Journal of Engineering Physics and Thermophysics, Vol. 65, No. 5, 1993

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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UDC 551.594.25:541.182.2

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 expendient 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 λ_a. It can easily be shown that the expression for λ_a has the form

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

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 $v = \varepsilon_0 u_0$, where ε_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, $\varepsilon_0 \approx$ (0.1-0.3). The function Φ 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 >> 1 [4], where

Academic Scientific Complex "The A. V. Luikov Institute of Heat and Mass Transfer", Academy of Sciences of Belarus, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 65, No. 5, pp. 539-547, November, 1993. Original article submitted November 6, 1992.

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$$\mathrm{Re} = \frac{2\rho r w}{\mu}.$$

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 λ_a depends very slightly on the aerosol radius, since almost always $r_a << r$. The dependence of λ_a on N for $r_a = 6\ \mu$m and $r = 300\ \mu$m is the following: for $N = 10^3$, $5\cdot10^3$, 10^4, and $5\cdot10^4$ m^{-3} the quantity $\lambda_a = 1.7\cdot10^3$, 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

$$f(x) = \exp(-x/\lambda_a)/\lambda_a, \tag{2}$$

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

$$p(L) = 1 - \exp(-L/\lambda_a). \tag{3}$$

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 λ_a: for $\lambda_a = 1.7\cdot10^3$, 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

$$B = Lr^2 N \sim L/\lambda_a \tag{4}$$

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

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

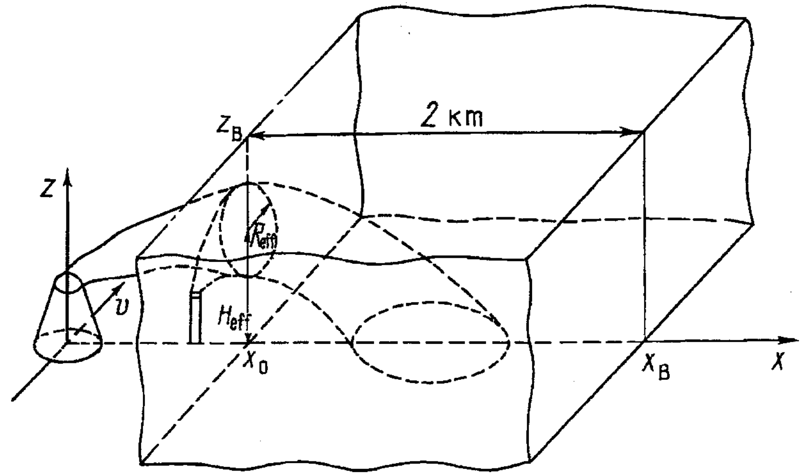

Fig. 1. Schematic representation of the displacement of the vent pipe and cooling tower plumes.

where H is the effective height of the intersection of the two plumes. Turbulent pulsations cause broadening in the direction normal to the wind [4]. The width of the trail of droplets deposited onto the earth l can easily be evaluated using the familiar estimate of the diffusional width

$$l \sim \sqrt{2k_y H/w\,(r_d)}\;. \tag{6}$$

Note that comparison with the numerical calculations given below demonstrates a sufficiently high accuracy of expressions (3), (5), and (6).

