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ANALYSIS OF PROCESSES OF AEROSOLPARTICLE TRANSFER AND DEPOSITION ON CHARACTERSURFACES OF INFRASTRUCTURENPP

The developed model of calculation of dynamics of distribution of waste substance emission in emergency situations is presented in this article. An assessment of the mechanisms of the deposition of radioactive substances on the characteristic surfaces of the NPP in emergency situations is made. The areas of preferential deposition of waste aerosols on the characteristic surfaces infrastructure for NPP are defined as a result of numerical simulation.

Introduction. The aim of the work was to analyze the processes of aerosol particle transfer and deposition on various types of surfaces under emergency situations on the territory of the NPP site. Assessing the level of possible radiation hazards is one of the most important tasks that must be addressed at all stages of the plant's life cycle. The main requirement is the principle of non-exceedance of marginal values for NPP radioactive emissions and for personnel radiation doses caused by them. NPP safety is ensured by analyzing the levels of possible contamination and by taking science-based measures to protect plant personnel. For the identification of hazards and exposure of NPP emission characteristics it is necessary to create a map of preemptive nuclear power plant site pollution on the basis of computer modeling of impurity substance transfer in emergency situations.

Formulation of the research problem. In this paper, in the framework of formalized template from software package COMSOL Multiphysics NPP site model analogue was developed (Fig. 1).

Impurity transport in the atmosphere and its depositing on the earth surface is a complex and multifaceted problem. Radioactive cloud distribution is influenced by various factors, including the weather conditions of the area, topography, etc.

The system of conservation equations for the individual phases is the basis for modeling of flow and transported dispersed impurity, which are solved numerically together with equations describing the interphone transfer processes. This system of conservation equations is complemented by corresponding sets of initial and boundary conditions, and also integral parameters of the anthropogenic sources.

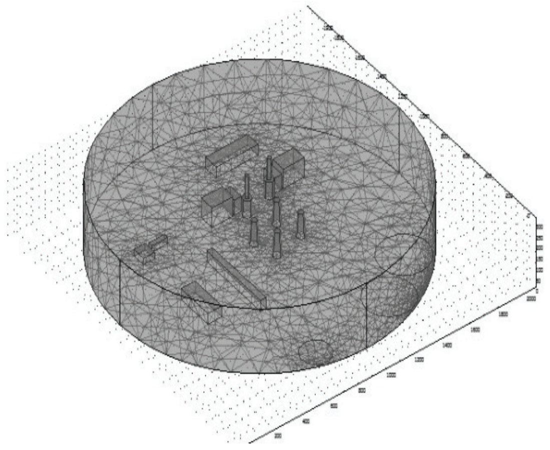

Fig. 1. Model analog and computational grid of NPP site (geometric parameters -2000×2000×300 m)

To model the dynamics of the carrying flow the following system of conservation equations is adopted [2]:

$$\frac{\partial \rho W_i}{\partial x_i} = 0; \tag{1}$$

$$\frac{\partial W_i}{\partial t} + W_j \frac{\partial W_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu_E \frac{\partial W_i}{\partial x_j} - \overline{W_i' W_j'}\right) + g_i \delta_{ij}; \tag{2}$$

$$\frac{\partial T}{\partial t} + W_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_j}\left(a_E \frac{\partial T}{\partial x_j}\right), \tag{3}$$

where $\overline{W_i' W_j'} = -\nu_{\mathrm{E}}\left(\frac{\partial W_i}{\partial x_j} + \frac{\partial W_j}{\partial x_j}\right) - \frac{2}{3}\delta_{ij} K_j$, W_i, W_j – Traffic flow velocity components along the axes x_i,

x_j (in this model $i, j = 1, 2, 3$, $i \neq j$; x_1, x_2, x_3 – spatial coordinates); t – time; P, T – pressure, temperature; ρis the density; g – acceleration of gravity; ν, a – coefficients of kinematic viscosity, thermal diffusivity; K – turbulent kinetic energy according to the «k-ε» turbulence model. Lower symbol E -effective value.

