Multi-Step Evolution of Radiation Dust under Gravitation in the Pollution Prediction Problems

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Abstract. **The article proposes the basis for calculation of the evolution in time and space of one of the most important factors causing damages in radiation accidents is radioactive dust. It has been proved that the decontamination of areas contaminated by radioactive dust should be carried out in several stages. If the first stage is related to the process of removing the large particles of the settled dust from the surface, then the second stage comprises removing the very small dust particles from the air, as they are especially dangerous to the respiratory system. Quantitative limits of three modes of evolution of the radioactive dust in the gravitational field have been determined and the influence of the boundary condition has been considered. The equations that give the description of the evolution of dust particles of arbitrary size have been derived.**

Keywords: **environmental impact, accident, radioactive dust, sedimentation.**

I. Introduction

Emissions of radioactive dust are one of the most important harming factors of accident related with spread of radiation . The struggle with the consequences of such accidents is usually limited to decontamination of surfaces on which dust settled down. This ignores the fact that the relative majority of dust consisting of particles of the smallest size, remains in the atmosphere for a very long time, and is likely to settle on the respiratory tract.

The necessity to analyze the problem is determined by the fact that at present there are no methods of complete localization of radioactive dust. The problem is complicated by the need to clearly define the limits of the environmental impact of radioactive dust, which contains particles of different sizes, depending on the parameters of these particles.

This problem is reflected in many of the regulations and laws and is widely discussed in scientific and practical literature and the press [1-3].

Thus, there is a scientific problem of calculating the amount of environmental contamination at military hardware release of radioactive dust – one of the most important factors causing the damage in accidents related with spread of radiation

II. Output Equation, Solving the Problem

The task of improving the accuracy of prognostic assessments of radiation characteristics of the radioactive contamination of military equipment, the environment and doses to personnel and the population, is among the most important tasks in the field of radiation safety. Therefore, the solution of such problems requires the original equations of motion, taking into account the behavior of particles at all time scales and distances. This approach allows us to make a consistent conclusion of approximate equations, which are then used to solve specific problems. At the same time taking full account of approximations performed to evaluate the accuracy of the results.

If we consider the radioactive dust, as a system of particles suspended in air, non-interacting with each other, then, the motion of a single particle is described by Langevin equation [4]:

$$M\frac{\partial v}{\partial t} = -bv - Mg + \rho_0 Vg + f_{st}. \qquad (1)$$

Here we, for simplicity, confine ourselves to the consideration of vertical movement.

The first term in (1) is the force of friction, and friction coefficient b on the one hand related to the diffusion coefficient D using Einstein's relation [5]:

$$D = \frac{k_B T}{b}, \qquad (2)$$

and, on the other hand, for spherical particles is determined by the formula of Stokes [5]:

$$b = 6\pi\eta R, \qquad (3)$$

where the quantity η is the viscosity of air. To determine the coefficient of friction, you can reference data and according to [6] it is $b = 2.85 \cdot 10^{-6} R$ [kg / s].

The second and third terms in Eq.(1) are defined by the presence of gravitational field, they incorporate he force of gravity and the Archimedes force. The value $M = \rho V$ is particle mass, $V = 4\pi R^3/3$ is volume, R is radius, and ρ is density of the particles, the value of g = 9.8 m/c^2 is gravity acceleration near Earth's surface, and ρ_0 is density of air.

The last term describes the contribution of random collisions of molecules of air and particle represented as a random force.

Equation (1) allows us to take so-called Fokker-Planck equation for the distribution function of particle velocities [7] $h = h(z,v)$:

$$\frac{\partial h}{\partial t} + v\frac{\partial h}{\partial z} - Mg\frac{\partial h}{\partial v} = \frac{b}{T}\frac{\partial}{\partial v}\left\{\frac{k_B T}{M}v\frac{\partial h}{\partial v} + h\right\}. \qquad (4)$$

Solutions of this equation [5] give us a complete picture of the evolution of dust in the gravitational field of view of diffusion.

