EVOLUTION OF AEROSOLS IN LARGE PRESSURIZED SPACES

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Results of experiments in pressurized spaces of 100 to 3200 m^3, including a manned space station, carried out to study the evolution of aerosols and ions in the course of their spontaneous decay and removal by an electric field or mechanical means are considered.

The construction of systems for cleaning and monitoring aerosol and ion climates in large isolated rooms requires information on the kinetics of the concentration and size of particles of diameter from 10^{-3} to 20 μm, including situations involving sources of ionizing radiation and electric fields. The practical aim of this work was to study the kinetics of concentration of aerosols under terrestrial conditions and conditions of weightlessness with and without forced aeroionization and in the case of inhalation and mechanical cleaning.

Experimental Techniques. Model experiments were carried out in aerosol chambers with volumes of 3200, 100, and 8 m^3 (steel cylinders with external heat insulation). Insoluble finely disperse particles (of metals, sand, and clay) were generated by pneumatic bubbling. Particles of soluble substances (NaCl, $(NH_2)_2CO$, etc.) were formed by fine-dispersion countercurrent pneumatic sprayers and by dispersers with a vibrating multinozzle membrane [1, 2]. A condensation-type smoke generator was used to simulate the evolution of bioactive aerosols [3]. Charged microparticles were generated by condensation of supersaturated vapor of water or petroleum products on corona-discharge ions [2].

Aerosol processes in a pressurized space under conditions of weightlessness and continuous purification of air were studied in terrestrial and manned 100-m^2 sections of the Salyut orbital station. The space flight was conducted in July–August 1988. A generator of model pyrolytic aerosols based on the principle of thermal destruction of polymer materials, a continuous filter of aerosols, a Spektr photoelectric counter, and two onboard DAES-type electrostatic analyzers of aerosols were used [4, 5].

Characteristic Background Spectra. It is of interest to compare typical natural and "chamber" spectra of the sizes of aerosols (Fig. 1). The former characterize the boundary layer in a wooded locality 100 km from Moscow and in Franz Josef Land [5].

The measurements in pressurized spaces of volume 8 and 3200 m^3 were made by the same apparatuses as under natural conditions. In the insulated chambers particles of a wide range of dimensions $D = 0.05$–20 μm are constantly present, and the concentration of coarsely disperse particles here is roughly an order of magnitude higher.

The unexpectedly high concentrations of aerosols in the pressurized spaces are explained by two basic factors: first, by microdeformations of and constant generation of dust by internal surfaces; second, by convective air exchange caused by nonuniformities of the temperature on the surfaces of the chamber.

Kinetics of Natural "Decay" of an Aerosol. The process of natural decay of hygroscopic and pyrolytic aerosols in a closed chamber is illustrated by Fig. 2. Aerosol particles were introduced into a cleaned and preliminarily humidified (to $H = 55$–65%) chamber of volume 3200 m^3 by pneumatic spraying of a 10% solution of carbamide. Droplets with an initial diameter of 0.5–10 μm (the mass-mean diameter of the drops is 1.5
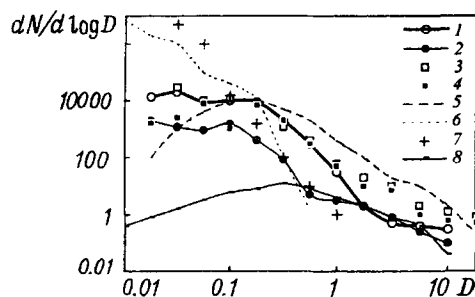

Fig. 1. Normalized distributions of aerosols by size D that are characteristic of a wooded locality near Moscow (1), spring Arctic (2), and pressurized chambers of volumes 3200 (3, 5, 6, 8) and 8 m³ (4, 7). Background distributions 3 and 4 are measured after keeping the medium still for 72 h; distributions 5-7 are measured after injection of microdroplets with $D = 1.5$ μm (cubic-mean diameter) of a 10% acqueous solution of carbamide (5), products of thermal destruction of wood (6), and irradiation of dust-free air with alpha particles (7). Distribution (8) is obtained after 5-h generation of ions of a corona discharge from a long filament. $dN/d \log D$, cm⁻³; D, μm.