To describe the process of dispersed radionuclide transport in the flow the initial system conservation equations (1)–(3) is supplemented by the equations of motion and conservation of aerosol particles [2]:

$$\frac{\partial N_{p,n}}{\partial t} + (W_{p,n})_i \frac{\partial N_{p,n}}{\partial x_j} = \\ = \frac{\partial}{\partial x_j}\left(D_{p,n} \frac{\partial N_{p,n}}{\partial x_j} \right) + J_{p,n}; \qquad (4)$$

$$N_{p,\Sigma} = \int\limits_{L_{\min}}^{L_{\max}} \left[\tilde{N}_p(L_n) \right] N_{p,n} d(L_n), \qquad (5)$$

where $N_{p,n}$ – the volume concentration of particles in the size L_n; $(W_{p,n})_i$ – particle size velocity component L_n; $D_{p,n}$ – diffusion coefficient of the particle size L_n; $[\tilde{N}_p(L_n)]$ – a function of the particle size distribution L_n; $J_{p,n}$ – source particle size L_n. The above equations are supplemented by initial and boundary conditions, taking into account the general plan of the NPP, including meteorological data and the topography of the underlying surface. On the territory of the NPP site, there are three main types of surface. One can assume that in an emergency the surface structure affects mainly the dynamics of propagation of accidental releases. For different categories of alarms emitted preferably iodine and cesium in the form of aerosol particles with a size of 1 mm [3]. Because of the low concentration of particulate matter flow equations (1)–(3) and (4)–(5) are solved independently.

For the numerical implementation of the model analogue of the NPP site was used finite element method in the interpretation of COMSOL Multiphysics.

Open water. As the results of full-scale experimental and computational studies, all aerosol strapped in the boundary layer ≈1 m above the precipitate in an aqueous environment without reentrainment.

Solid surface. Aerosol deposition efficiency is determined by the structure of the flow and aerosol properties.

To compare various types of ground surface by deposition rates and the formation of the surface concentration of radioactive substances can be used for effective data rate of deposition v_{sed}. The value has the dimension of speed m/s (Table, [4]). Values can be used to determine the intensity of precipitation of the known concentration of fission products in the atmosphere by the formula

$$d = q \cdot v_{sed}, \qquad (7)$$

where in q – concentration in the air Bq/m3; d – intensity of precipitation, Bq/(m^2·s).

The values of the deposition rate
of fission products, v_{sed}

Type of the underlying surface	$v_{sed} \cdot 10^2$, м
Grass meadow	0.25–4.00
Mown grass	0.59
Dry soil	0.33

Experimental data refer to aerosol particles of ≈0.2 mm size under turbulent mechanism of deposition.

Surface with "roughness". The analysis of the data given in the table has shown that the intensity of deposition of radioactive substances on the mown grass or lawn is approximately twice as high than the same for the dry solid surface. In case of more rich vegetation the intensity of deposition will be even higher. Such a divergence in deposition intensity is caused by the fact that the vegetation which covers the surface may have different specific deposition surface (per unit of a ground surface) and a different degree of inhibition of the air flow which carries aerosol particles. When using exact models of the deposition processes the rich vegetation may be simulated by a porous medium with a different degree of porosity and different permeability coefficient.

The process of radioactive substances deposition on specific surfaces of NPP territories depends also on local hydro meteorological conditions such as humidity, precipitation, winds, atmospheric phenomena, temperature inversion.

The climate of the NPP industrial site is temperate continental with quite warm and long summer and moderately cold winter. The average annual temperature is 5.4°C, an absolute maximum is +35°C, an absolute minimum is –40°C.

Research results. The diagram of the computational experiment on the model evaluation standard is shown in the Fig. 2 [1]:

– height of the cubic-shaped building $H = 60$ m;

– wind $U_0 = 7$ m/secon the left boundary of the computational domain. Wind direction from left to right;

– the centre of the cube is located at a distance 3.5H from the left edge;

– near the ground source at a distance 0.25H behind the building.

Concentration of contaminants emissions was measured on the lines L_3L_4 and on the track axis.

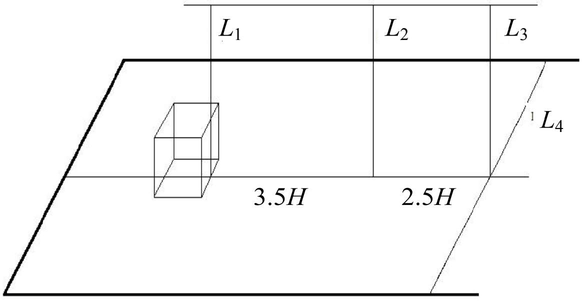

Fig. 2. Scheme of standard procedure of models evaluation (designations are given according to the text)

Calculations based on the given experiment scheme with the use of a number of model products are shown in Fig. 3.