Mathematical Model. Below we present a mathematical model and the results of calculations of the washout of aerosol for the pipe-cooling tower system of an NPS power-generating unit with a power of 1000-1300 MW. The parameters of the cooling tower are: height $H_{tow} = 180$ m, mouth radius $R_{tow} = 48$ m, vertical velocity of the plume at the exit from the mouth $w_{tow} = 5$ m/sec, water flow rate through the cooling system $Q_{tow} = 50$ m^3/sec. The parameters of the pipe are: height $H_p = 150$ m, mouth radius $R_p = 2.5$ m, vertical velocity of the plume at the exit from the mouth $w_p = 10$ m/sec. The distance between the pipe and the cooling tower is 200 m. We consider two versions of the relative location of the pipe and cooling tower with respect to the wind direction: the pipe is located on the windward and leeward side of the cooling tower. Laboratory modeling shows [7] that in these cases the plume of the cooling tower captures the pipe plume, and intensive mixing of them occurs. In the mixing zone of the plumes the aerosol particles are absorbed by water droplets, transported by an air stream, and are deposited on the surface of the earth. In Fig. 1 the domain of numerical solution of the equations of the model is depicted. The boundary of the mixing zone of the plumes is located on the inlet boundary of the region, and the geometric characteristics of the mixing zone (distance from the center of the cooling tower x, effective height H_{ef} and radius R_{ef}) are determined from data of the laboratory modeling of different regimes of flow around the pipe-cooling tower system, presented in detail in [7]. When the processes of the washout of impurities from the atmosphere are modeled, the washout speed for an impurity having the volumetric concentration c is usually formulated in the form of a Stokes component λc is the coefficient of washout [8]). When aerosol particles of radius r_a are absorbed as a result of collisions with differently sized droplets described by the radius distribution function $n(r_d)$, the washout coefficient has the form

$$\int K\,(r_a\,,\;r_d)\;n\,(r_d)\;dr_d\,,$$

where $K(r_a,\,r_d)$ is the coeffficient of the turbulent-gravitational coagulation of droplets and aerosol particles, which depends on the rate of the turbulent energy dissipation. Thus, to calculate the three-dimensional field of the coefficient λ, it is necessary to have the fields of $n(r_d)$ (simulation of the microphysics of the nucleation and evolution of droplets) and ε (simulation of turbulent aerodynamics). In estimation computations, the microphysical processes can be neglected, taking into consideration that mainly large droplets of radius ~ 100 μm will wash out the aerosol. First, the collision cross section of such droplets and aerosol particles is close to unity and falls rapidly to zero with a decrease in the radius of the droplets [9]. Second, droplets of smaller radius under normal atmospheric conditions have no time to reach the surface of the earth because of evaporation [10], and therefore the aerosol captured by them will not be deposited. Since the size distribution function of the droplets in the plume of the cooling tower is unknown, we assume for simplicity that all of the droplets are of the same size. Let us evaluate the concentration and radius of large droplets. The overall water content of the cooling tower plume, i.e., the quantity of water in unit volume in vapor and droplet-liquid phases can be estimated by taking into account the fact that about 2.5% of the water is lost from the cooling system in the cooling tower:

$$\delta = \frac{0.025 Q_{\mathrm{tow}} \rho_{\mathrm{w}}}{\pi R_{\mathrm{tow}}^2 w_{\mathrm{tow}}} = 50 \ \mathrm{g \cdot m^{-3}}$$

Large droplets fall within the plume mainly as a result of sputtering, fragmentation and entrainment by air stream and also coagulation of fine droplets. It is rather difficult to estimate theoretically the water content of the droplet phase of the plume. We assume that by the order of magnitude $\delta_{\mathrm{d}} = 10 \ \mathrm{g \cdot m^{-3}}$, i.e., large droplets contain on the order of 20% of the water lost. To estimate the concentration of large droplets, we shall avail ourselves of the formula that is usually used to describe the spectrum of large droplets in clouds [9]:

$$N(r_{\mathrm{d}}) = N_1 (r_1/r_{\mathrm{d}})^{\alpha}, \quad r_1 \le r_{\mathrm{d}} \le r_2, \quad \alpha \ge 2,$$

where $N(r_{\mathrm{d}})$ is the concentration of droplets of radius larger than r_{d}; N_1 is the total concentration of large droplets; $r_1 = 85 \ \mu$m, r_2 changes in wide ranges in accordance with the type of clouds but rarely exceeds 1500 μm. Assuming that intense fragmentation of droplets occurs inside a cooling tower and therefore their spectrum is rather wide, we adopt the minimum value $\alpha = 2$ and find the concentration of large droplets at the outlet from the cooling tower mouth

$$N_{\mathrm{tow}} = N_1 = \frac{\delta_{\mathrm{d}}}{\frac{4}{3}\pi\rho_{\mathrm{w}} r_1^3 \left(\frac{3r_2}{r_1} - 2\right)} = 7.6 \cdot 10^4 \ \mathrm{m^{-3}}$$

and the radius of the droplets

$$r_{\mathrm{d}} = r_1 \left(\frac{3r_2}{r_1} - 2\right)^{\frac{1}{3}} = 315 \ \mu\mathrm{m}.$$