III. The problem of Sedimentation

Consider the problem of sedimentation of dust particles in a gas under the influence of gravity. In terms of equation (3) there are three known specific types of evolution. Large particles (R> 100 microns) misses the moment of seting on the stationary regime, and these particles fall into the gravitational field with increasing speed, but with diminishing acceleration. Smaller particles (R <100 microns) have the time to reach the stationary regime falls, i.e. the mode of motion with constant speed. For such particles the solution of equation (3) allows us to take the diffusion equation in the gravitational field, so-called Smoluchowski equation [8-12]:

$$\frac{\partial n}{\partial t} = D\frac{\partial}{\partial z}\left\{\frac{\partial n}{\partial z} + \frac{Mg}{k_B T}n\right\}. \qquad (4)$$

Here $n = n(z)$ is number of particles per unit volume.

$$n(z) = \int h(v,z)dv. \qquad (5)$$

Equation (4) is the basic equation for solving the problem under consideration, it allows us with the necessary degree of accuracy to determine the temporal and spatial evolution of systems of particles in external fields. It is convenient to rewrite this equation in another form:

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial z^2} + c\frac{\partial n}{\partial z} = \frac{k_B T}{b}\frac{\partial^2 n}{\partial z^2} + \frac{Mg}{b}\frac{\partial n}{\partial z}. \qquad (6)$$

This equation is clearly marked in two terms that correspond to different physical mechanisms. The first is a blur, due to diffusion phenomena with a characteristic diffusion coefficient

$$D = \frac{k_B T}{6\pi\eta R}. \qquad (7)$$

The second term describes the so-called "demolition" (or "drift"), is directed movement by external force with a constant speed

$$c = \frac{Mg}{b} = \frac{2}{9}\frac{\rho R^2 g}{\eta}. \qquad (8)$$

This stationary velocity is determined in main by its size and the air viscosity.

The evolution of particle systems is the competition of these two mechanisms. Thus the relative contribution of each mechanism is determined, above all, the size of particles. If the particles of large (R > 1 *mm*) dimension will move down with enough large, but constant speed, then the particles of the very small sizes are going to slowly diffuse into the atmosphere.

Consider a typical solution of the problem of the evolution of clouds of radioactive dust in the gravitational field. Suppose that at the initial time all particles located at some height z_0, ie the initial condition is:

$$n(z, t=0) = n_0 d\delta(z - z_0), \qquad (9)$$

where d is thickness of the dust layer, n_0 is the density at the initial time, and $\delta(z)$ is the Dirac function.

As the boundary condition we choose the requirement for the flux to be equal to zero at the boundary.

$$j(z=0,t) = D\frac{\partial n}{\partial z} + cn = 0. \qquad (10)$$

The solution of this problem [3] is:

$$n(z,t) = \frac{n_0 d}{2\sqrt{\pi D t}}\left\{\exp\left(-\frac{(z-z_0)^2}{4Dt}\right) + \exp\left(-\frac{(z+z_0)^2}{4Dt}\right)\right\}\times$$

$$\times\exp\left[-\frac{c}{2D}\left(z - z_0 + \frac{ct}{2}\right)\right] +$$

$$+\frac{c\cdot n_0 d}{2D}\exp\left(-\frac{cz}{D}\right)\mathrm{erfc}\left(\frac{\mathrm{z - z_0 - ct}}{\sqrt{4Dt}}\right), \qquad (11)$$

where $erfc(x)$ - integral error.

The typical dependencies on the height at certain points in time are presented in Figures 1, 2 and 3. In these figures one can observe how physically different mechanisms determine the evolution of the system depending on the size of the particles.

In the case of very small particles (Fig.1) we observe just diffusion relaxation with almost immovable center of gravity.