μm, and the diameter of the dry core is 0.25 μm) were vaporized. At the humidity indicated, the spectrum of the sizes of the aerosol shown in Fig. 1 (curve 5) was formed.

The volatilization of a polymer sample based on polyvinyl chloride proceeded at 350°C, which, according to [6], corresponds to the maximum yield of fine particles. The form of the spectrum of a pyrolytic aerosol with a time of generation of 5 min is characterized by curve 6.

Two interesting features can be noted. First, there was no special difference in the kinetics of the concentration of particles of different materials even with different means of generation. Over the period of observation (about 70 min) the overall concentration of the particles decreased by four orders of magnitude. Second, the changes in the total number density and mass concentration of the aerosol turned out to be synchronous. This indicates not only strong conservatism of the size distribution function of the particles for virtually the entire period of observation, but also, which is not at all trivial, good mixing of the aerosol medium even in closed heat-insulated spaces.

Let us consider the physical picture of the phenomenon. We will represent the equation of state of an aerosol in a pressurized space in a form [7] that takes into account the internal source of the particles q, their enlargement due to coagulation, and outgo to the walls:

$$dN/dt = q - \gamma N^2 - \beta N .$$ (1)

For the obvious boundary conditions $N = N_0$ for $t = 0$ and $N = N_\infty$ for $t = \infty$, the solution of Eq. (1) has the form

$$N(t) = N_\infty + \frac{(N_0 - N_\infty) \exp(-t/\tau)}{1 + \gamma\tau (N_0 - N_\infty) [1 - \exp(-t/\tau)]} ,$$ (2)

where $\tau = (\beta^2 + 4q\gamma)^{-\frac{1}{2}}$ is the characteristic time of relaxation of the aerosol system; $N_0 = (\tau^{-1} - \beta)/2\gamma$.

We will examine the characteristic times of the processes in the given aerosol system, having in mind the following basic processes: coagulation, sedimentation, and Brownian and turbulent diffusion of the particles. Taking into account the conservatism of the spectrum of the size of the dust particles, for the times of their coagulation τ_c, sedimentation τ_{sed}, and Brownian diffusion τ_{dif} the following relations hold:
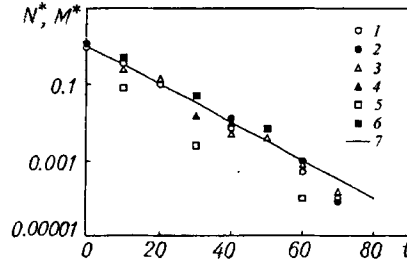
Fig. 2. Change in the dimensionless number density N^* (1, 3, and 5) and mass concentration M^* (2, 4, and 6) of an aerosol in a chamber of volume 3200 m^3 with time: 1, 2) pyrolytic aerosol; 3, 4) hygroscopic aerosol; 5, 6) 1 h after electrostatic precipitation *in situ*; 7) calculation by Eq. (5). t, h.

$$\tau_c = (\gamma N)^{-1}, \tau_{sed} = 9h\eta\,(1 + AL/R)/2R^2\rho g, \tau_{dif} = 6\pi\eta Rd^2/4\mu^2 kT\,(1 + AL/R).$$

Calculations for a chamber of diameter $d = 15$ m and height $h = 15$ m give numerical estimates for the times: $\tau_c > 10^5$–10^6 sec (for $N < 10^4$ cm^{-3} and $\gamma = 10^{-9}$ cm^3·sec^{-1}), $\tau_{sed} = 10^8$ sec, and $\tau_{dif} = 10^9$ sec ($R = 0.1$–0.2 μm is the mean radius of the aerosol), i.e., they are much higher than those observed in the experiment given in Fig. 2: $\tau_{exp} \sim 10^5$ sec. This means that the sedimentation and the Brownian diffusion exert little influence on the behavior of aerosols in pressurized spaces.