The formula for the coefficient of the coagulation of droplets of radius r_{d} and aerosol particles of radius r_{a} has the form [9]

$$K(r_{\mathrm{d}}, r_{\mathrm{a}}) = \pi (r_{\mathrm{d}} + r_{\mathrm{a}})^2 (g + g_t) \frac{\tau_{\mathrm{d}} - \tau_{\mathrm{a}}}{\varphi(\mathrm{Re})} E + 2K_{tb}. \tag{7}$$

Here g is the free fall acceleration, $g_t = 4.8/\pi(\varepsilon^3/\nu)^{1/4}$ is the effective turbulent acceleration, ε is the rate of turbulent energy dissipation, ν is the kinematic viscosity of air, $\tau_{\mathrm{d}} = 2/9\, \rho_{\mathrm{w}} r_{\mathrm{d}}^2/\mu$, $\tau_{\mathrm{a}} = 2/9\, \rho_{\mathrm{a}} r_{\mathrm{a}}^2/\mu$ are the relaxation times for droplets and aerosol particles, μ is the dynamic viscosity of air, $\varphi(\mathrm{Re})$ is a correction factor taking into account the deviation of the law that governs the motion of droplets in air from the Stokes law with growth in the Reynolds number, E is the collision cross section of droplets and aerosol particles. For droplets of radius $r_{\mathrm{d}} = 315 \ \mu$m the speed of fall is $w_{\mathrm{d}} = 2.59$ m/sec [11], $\mathrm{Re} = 2r_{\mathrm{w}}w_{\mathrm{d}}/\nu = 121$, $\varphi(\mathrm{Re}) = 4.64$ [9]. The collision cross section for Re >> 1 can be calculated from the formula of Langmuir and Blodget [10]:

$$E = \mathrm{Stk}^2/(\mathrm{Stk} + 0.125)^2 ,$$

where

$$\mathrm{Stk} = \frac{\rho_a r_a^2 (w_d - w_a)}{9 \mu r_d}$$

is the Stokes number, w_a is the velocity of the gravitational deposition of aerosol. When $r_d > 50\ \mu$m, the speed of the fall of droplets depends almost linearly on the radius, and therefore the quantity E depends mainly on the radius of aerosol and differs substantially from zero when $r_a > 1\ \mu$m. We consider aerosol particles of density $\rho_a = 2.5$ g/cm^3 and radius $r_a = 6\ \mu$m ($w_a = 2.85 \cdot 10^{-3}$ m/sec, Stk = 4.79, $E = 0.97$). For these particles experimental data on the speed of dry deposition onto the surface are available. This speed enters into the boundary condition for the concentration of free aerosol.

The diffusional part of the coagulation coefficient is described by the term

$$K_{tb} = 1.7\ (\varepsilon/\nu)^{1/2}\ (r_d + r_a)^3 .$$

The rate of turbulent energy dissipation at the exit of the plume from the cooling tower can be estimated from the formula

$$\varepsilon_{\mathrm{tow}} \simeq \nu\ \overline{u'^2}/l_t^2 ,$$

where $\overline{u'^2}$ is the mean square of velocity pulsations; l_t is the microscale of turbulent pulsations. If we avail ourselves of the experimental results for axisymmetric turbulent jets [12], then

$$(\overline{u'^2})^{1/2} \simeq 0.2\ w_{\mathrm{tow}} , \quad l_t \simeq 1.23\ (2\ R_{\mathrm{tow}}\ w_{\mathrm{tow}}/\nu)^{1/2}\ \Delta Z ,$$

where ΔZ is the distance from the cooling tower mouth in the vertical direction. Assuming for estimation that $\Delta Z = R_{\mathrm{tow}}$, we obtain $l_t = 10^{-2}$ m, $\varepsilon_{\mathrm{tow}} = 0.17$ m/sec^2. Since the turbulence of the plume has a much greater intensity and much finer scale than the atmospheric boundary layer turbulence, we can approximately regard the rate of dissipation in the plume to be a scalar field, which is transferred by the air stream and is "blurred" by the atmospheric turbulence. Then the equation for ε has the form

$$\partial_t \varepsilon + U \partial_x \varepsilon = k_y\ \partial_{yy}^2 \varepsilon + \partial_z k_z \partial_z \varepsilon . \tag{8}$$