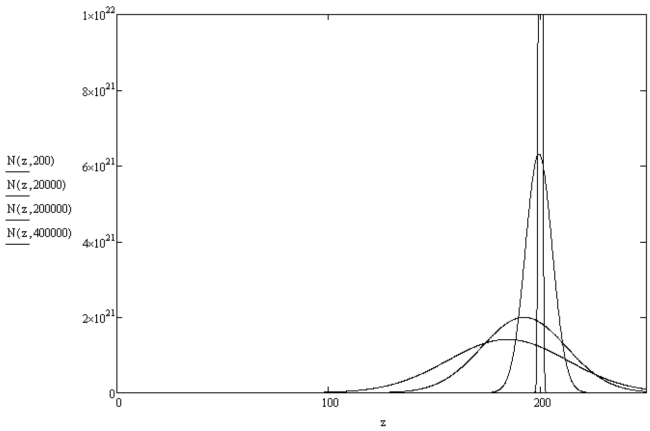

Fig. 1. Spatial distribution at different times for the small sizes of dust

In this situation the second term (drift term) in Eq. 6 much smaller then the first term, that describes diffusion. The approximate solution at the beginning of evolution can be written as follows:

$$n(z,t) = \frac{n_0}{2\sqrt{\pi Dt}}\left(-\frac{(z-z_0+ct)^2}{4Dt}\right) \qquad (12)$$

In the figures we present the normalized function

$$N(z,t) = \frac{1}{2\sqrt{\pi Dt}}\left(-\frac{(z-z_0+ct)^2}{4Dt}\right) \qquad (13)$$

In the case of very big particle, when the contribution of the fist term in Eq. 6 is small, one can observe the falling in a gravitational field with a small spreading (see Fig. 2)

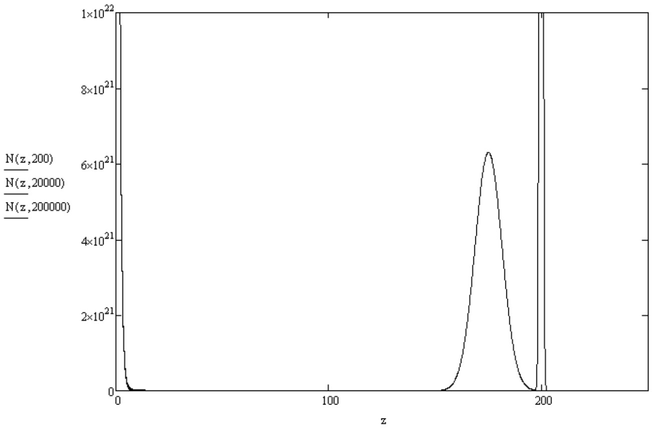

Fig. 2. Spatial distribution at different times for the large sizes of dust

In this situation the second term (drift term) in Eq. 6 is much greater then the first term, that describes diffusion.

Finally, in the case of particle with intermediate sizes we observe the simultaneous action of diffusion and falling.

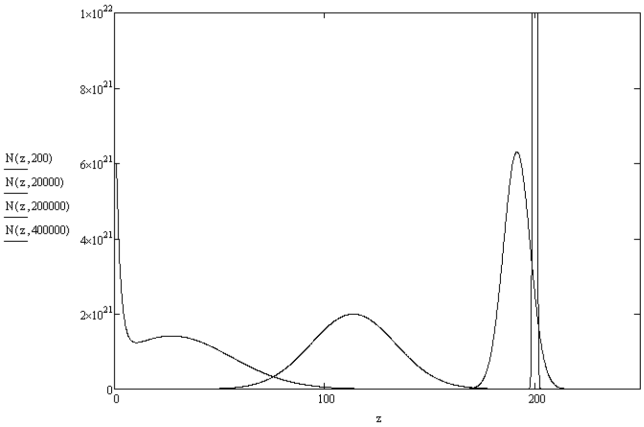

Fig. 3. Spatial distribution at different times for the medium sizes of dust

IV. Conclusion

As a result, the analysis of the problem has allowed us to identify the quantitative limits of the three modes of evolution of radioactive dust in the gravitational field. The equation has been obtained giving a description of the evolution of dust particles of the arbitrary size.

The main conclusion of the article is the fact that decontamination of areas contaminated by radioactive dust should be carried out in several stages. If the first stage be cleaning the surface, which quickly settled dust particles large, then the second stage should be to clean the air of very small particles, the more that these particles are most dangerous to the respiratory tract.

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