Detailed investigations of the diffusion of a passive admixture showed that even in the interior of a quiet (stilled) pressurized chamber there always are differently directed induced air flows with a mean velocity of the order of units of cm/sec. Fluctuations can generally be described by the mean effective coefficient of turbulent diffusion $D_t = 1$ cm^2/sec [7].

The characteristic time of dissipation of an aerosol in a cylindrical vessel due to turbulent diffusion will be written in the form

$$\tau_t = d^2/4\mu^2 D_t = 10^5 \text{ sec}.$$

This time turns out to be of the order of that observed in the experiments given in Fig. 2: $5 \cdot 10^4$–$5 \cdot 10^5$ sec, which allows one to consider the mechanism of turbulent diffusion as the basic one. Correspondingly, Eq. (1) is reduced to the simple form

$$dN/dt = q - \tau^{-1}N_\infty, \tag{3}$$

where $\tau = \tau_t$; $q = (4\tau^2\gamma)^{-1} = 0.025$ cm^{-3}·sec^{-1}; $N_\infty = (2\gamma\tau)^{-1} = 5000$ cm^{-3}. The computational evaluations of the time behavior of the instantaneous N and background N_0 concentrations are close to those observed experimentally (see Figs. 1 and 2).

Thus, the basic mechanism of natural removal of aerosol particles from the considered pressurized vessels of volumes from tens to thousands of cubic meters is turbulent diffusion.

Long-duration quiscence of the vessels (more than 2–3 days) does not lead, however, to a decrease in the concentration of the aerosols, which is explained by the establishment of a certain equilibrium between the reduction of the particles and their arrival in the space, in particular, due to the production of dust by the internal surfaces of the vessel or to its secondary rise.

Therefore, it is of interest to consider active methods of dust suppression, i.e., the case where the air inside the space is acted upon physically with a view to changing its aerosol composition.

Kinetics of an Aerosol in Air Ionization. There are several techniques for ionization of an air medium: by ions of different polarities or bipolar ions, by unipolar ions, and by ions in the presence of a strong electric field [3].

Bipolar ions can be produced most easily by exposing air to ionizing radiation. Here the ions diffuse with a velocity of the order of 0.05 cm^2/sec to the aerosol particles and charge them with heteropolar charges, which accelerates the process of coagulation and coarsening of the aerosol. However, the problem is that under certain conditions bipolar ionization leads to the appearance of new (radiolytic) aerosol particles [8]. Figure 1 shows the spectrum of the size of particles that appeared in a chamber of volume 8 m^3 after dust-free air was subjected to irradiation by alpha-particles for 6 h. A plane source based on substrates of the isotope plutonium-239 with a mean energy of the particles of $8.32 \cdot 10^{-13}$ J provided an ionizing current of 10^{-6} A.

As is seen from Fig. 1, in spectra of a radiolytic (just like a pyrolytic) aerosol highly disperse particles of size less than 1 μm prevail. On stoppage of the generators the concentration of the particles undergoes relaxation in a time of the order of 1000 sec or less as a result of coagulation.

Injection of *unipolar ions* accelerated the removal of finely disperse aerosols from a 3200-m^3 chamber by tens of times (see Fig. 2). Negative ions were generated by a Chizhevskii chandelier [9] with 30 points displaying a corona on a wire sphere 60 cm in diameter. We note that the rate of removal of aerosols with a diameter larger than 0.5 μm turned out to be very low.

Much better results were shown by the method of *injection of ions in the presence of a unipolar electric field* [10], and it makes sense to consider this method in more detail. At the center of the 3200-m^3 chamber a 100-μm-diameter and 8-m-long constantan wire was hung vertically. On supplying a voltage higher than 10 kV, a unipolar corona discharge appeared in the space between the wire and the chamber. The main products of the corona discharge are negative light ions of mean mobility about 2 cm^2/(V·sec).