The concentration of droplets is determined by the transfer by the air stream, gravitational deposition, and turbulent diffusion:

$$\partial_t N + U \partial_x N - w_d\ \partial_z N = k_y\ \partial_{yy}^2 N + \partial_z k_z \partial_z N . \tag{9}$$

The equation for the concentration of the free aerosol is supplemented with the term that describes the washout:

$$\partial_t c_a + U \partial_x c_a - w_a\ \partial_z c_a = k_y\ \partial_{yy}^2 c_a + \partial_z k_z \partial_z c_a - \lambda c_a . \tag{10}$$

The concentration of the aerosol captured by droplets is determined by the transfer by the air stream, gravitational deposition of droplets, turbulent diffusion, and influx due to the washout of the free aerosol

$$\partial_t c_d + U \partial_x c_d - w_d\ \partial_z c_d = k_y\ \partial_{yy}^2 c_d + \partial_z k_z \partial_z c_d + \lambda c_a . \tag{11}$$

In the case of droplets of the same radius, the coefficient of the washout of the free aerosol is

$$\lambda = K(r_d, r_a)\, N. \tag{12}$$

The system of equations (7)-(12) is closed by boundary conditions for ε, N, c_a, c_d.

At the inlet boundary $x = x_0$ the condition of equality of the fluxes of scalar quantities through the mouths of the sources and the inlet boundary yields

$$\{\varepsilon, N, c_a, c_d\} = \begin{cases} \{\varepsilon_{tow}\, w_{tow}\, R_{tow}^2,\ \ N_{tow}\, w_{tow}\, R_{tow}^2,\ \ c_p\, w_p\, R_p^2,\ \ 0\}/U(z_{ef})\, R_{ef}^2 \\ \text{when } y^2 + (z - z_{ef})^2 \le R_{ef}^2; \\ 0 \text{ when } y^2 + (z - z_{ef})^2 > R_{ef}^2, \end{cases}$$

where c_p is the concentration of the free aerosol at the exit of the plume from the vent pipe mouth.

Since in the majority of cases the height of the atmospheric boundary layer lies within the height of the integration region $z_w = 1000$ m and there are no vertical turbulent streams through the upper edge of the boundary layer, then at $z = z_w$

$$\partial_z \varepsilon = \partial_z N = \partial_z c_a = \partial_z c_d = 0.$$

On the lower boundary $Z = 0$ we adopt the condition of reflection for the rate of dissipation and the condition of the full absorption of droplets

$$\partial_z \varepsilon = N = c_d = 0.$$

For the free aerosol the boundary condition on the underlying surface is usually formulated as [13]

$$k_z\, \partial_z c_a + w_a c_a = a\, c_a,$$

where a is the speed of dry deposition. Its dependence on friction velocity and the speed of gravitational deposition was derived experimentally in [14]: $a = bu_* + w_a$, $b = 4 \cdot 10^{-2}$ for particles with $r_a > 5\ \mu$m.

Since, as is done in the models of impurity propagation in the boundary layer of the atmosphere, we neglect turbulent diffusion along the flow, the values of the variables at the exit boundary $x = x_w$ can be calculated from equations.