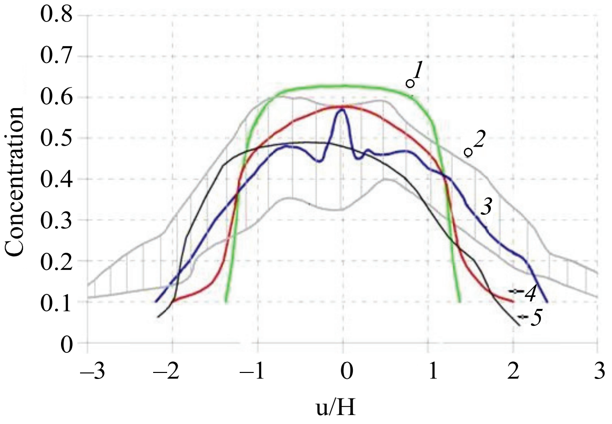

Fig. 3. Relative concentration of contaminants emissions on the line L_4 normalized to the concentration of the test source(Fig. 2): *1* – the model of the RANS type of the Lawrence Livermore National Laboratory, LLNL); *2* – the range of the measured values of concentration (vortex meandering flow); *3* – the model of the LES type of the Lawrence Livermore National Laboratory, LLNL; *4* – FLUENT; *5* – calculations of the Nuclear Safety Institute of the Russian Academy of Sciences (IBRAE)

Fig.4 (analog of Fig. 3) demonstrates the measurements across the track (taking into account the observed spread of values – vortex flow).

Calculations were performed with the use of the developed model of the dynamics of aerosol particles emissions distribution in emergency situations. Verification of this model was carried out according to the data of the Nuclear Safety Institute of the Russian Academy of Sciences (IBRAE) (Russia).

The comparative analysis of the different model products confirms an authenticity of the developed software module whereby it is possible to come to a conclusion that this module may be used for safety justification of the NPP under construction in the Republic of Belarus.

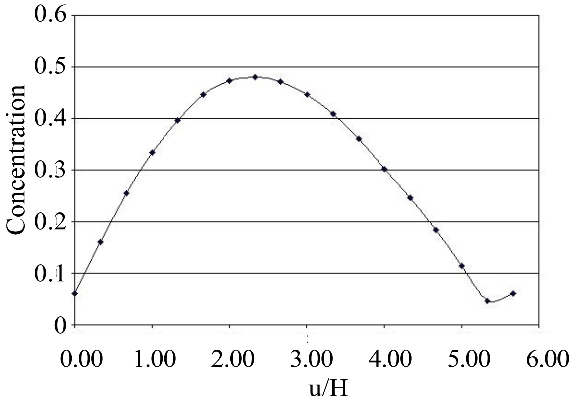

Fig. 4. Concentration of contaminants emissions (calculations were performed by the methodology represented in the present paper according to the scheme in Fig. 3)

It should be emphasized that the distinctive peculiarity of the developed model is the consideration of not only dynamic but also thermal parameters of impurity particles emissions out from technological elements of NPP that can significantly affect the emission plume, especially in emergency conditions.

In the framework of the model computational experiments there were conducted test calculations on the analysis of the dynamics of radionuclides distribution in emergency situations with the release out from the vent tube. An accidental release was a plume along the wind.

Calculations were carried out for the specific NPP master plan and summer conditions: environment temperature was 20°C, maximum speed of wind current – 10 mps. Settling velocity of aerosol particles in the carrier current at 10 m height was 0,1 mps, what conforms to the particles of 30 μm in diameter and 1000 kgpm^3 [3] in density. In the calculations, two principal deposition mechanisms were emphasized: gravitational and diffusive. The deposition mechanisms for impurity matters may be accounted in the general system of conservation equation, allowing presence of transparent substructure.

Results of the calculation of three-dimensional fields of concentrations and deposition of impurity matters on the substructure on the NPP territory are cited in Fig. 5. From the type of the concentration fields in Fig 5, in particular, follows that account of thermal values of emission, i.e. thermal convection, results in more real concentration profiles. In particular, presence of deposition not only on the downwind side of the source, but on the opposite one as well.

Fig. 6 may serve as illustration of the influence of thermal convection, as well as diffuse condensed moisture from cooling towers on emission flume of impure particles from the industrial ventilation tube.