In the presence of the potential on the wire displaying a corona, aerosol particles gradually arrived at the chamber walls from the interior. By the end of a five-hour cycle a stationary spectrum of the size of the particles was formed in the chamber virtually irrespective of the initial conditions (curve 8 in Fig. 1).

As is seen, after electrostatic precipitation the concentration of particles with $D = 10^{-2}$–10 μm was decreased by a factor of 1000 and was equal to 20 cm^{-3}. The finest fractions ($D = 0.01$–0.1 μm) virtually disappeared, and the concentration of particles with a diameter of 1 μm was decreased to 1 cm^3/sec, in complete correspondence with the requirements on the dust content of clean rooms of class of cleanness 100,000.

For a theoretical description of the dynamics of cleaning a chamber we will consider the spectral behavior of the time of electrical relaxation (electrostatic precipitation) of the concentration of the aerosol:

$$\tau_{el}(D) = \frac{xf}{u(D, Q)E}, \tag{4}$$

where E is the mean electric-field strength in the space, $x = 7.5$ m, $f = 1 - \exp(-1/2) \sim 0.4$ is a factor. As is seen from Fig. 3, the experimental dependence has a maximum in the region of $D = 1$ μm, i.e., the finest and largest particles are removed from the volume more rapidly than particles of diameter $D = 1$ μm.

For a theoretical description of the function $\tau(D)$ we will represent the expression for the electrical mobility of the particles u in the form of the well-known Stokes–Cunningham approximation

$$u(D, Q) = \frac{Q(1 + 2AL/D)}{3\pi\eta D}. \tag{5}$$

According to [11], the total charge of an aerosol particle Q is equal to the arithmetic sum of the contributions of the diffusional Q_d and impact-excitation Q_e mechanisms of charging:

$$Q = Q_d + Q_e, \tag{6}$$

where the components Q_d and Q_e are defined below.

The *diffusional* mechanism is responsible for ionic charging of fine particles. An analysis has shown [3] that in the case of fine particles with $D < 0.5$ μm the best approximation to the results of experiments is given by the Arendt–Kalman relation
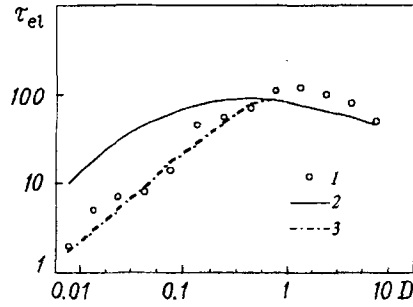
Fig. 3. Measured evaluations (1) and evaluation calculated by Eqs. (4) and (8) (2) and Eq. (9) (3) for the time of relaxation of the concentration of aerosol particles in a cylindrical chamber of volume 3200 m^3 equipped with a wire electrode displaying a corona at a potential of 30,000 V and a current strength of 25 μA. The length of the wire is 8 m, and the diameter is 100 μm. The mean electric-field strength in the gap is 50 V/cm. τ_{el}, min.

$$Q_d = 2\pi\varepsilon\varepsilon_0 e^{-1} DkT \ln\left[1 + \frac{C_i e^2 Dnt_Q}{8\varepsilon_0 kT}\right].$$ (7)

It follows from Eq. (7) that the mean diffusional charge Q_d is determined by the charging parameter nt_Q. The higher the concentration of aeroions n and the time of charging t_Q, the higher the value of Q_d. We note that within the framework of this consideration the relaxation time $\tau(D)$ is adequate for the time of the charging of the particles t_Q.

The contribution of the *impact-excitation* mechanism increases with increase in the size of the particle and the electric-field strength and is usually evaluated by means of Potenier and Moro-Ano's well-known formula [3]

$$Q_e = \pi\varepsilon\varepsilon_0 ED^2 \delta \ [eu_i\, nt_Q/(4\varepsilon_0 + eun_i\, t_Q)] .$$ (8)

The parameter δ takes into account the dielectric constant (ε_a) of the material of the particles: $\delta = (\varepsilon_a - 1)/(\varepsilon_a + 2)$.

