0 u,$$

where p=0,15; m=1; k_1=0,2; z_1=1 m; k_0=0,1; u_1 - wind speed at height z_1=1m.

The wind speed and direction are input parameters for the task and set as the data of meteorological observations.

Since the process of spreading radionuclides within the industrial site is being considered, the influence of buildings (power units) on the formation radioactive contamination areas should be taken into account.

That is, it is necessary to solve the aerodynamics task - to calculate the field of air flow velocity on an industrial site in the building conditions. To solve this task, a potential motion model is used.

In this case, the model equation of aerodynamics has the form:

$$\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}+\frac{\partial^2 P}{\partial z^2}=0, \qquad (2)$$

where P - speed potential.

Boundary conditions for the modeling equation (2):

1. $\frac{\partial P}{\partial n}=0$ on impenetrable borders.
2. $\frac{\partial P}{\partial n}=0$ on the upper border.
3. $\frac{\partial \mathrm{P}}{\partial n}=u(z)$ at the boundary where the flow flows into the computational domain, (u(z) is the air flow velocity, which changes with height).
4. *P=const 4. P*=const at the boundary of the flow exit from the computational domain.

The projections of the airflow speed vector on the axes of the Cartesian coordinate system are defined as follows:

$$u=\frac{\partial P}{\partial x};\quad v=\frac{\partial P}{\partial y};\quad w=\frac{\partial P}{\partial z}, \tag{3}$$

Thus, in order to analyze the formation of radioactive contamination zones in the atmosphere on the territory of an industrial site during an accidental emission at a power unit, it is necessary to solve the boundary value task (2) and calculate the components of the airflow speed on the industrial site based on dependencies (3). Further, using the data of the airflow speed field, calculate equation (1) and obtain the distribution of volumetric activity on the industrial site for a certain time after the start of the accidental emission of radionuclides on the territory of the NPP.

To solve the boundary value task (1), (2) in the conditions of a complex form the computational domain, which is an industrial site with buildings of power units, finite difference methods of numerical integration are used.

The solution of models' equations (1) and (2) is carried out by numerical means. To build a numerical model, a rectangular difference grid is used. The speed potential and the volumetric activity value are determined at the centers of the difference cells. The values of the components the airflow speed vector are determined on the sides of the difference cells.

The Liebman method is used for the numerical integration of equation (2). According to this method, the finite-difference approximation of the Laplace equation (2) has the form:

$$\frac{P_{i+1,j,k}-2P_{i,j,k}+P_{i-1,j,k}}{\Delta x^2}+\frac{P_{i,j+1,k}-2P_{i,j,k}+P_{i,j-1,k}}{\Delta y^2}+\frac{P_{i,j,k+1}-2P_{i,j,k}+P_{i,j,k-1}}{\Delta z^2}=0.$$

The value of the speed potential P i,j,k at the centers of the difference cells is determined from this dependence:

$$P_{i,j},k=\frac{\left[\frac{P_{i+1,j,k}-P_{i-1,j,k}}{\Delta x^2}+\frac{P_{i,j+1,k}-P_{i,j-1,k}}{\Delta y^2}+\frac{P_{i,j,k+1}-P_{i,j,k-1}}{\Delta z^2}\right]}{A},,$$

where $A=\left(\frac{2}{\Delta x^2}+\frac{2}{\Delta y^2}+\frac{2}{\Delta z^2}\right)$.

The components of the airflow speed vector are calculated on the sides of the difference cells based on the following dependencies:

$$u_{i,j,k}=\frac{P_{i,j,k}-P_{i-1,j,k}}{\Delta x},v_{i,j,k}=\frac{P_{i,j,k}-P_{i,j-1,k}}{\Delta y},\mathrm{w}_{i,j,k}=\frac{P_{i,j,k}-P_{i,j,k-1}}{\Delta z}.$$

The following splitting is carried out for the numerical solution of the mass transfer equation (1):

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}+\frac{\partial wC}{\partial z}=0, \tag{4}$$

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}\left(\mu_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_y\frac{\partial C}{\partial y}\right)\frac{\partial}{\partial z}\left(\mu_z\frac{\partial C}{\partial z}\right), \tag{5}$$

$$\frac{\partial C}{\partial t}=\sum Q_i(t)\delta(x-x_i)\delta(y-y_i)\delta(z-z_i), \tag{6}$$

A variable-triangular splitting scheme is used for the numerical integration of the convective equation (4):

- first rock splitting

$$k=n+\frac{1}{4}:$$

$$\frac{C_{i,j,k}^k-C_{i,j,k}^n}{\Delta t}+\frac{1}{2}\left(L_x^+C^k+L_y^+C^k+L_z^+C^k\right)=0; \tag{7}$$

- second splitting step

$$k=n+\frac{1}{2};\ c=n+\frac{1}{4}:$$

$$\frac{C_{i,j,k}^k-C_{i,j,k}^c}{\Delta t}+\frac{1}{2}\left(L_x^-C^k+L_y^-C^k+L_z^-C^k\right)=0; \tag{8}$$

- third splitting step

$$k=n+\frac{3}{4};\qquad c=n+\frac{1}{2}:$$

calculation of concentration based on dependence (8);

