SIMULATION OF THE PROCESS OF AEROSOL WASHOUT FROM THE VENT PIPE PLUME OF A NUCLEAR POWER STATION ON INTERACTION WITH THE STEAM-AIR PLUME OF A WATER-COOLING TOWER

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Based on results of mathematical simulation and laboratory modeling, estimates are obtained for the effect of the washout of aerosol and its deposition on the surface of the earth in mixing of the plumes from the vent pipe and cooling tower of a nuclear power station (NPS).

Introduction. The accident at the Chernobyl NPS has spurred interest in the ecological aspects of the operation of nuclear power stations, including rather subtle effects. Thus, great interest is shown in the possibility of depositing radioactive aerosols, expelled from the vent pipe of an NPS by water droplets from the steam-air plume of the cooling tower in a manner like the process of "gas scrubbing" in industry [1]. A detailed simulation of the process of washout of aerosol particles by water droplets is a complex multiple-factor problem. To model hydrodynamic fields, one has to solve the three-dimensional problem of the mixing of turbulent plumes from a cooling tower and a vent pipe in a turbulent wind stream perturbed by the tower. The quantitative description of the hydrodynamics of mixing is necessary to correctly simulate the microphysical processes of the formation and growth of droplets and their interaction with aerosol particles. The latter problem is aggravated by the fact that generally the size distribution function of droplets at the exit of the tower is unknown. To avoid these difficulties and at the same time to obtain a sufficiently precise estimate for the efficiency of the aerosol washout, we used in this work a simplified mathematical model of the process, similar to the models for the transfer of impurities in the boundary layer of the atmosphere [2]. We should mention a conceptually close work [3] in which great attention was paid to the simulation of the processes of the initiation and evolution of droplets. But in that work account was taken only of the small-scale region of the spectrum of droplets having a radius smaller than 30 µm. Also, complete absorption of impurity by droplets was assumed, which, in our opinion, is valid only in special situations.

Qualitative Estimates. Before presenting the results of detailed quantitative calculations involving the results of laboratory modeling it seems expedient to give qualitative estimates of the magnitude of the effects studied [4]. We start out with the estimation of the probability for aerosol of radius r_a to be captured by water droplets of radius r. Using an analogy with the kinetic theory of gases [5, 6], we introduce the notion of the mean free path of aerosol \( \lambda_a \). It can easily be shown that the expression for \( \lambda_a \) has the form

\[
\lambda_a = \frac{1}{\pi (r_a + r)^2 \Phi (v/w) N},
\]

where \( N \) is the number of droplets of radius \( r \) in a unit volume; \( v \) is the velocity of aerosol moving under the influence of turbulent pulsations; \( w(r) \) is the developed velocity of droplets moving under the action of gravity. By the order of magnitude the velocity \( v \) is equal to \( v = \epsilon_0 u_0 \), where \( \epsilon_0 \) is the degree of flow turbulence; \( u_0 \) is the velocity of the flow (of the plume in the zone of mixing). As a rule, \( \epsilon_0 \approx (0.1-0.3) \). The function \( \Phi \) varies from 1 for motionless droplets to the value \( (1+w/v) \). For subsequent numerical evaluations we will take the intermediate value \( \Phi = 2 \). The aerosol is captured by a droplet when the Reynolds number \( Re \gg 1 \) [4], where
Re = \frac{2prw}{\mu}.

In what follows, we will assume that rather large droplets participate in the capture of aerosol, so that Re >> 1. It is important to note that the value of the mean free path \( \lambda_a \) depends very slightly on the aerosol radius, since almost always \( r_a << r \). The dependence of \( \lambda_a \) on \( N \) for \( r_a = 6 \mu m \) and \( r = 300 \mu m \) is the following: for \( N = 10^3, 5 \cdot 10^3, 10^4, \) and \( 5 \cdot 10^4 \) m\(^{-3}\) the quantity \( \lambda_a = 1.7 \cdot 10^3, 340, 170, \) and \( 34 \) m, respectively. It is interesting to note that the speed of the developed fall of a droplet with \( r = 300 \mu m \) amounts to 2.5 m/sec [4].

The probability density \( f(x) \) for the path \( x \) to be traversed without collisions within the framework of the mean free path approximation [5] is equal to

\[
f(x) = \exp\left(-\frac{x}{\lambda_a}\right)/\lambda_a, \tag{2}\]

and then the probability \( p(L) \) for the aerosol to be captured by droplets over the path \( L \) is

\[
p(L) = 1 - \exp\left(-\frac{L}{\lambda_a}\right). \tag{3}\]

The efficiency of the mean free path approximation is associated with the fact that in the cooling tower plume the density of droplets is such that the distance between droplets is much larger than the characteristic radius of the droplets. The probability for the aerosol particles to be captured by droplets for \( L = 100 \) m depends in the following way on the free mean path \( \lambda_a \): for \( \lambda_a = 1.7 \cdot 10^3, 340, 170, \) and \( 34 \) m the quantity \( p = 0.06, 0.25, 0.44, \) and \( 0.94 \).

As is seen, for \( L = 100 \) m and \( \lambda_a = 170 \) m about 44% of aerosol particles are captured by droplets. Note that in the course of the analysis the dimensionless quantity

\[
B = Lr_a^2 N - L/\lambda_a, \tag{4}\]

appears, which virtually determines the efficiency of the capture of aerosol by water droplets. When \( B << 1 \), the probability of capture is low, while with \( B >> 1 \) actually all of the aerosol particles are captured by water droplets. As follows from Eq. (2), the efficiency of capture is high if \( L \sim \lambda_a \). Expressions (1) and (4) can easily be generalized to take into account the size distribution function of droplets. In fact

\[
\lambda_a = \frac{1}{\pi \int n(r_d)(r_a + r_d)^2 dr_d \Phi(v/w_d)}, \quad N = \int n(r_d)dr_d.
\]

Thus, the physical meaning of the effective radius of a droplet \( r \) in Eqs. (1)-(4) is clear from the following formula:

\[
(r_a + r)^2 = \int n(r_d)(r_a + r_d)^2 dr_d/N.
\]

It is very difficult to determine theoretically the quantity \( L \); however, we may assume for qualitative evaluations that \( L \) is of the order of the exit plume diameter of the cooling tower.

The further evolution of the droplets will be determined by their motion under gravity, the sweeping by horizontal wind with velocity \( U \), and diffusional spreading under the influence of turbulent pulsations (we use \( k_y \) to denote the coefficient of turbulent diffusion). In this case, if we neglect the influence of the process of evaporation of droplets on the dynamics of motion (which is valid in the majority of practically interesting situations), all the water droplets will be swept a distance

\[
\Delta x \sim HU/w(r_d), \tag{5}\]