Results of calculations by Eqs. (4) and (8) are illustrated by curve 2 in Fig. 3. We see that the computational function correctly describes the character of the spectral dependence of the relaxation time. However, one can see a noticeable underestimation (by a factor of 3–5) by the calculated data on the efficiency of removal of the finest particles (0.01–0.1 μm).

It is noted in [10] that along with the directed motion of charged particles in a homogeneous electric field of strength $E(x)$ the particles also leave the volume under the action of the field of the volumetric electric charge created by the charge-carrying aerosol particles. The characteristic time of the process of electrostatic repulsion is evaluated by the formula

$$\tau_{el} = \frac{\varepsilon_0}{NQu(D, Q)},$$

which, with account for Eq. (5), can be brought to the form

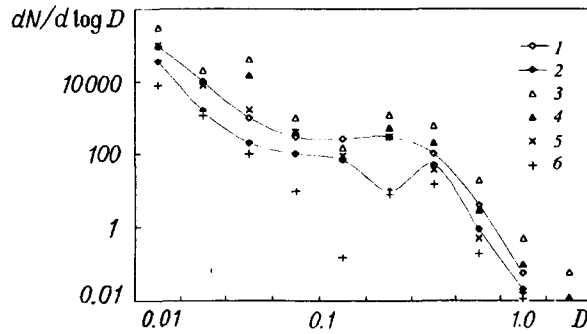$$\tau_{el} = \frac{3\pi\eta\varepsilon_0 D}{(1 + 2AL/D) NQ^2}.$$ (9)

Fig. 4. Averaged size distributions of aerosols under different conditions of vital activity in a pressurized space of the Salyut orbital station (July–August 1988): 1, 2) intervals of background values (66 spectra); 3, 4) during training of astronauts (233 spectra); 5, 6) while taking meals (36 spectra).

As is seen from Fig. 3 (curve 3), use of Eq. (9) provides a much closer approach of the calculated and experimental data in the spectrum of the size of aerosol particles smaller than 1 μm.

Thus, in a unipolar corona discharge produced in large (of the order of several meters or more) unblown spaces in the presence of aerosol particles, the interrelated processes of ion charging of the particles, drift, and removal of light and heavy ions from the space under the action of a static field and an electric field induced by the heavy ions occur virtually simultaneously .

Pressurized Space under Conditions of Weightlessness. The special characteristics of the aerosol climate in the space of a manned space station consists in the presence of an internal source and an internal filter-cleaner of aerosols under conditions of weightlessness. In this section we analyze results of on-board experiments on the Salyut orbital station, whose free volume is 100 m^3. First we will dwell on the characteristic background spectra of the sizes presented in Fig. 4. We can note that the mean values of the background concentration of all the fractions of sizes in the range $D = 0.01-2$ μm are small relative to the usual background values in the terrestrial air layer (see Fig. 1).

However, from the measurements made it was found that the background values of the concentration of aerosol particles fluctuate appreciably with a relative standard deviation (with respect to the mean spectrum) of several units (about 5). At the same time the maximum concentration exceeds the mean one by approximately one and one-half orders (see Fig. 2). We also note (see Fig. 4) that carrying out sanitation procedures causes a slight increase in the concentration in the region of particles with $D = 0.01$ and 0.1 μm but a considerable one (10–100-fold) for the particles of the remaining fractions of sizes. The increase in the concentration of the particles can be explained foremost by the generation of dust in using on-board training appliances of the type of a moving track, etc.