- fourth splitting step

$$k = n+1; \qquad c = n + \frac{3}{4}:$$

calculation of concentration based on dependence (7);

Dependencies (7), (8) use the following notation for difference operators:

$$L_y^{+} C^{n+1} = \frac{\partial v^{+} C}{\partial y} \approx$$
$$\approx \frac{v^{+}_{i,j+1,k} C^{n+1}_{i,j,k} - v^{+}_{i,j,k} C^{n+1}_{i,j-1,k}}{\Delta y},$$
$$v^{+} = \frac{v + |v|}{2};$$
$$L_x^{-} C^{n+1} = \frac{\partial u^{-} C}{\partial x} \approx \frac{u^{-}_{i+1,j,k} C^{n+1}_{i+1,j,k} - u^{-}_{i,j,k} C^{n+1}_{i,j,k}}{\Delta x},$$
$$u^{-} = \frac{u - |u|}{2}$$

Determination of the value of volumetric activity on the basis of dependences (7), (8) is carried out according to an explicit formula.

For the numerical integration of the diffusion equation (5), the total approximation scheme is used. The various equations in this case are:

- at the first splitting step:

$$\frac{C_{i,j,k}^{n+\frac{1}{2}} - C_{i,j,k}^{n}}{\Delta t} = \left[\mu_x \frac{-C_{i,j,k}^{n+\frac{1}{2}} + C_{i-1,j,k}^{n+\frac{1}{2}}}{\Delta x^2}\right] + \left[\mu_y \frac{-C_{i,j,k}^{n+\frac{1}{2}} + C_{i,j-1,k}^{n+\frac{1}{2}}}{\Delta y^2}\right] + \left[\mu_z \frac{-C_{i,j,k}^{n+\frac{1}{2}} + C_{i,j,k-1}^{n+\frac{1}{2}}}{\Delta z^2}\right]; \qquad (9)$$

- at the second splitting step:

$$\frac{C_{i,j,k}^{n+1} - C_{i,j,k}^{n+\frac{1}{2}}}{\Delta t} = \left[\mu_x \frac{C_{i+1,j,k}^{n+1} - C_{i,j,k}^{n+1}}{\Delta x^2}\right] + \left[\mu_y \frac{C_{i,j+1,k}^{n+1} - C_{i,j,k}^{n+1}}{\Delta y^2}\right] + \left[\mu_z \frac{C_{i,j,k+1}^{n+1} - C_{i,j,k}^{n+1}}{\Delta z^2}\right]. \qquad (10)$$

Determining the value of volumetric activity on the basis of dependencies (9), (10) is also carried out according to an explicit formula.

The Euler method is used for the numerical integration of equation (6).

On the basis of the constructed numerical model, a computer code has been developed, the programming language is FORTRAN.

This will make it possible to simulate the spread of a radioactive cloud almost in real time and quickly respond to the dynamics of the situation.

Conclusions

1. The developed methodology for modeling the spread of release products at the power unit of a nuclear power plant takes into account the critical factors affecting the spread of radionuclides, wind speed and direction, the impact of buildings on the territory, that is, the task of aerodynamics is solved.

Based on the data, the volumetric activity at the industrial site is obtained for a certain time after the accidental release of radionuclides.

2. The application of the speed potential calculation allows optimizing a rectangular difference grid, which reduces the time for calculating various scenarios for the development of an accident with the release of radionuclides.

In this case, for the numerical integration of the conventional equation, a variable-triangular splitting scheme is used.

The determination of the volumetric activity is carried out by an explicit formula, and for the numerical integration of the diffusion equation, the total approximation scheme is used.

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Методологія моделювання поширення радіоактивних речовин у випадку аварійного викиду на атомній електростанції

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Анотація. Розроблено методологію моделювання поширення аварійних викидів радіонуклідів енергоблока атомної електростанції. Розрахунковий апарат враховує найбільш критичні чинники поширення хмари - напрямок і швидкість вітру, зміну інтенсивності викиду радіонуклідів: напівнеперервний викид, тривалий викид, миттєвий викид. Також враховані дифузійні процеси і наявність перешкод у вигляді будівель. Для рішення моделюючого рівняння аеродинамічної моделі розв’язується рівняння потенціалу швидкості. Застосування цього рівняння замість традиційного рівняння Нов'є Стокса дозволяє раціоналізувати процес розрахунків з точки зору швидкості отримання модельованих даних. Для побудови чисельної моделі використовується прямокутна різницева сітка. Потенціал швидкості та значення величин об’ємної активності визначається у центрах різницевих комірок. Значення компонент вектора швидкості повітряного потоку визначається на сторонах різницевих комірок. Для чисельного інтегрування рівняння конвективно- дифузійного переносу радіонукліідів використовується кінцево- різницева схема розщеплення. На базі побудованої чисельної моделі розроблено комп’ютерний код, мова програмування – Fortran. Застосований підхід дозволяє скоротити час отримання одного сценарію розвитку аварії. Визначення динаміки поширення хмари здійснюється практично у режимі реального часу. Це дозволяє оперативно реагувати на зміну ситуації й приймати адекватні рішення.

Ключові слова: ядерна аварія; математична модель; аеродинамічна модель; прогнозування.