Equations (7)-(11) and boundary conditions contain as parameters the horizontal speed of the wind $U(z)$, the coefficient of turbulent diffusion in the horizontal $k(x, z_y)$ and vertical $k_z(z)$ directions, and the friction velocity u_*. These parameters are calculated with the help of a semiempirical model of the boundary layer of the atmosphere based on the balance equations for the kinetic energy of turbulence and the rate of dissipation [15]. In this case the coefficient k_y can be represented in the form [2]

$$k_y(x, z) = U(z)\,(k_0 + \beta^2 x),$$

where k_0 is a constant depending on stratification; β^2 is the variance in the fluctuations of the direction of the wind velocity vector. This form of representation allows one to reduce the problem to a two-dimensional one with the aid of the substitution

$$\varepsilon(x, y, z) = \varepsilon^*(x, z)\, \frac{\exp(-y^2/2\sigma^2)}{\sqrt{2\pi\sigma^2}}, \quad \sigma^2(x) = 2kx_0 + \beta^2 x^2$$

and similar substitutions for the remaining variables.

The stationary solution of the problem for ε^*, N^*, c_d^*, and c_a^* is found numerically by a time-dependent technique with zero initial conditions. It uses an algorithm of splitting into the physical processes of advection,

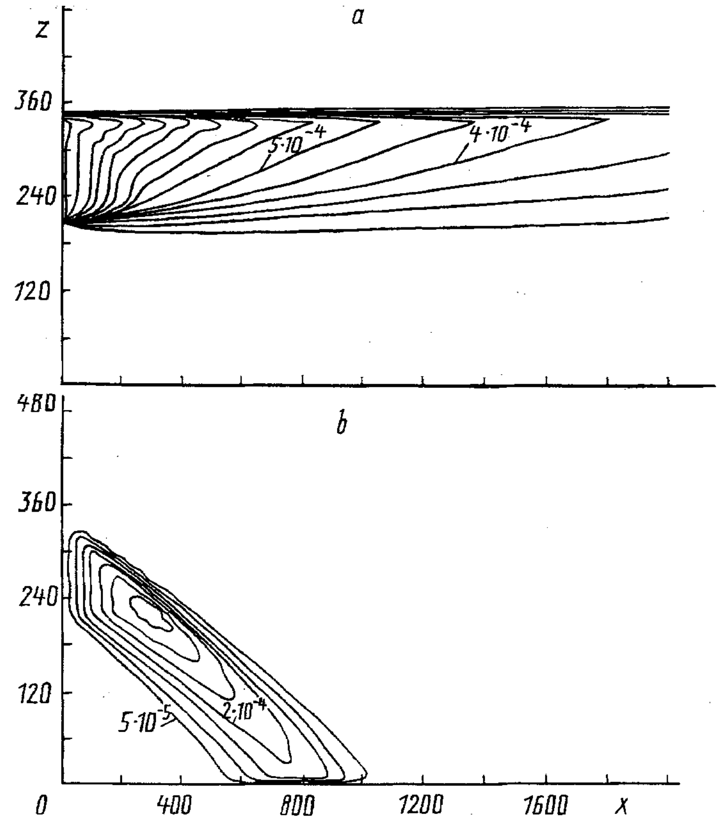

Fig. 2. Isolines of the dimensionless concentration field of the free (a) and captured (b) aerosol at $y = 0$. x, z, m.

diffusion, and washout. The advection stage is calculated with the help of a semi-Lagrangian scheme with bilinear interpolation [16], and the stage of diffusion is calculated with the help of a conservative scheme of the second order of approximation [17]. The grid step is $\Delta x = 50$ m in the horizontal direction and $\Delta z = 4$ m in the vertical direction (the dimensionless steps are equal to 0.05 and 0.04, respectively).

To characterize the efficiency of washout, we introduce the integral coefficient of the washout as the ratio of the overall flow of bound aerosol onto the surface of the earth to the flow through the pipe mouth

$$\Lambda = \iint_{z=0} (k_z \, \partial_z \, c_d + w_d \, c_d) \, dxdy / c_p \, w_p \, \pi R_p^2 .$$

Since the concentration of captured aerosol on the surface of the earth is equal to zero, we actually take the values of the integrand at the first computational level $z = 4$ m, allowing for the constancy of the turbulent flow in the near-earth layer [18]: $k_z \partial_z c_d |_{z=4} = k_z \partial_z c_d |_{z=0}$.