In the periods of taking meals the concentration of dust was roughly at the background level. We were able to study the kinetics of the aerosol in a manned pressurized space in active on-board experiments when a pyrolytic aerosol, i.e., the product of low-temperature heating of polyethylene samples, was formed in the space (Fig. 5). It is seen from the figure that the rate of decrease of the number density N and the volume concentration V is noticeably different: 15 min after switching off the generator the number density decreased by approximately a factor of 20, and the volume concentration by less than a factor of three. This means that in the process of "decay" the spectrum of the aerosol sizes undergoes qualitative changes caused by coagulation and filtration of the aerosol. The time behavior of $N(t)$ calculated from Eq. (1) agrees well with the experimental results. Values of the effective constant of coagulation γ were obtained from the experimental data by the relation
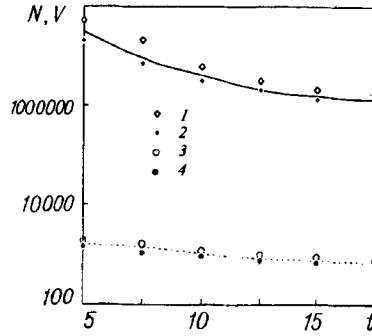
Fig. 5. Time behavior of the number density (1, 4) and volume concentration (2, 3) of an aerosol in a manned pressurized space after switching off the generator of the pyrolytic aerosol: 1, 2) measurements; 3, 4) calculations by Eqs. (2) and (4). N, cm^{-3}; V, μm$^3 \cdot$cm^{-3}; t, min.

$$\gamma \approx \frac{N(t_1)/N(t_2) - \exp\frac{t_2 - t_1}{\tau^*}}{\tau^* N(t_1)\left[\exp\frac{t_2 - t_1}{\tau^*} - 1\right]} = 6 \cdot 10^{-10} \ \text{cm}^3/\text{sec} .$$

The coagulation of the particles plays a less significant role in the changes in the volumetric concentration, and the kinetic equation can be represented in the form

$$dV/dt = q - V/\tau^* . \tag{10}$$

Here t is the time elapsed after termination of generation of the pyrolytic aerosol. The time constant of relaxation of the aerosol τ^* is determined first of all by the efficiency of the on-board filter, the rate of air exchange, and the pressurized-space parameters. Consequently, at this stage, for its evaluation it is advisable to use the results of experiments (Fig. 5):

$$\tau^* \approx (t_2 - t_1)/\ln \ [V(t_1)/V(t_2)] \approx 10^3 \ \text{sec} .$$

The solution of Eq. (10) can be written in the form

$$V(t) = V_\infty + [V(t_1) - V_\infty] \exp\left(-\int_{t_1}^{t} \frac{dt}{\tau^*}\right), \tag{11}$$

where t_1 is the time of the beginning of the experiment $(t > t_1)$, $V_\infty = q\tau^*$, $V_\infty \approx 10 \ \mu$m$^3 \cdot$cm^{-3} is the established (background) value of the volume concentration. The established value of the number density is $N_\infty \approx 2 \cdot 10^4$ cm^{-3}. It is seen from Fig. 5 that there is good agreement between the experimental and calculated data.

We note in conclusion that the results of the experiments carried out on the Salyut orbital station and on the on-ground model of the station agreed satisfactorily. It follows from this that the evolution of aerosols under conditions of weightlessness can be studied by physical simulation under terrestrial conditions.

NOTATION

$u(D, Q)$, mobility of aerosol particles of diameter D and charge Q; N and V, number density and volume concentration of the aerosol; N_0, background concentration; ε_a, dielectric constant of the aerosol material; $\rho = 2$ g/cm^3, mean density of the aerosol material; q, efficiency of the intrinsic source of the aerosol particles,

$cm^3 \cdot sec^{-1}$; γ, coefficient of coagulation, cm^3/sec; β, intensity of the outgo of the particles to the chamber walls, sec^{-1}; τ, characteristic time of relaxation; T, H, and η, temperature, relative humidity, and dynamic viscosity of air; $A \approx 2$, Cunningham's correction; L, mean free path of the molecules; k, Boltzmann constant; C_i, thermal velocity of the ions; $\mu = 2.4048$, first root of the zero-order Bessel function; g, free-fall acceleration; $\varepsilon = 1$, dielectric constant of air; $\varepsilon_0 = 8.85 \cdot 10^{-10}$ F/m; e, charge of the aeroion, equal to the elementary one.

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