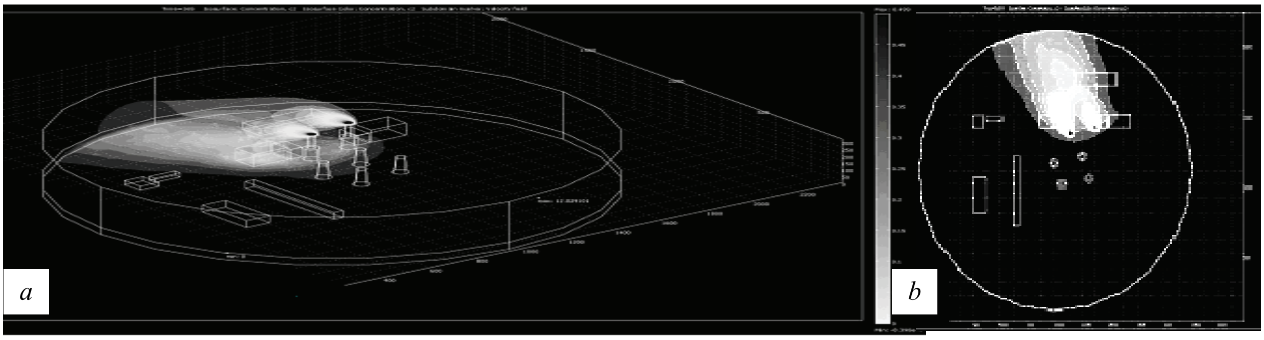

Fig. 5. Distribution of concentrations of aerosol particles in the NP infrastructure (geometrical characteristics conform to Fig. 1):
a – space distribution of concentrations in the task on determination;
b – projection of the concentrations field on substructure (range of concentrations change from $8 \cdot 10^{-4}$ to 0.5)

Fig. 6 cites results of the computing experiments on definition of maximum aerosol concentration on substructure at emission from the ventilation tube with the account of the cooling tower at their various placements in respect to the wind current. Within the framework of the computing experiments the following situations were analyzed: *situation # 1* – emission only form the industrial ventilation tube 100 m high; *situation # 2* – joint emission from the industrial ventilation tube and "cold" emission of condensed moisture from the cooling tower 170 m high at its placement behind (along the wind current) the industrial ventilation system; *situation # 3* – reciprocal to the *situation # 2*; *situation # 4* – *situation # 2* + «hot» emission from the cooling tower; *situation # 5* – reciprocal to the *situation # 4*.

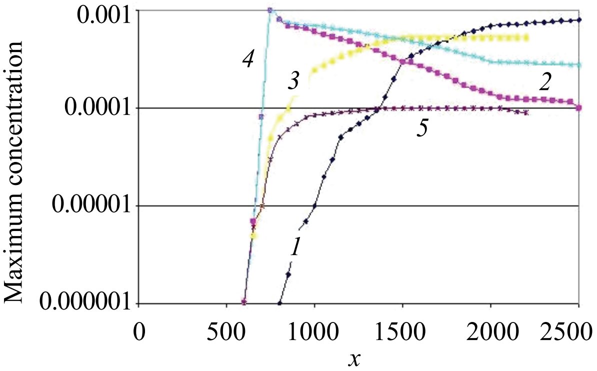

Fig. 6. Maximum concentration on the substructure at the emission from the ventilation tube with the account of the cooling tower:
1 – situation # 1 (according to the text); *2* – situation # 2;*3* – situation # 3; *4* – situation # 4; *5* – situation # 5 (concentration range from 10^{-7} to 10^{-4} kg /m^3, range of changes of distance from the source from 0 to 2500 m)

Aerosol concentration in the places of near-surface accumulation of radioactive aerosols makes up value of about 0,001–0,100% of the concentration at the initial point of emission (at the exit from the ventilation tube). Secondary pollution of the atmosphere from the ground surface may happen because of secondary dust formation in the air and carrying over of the precipitated radionuclides by wind.

Rise of the radionuclides from the ground surface does not depend on their physical and chemical characteristics. It results from the characteristics of the activity carrier only – dispersed particles. However, the measurements have shown [4] that indexes of radioactive products rise by wind are insignificant.

Conclusion. Within the framework of programming environment for computer procedure COMSOL, computer module was originated for calculation of processes of transport and precipitation of aerosol particles on specific surfaces of the NPP infrastructure.

Process of precipitation of aerosol particles on various types of surface in emergency situations on the NPP site territory was analyzed. It was found out that the area of dominating radioactive aerosols precipitation depends on aerosol particles characteristics, outside weather conditions, condition of the ground surface, NPP site territory infrastructure, as well as flowing thermal currents form the cooling tower.

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