Results of the Calculations. We performed calculations for four versions differing by the relative positions of the pipe and cooling tower and by the speed of the geostrophic (at the upper edge of the boundary layer) wind U_g. The following parameters characterize the boundary layer of the atmosphere: roughness parameter (characteristic dimension of the irregularities of the surface) $z_0 = 1$ cm; the Coriolis parameter $f = 2\Omega \sin \varphi = 10^{-4}$ corresponds to the latitude $\varphi = 40^0$ (Ω is the angular speed of the rotation of the earth). The air temperature near the earth's surface of 17^0C and the stable temperature stratification of the upper part of the boundary layer correspond to the mean conditions of summer for the Moscow region [10]. The temperature stratification of the lower part of the boundary layer is neutral.

The results of calculation of Λ are the following:

U_g, m/sec	10	−10	5	−5
Λ, %	17	26	43	45

TABLE 1. Dependence of the Integral Coefficient of Washout Λ on the Water Content of the Cooling Tower Plume

δ_d, g/m^3	Λ, %		δ_d, g/m^3	Λ, %	
	U_g = 10 m/sec	U_g = −5 m/sec		U_g = 10 m/sec	U_g = −5 m/sec
10	26	45	30	52	90
20	42	73	40	57	98

Positive values of U_g correspond to the position of the pipe on the leeward side of the cooling tower, and negative values on the windward side. In Fig. 2 the isolines of the dimensionless concentration fields are given for a free c_a/c_p and captured c_d/c_p aerosol at the section $y = 0$ for the second version.

The main conclusion that can be drawn taking into account the estimation character of the calculations is that the fraction of the washed out aerosol is appreciable, i.e., it amounts to dozens of a per cent. A perceptible growth in Λ with a decrease in the wind speed is due to the increase in the local rate of washout because of the rise in the concentration of droplets and aerosol in the mixing zone of the plumes. We also note some increase in Λ for the case of the position of the pipe on the leeward side of the cooling tower due to the increase in the concentration at the inlet to the mixing zone.

Table 1 conveys the change in Λ with an increase in the water content of the droplet phase of the cooling tower plume. We note the nonlinear character of the dependence: to double the fraction of the washed-out aerosol it is necessary to increase the water content by a factor of three.

Discussion of the Results and Conclusion. As a result of theoretical investigations and mathematical simulation it is shown that the efficiency of the capture of aerosols, including radioactive ones, by water droplets depends on many factors. The main ones are the dimensions of the mixing zone of the two plumes and two moments of the droplet radius distribution function (zeroth and second). This work proved that the intensity of turbulent agitation in the mixing zone and the speed of the stalling wind are also significant. Large droplets that captured the aerosol precipitate onto the earth. The magnitude of sweeping depends on the effective height of the mixing zone of the plumes, the mean horizontal speed of the stalling wind, and the speed of steady gravity-induced fall of droplets of size equal to the mean size of droplets in the distribution function introduced above. As a result of turbulent agitation in the boundary layer of the atmosphere, the cloud of droplets broadens in the direction normal to the wind speed. The characteristic dimension of the droplet cloud broadening on the underlying earth surface depends on the effective height of the mixing zone of the two plumes, the fall time of the droplets, and the coefficient of turbulent diffusion.

It is interesting to note that the process of the washout of radioactive aerosols by liquid droplets attracts the attention of engineers and research workers looking for ways of reducing the consequences of grave accidents at NPS not only in the free atmosphere, but also in the atmosphere of the containment [19]. It is natural that due to the much higher concentration of aerosol than that in the regime investigated here, effects that depend nonlinearly on the aerosol concentration play an important part.

In conclusion we wish to express our gratitude to N. I. Lemesh and L. A. Senchuk for kindly providing the experimental data and to V. P. Reshetin for interesting discussions of the problem.

NOTATION

r_a, aerosol radius; λ_a, mean free path of aerosol; r_d, droplet radius; $w(r_d)$, steady-state fall velocity of a droplet; c, volumetric concentration of impurity; λ, coefficient of washout; E, collision cross-section of droplet and aerosol; $U(z)$, horizontal wind speed; Λ, integral coefficient of washout; U_g, speed of geostrophic wind; f, Coriolis parameter; δ_d, water content of the droplet phase.

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