Numerical study of aspiration of aerosol particles from a flux into an annular slit sampler

A.A. Medvedev, N.N. Trusova, S.G. Chernyi, and S.V. Sharov

Scientific Research Institute of Aerobiology,
State Scientific Center for Virology and Biotechnology "Vector,B Novosibirsk Region
Institute of Computer Technology, Siberian Branch of the Russian Academy of Sciences, Novosibirsk
Received March 3, 1999

The efficiency of aspiration of aerosol into an annular slit inlet has been calculated by numerical solution of the three-dimensional Navier–Stokes equations. The aspiration efficiency is represented as a function of the following similarity criteria: the Stokes number, flow velocity ratio, and ratio of sampler characteristic dimensions. The results of these calculations can be used to estimate the aspiration errors and determine the optimal parameters of the sampler.

1. Introduction

To collect samples of aerosol particles (by aspiration), sondes of various designs are used. In this situation, as a consequence of the inertia of the particles (non-alignment of their trajectories with the flux lines of the air flow) significant distortions of the measured concentration and dispersed state of the aerosol can arise. The aspiration efficiency $A = c/c_0$, where c and c_0 are the flux concentration of the given aerosol fraction inside the sampler and in the surrounding air, respectively, may serve as a measure of these distortions. To reduce the aspiration errors, devices have been proposed whose intake opening is fashioned in the form of an axisymmetric slit.[1,2] The choice of such a geometry is motivated by an effort to reduce the aspiration errors arising due to changes in the wind direction. In addition, a slit entrance makes it possible to build devices with a large volume flow rate of the sampled air. At the same time, data on the aspiration efficiency of slit samplers are essentially absent.

The published experimental results,[3,4] which are quite disparate in nature, are difficult to use to select the parameters of the sampling devices or to estimate their aspiration efficiency. A systematic study of the characteristics of slit samplers would require a large number of tedious experiments. The aim of the present work is to mathematically model aspiration of aerosol particles in a slit sampler from an external flow by solving the three-dimensional Navier–Stokes equations.

The present work employs the simplest possible model of a slit sampler: two parallel disks, into the gap between which air is drawn. Such a model allows one to investigate the effect on the aspiration efficiency of the following parameters: width of the gap between the disks, mean air flow rate in the entrance cross section of the sampling device, and velocity of the incident flux.

So that the results of this work can be applied to sampling devices with different dimensions and air flow rate, it is necessary to determine the dependence of the aspiration efficiency on the similarity criteria. The aspiration efficiency (A) of a slit sampler can be represented in the form

$$A = f(D, h, W, V, d_p, \mu, \rho, \rho_p) , \quad (1)$$

where D is the diameter of the sampling device (disk), h is the distance between disks (width of the gap), and W is the velocity of the outer flow, $V = Q/\pi Dh$ is the mean velocity over the entrance cross section of the sampling device, Q is the flow rate of air through the sampler, d_p is aerodynamic diameter of aerosol particles, ρ_p is the density of the particles, ρ is the density of air, and μ is the viscosity of air.

According to the π similarity theorem (see, e.g., Ref. 5), the equation relating these nine physical quantities having three independent dimensions (mass, length, and time), can be transformed into an equation linking $9 - 3 = 6$ dimensionless criteria composed from these quantities. Consequently, Eq. (1) can be rewritten in the form

$$A = f(\mathrm{Stk}, L, k, \mathrm{Re}, \mathrm{Re}_p) , \quad (2)$$

where $\mathrm{Stk} = \rho_p d_p^2 W/18\mu h$ is the Stokes number, $\mathrm{Re} = \rho h W/\mu$ is the Reynolds number of the sampler, $\mathrm{Re}_p = \rho d_p W/\mu$ is the Reynolds number of the particle, $L = D/h$ is the ratio of characteristic dimensions of the sampler, and $k = V/W$ is the ratio of velocities.

The Reynolds number Re determines the nature of streamline flow of the outer flux around the device. The nature of the resistance of air to the motion of a particle is determined by the Reynolds number of the particle Re_p. If the latter is less than unity, then the resistance of air satisfies Stokes' law and is independent of the Reynolds number. In a series of experimental and theoretical works dedicated to sampling into a tube[6,7] it was shown that the influence of the Reynolds numbers Re and Re_p on the aspiration efficiency is small. On the basis of this fact, the present paper investigates for the first time the dependence of the aspiration efficiency on the Stokes number (Stk), the

0235-6880/99/06 543-03 $02.00

velocity ratio (k), and the ratio of dimensions of the sampler (L).

2. Numerical method

We used a numerical method similar to the one developed in Ref. 8 to study aspiration into a tube. The aspiration process is modeled in two steps. In the first step, by numerical solution of the Navier–Stokes equations, we calculated the air velocity field in the vicinity of the disks and in the gap between them. The air flow was taken to be laminar, stationary, and incompressible. In the second step, by integrating the equations of motion of the particles, we calculated the trajectories of the individual particles and the aspiration efficiency.

The three-dimensional Navier–Stokes equations were solved with the help of an original finite-difference method based on the concept of an artificial viscosity.[9] The calculation volume was partitioned into a grid of control volumes defined in a cylindrical coordinate system whose z axis coincides with the symmetry axis, and whose x axis is parallel to the direction of the external flow, and whose origin is located halfway between the disks. The problem has two symmetry planes: $y = 0$ and $z = 0$. By virtue of this fact, the flowfield was calculated in one-fourth of the investigated region, and the flowfield in the rest of the region was constructed by the appropriate symmetry mapping of the obtained field relative to the indicated planes.

Figure 1 shows a cross section of the calculation region in the $y = 0$ plane, and also the main geometrical parameters. The calculation region is a cylinder of radius R and height H_0. Air is drawn into the gap of width h between the disks of diameter D with a flow rate Q. The outflow boundary for the drawn-in air is a cylindrical surface of radius r=0.1D located between the disks.

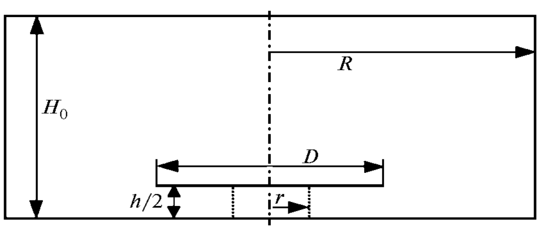

Fig. 1. Cross section of calculation region in the symmetry plane.

The values of R and H_0 were chosen large enough that perturbations from the sampler did not reach the outer boundaries. The boundary conditions on the outer boundaries of the calculation region were set on the assumption that the influence of viscosity on the flow far from the tube is insignificant. On the inner and outer surfaces of the disk the velocity and normal pressure gradient were set equal to zero. The pressure on the outflow boundary inside the sampler was set to a value that ensured the necessary flow rate of the drawn-in air while the velocity components were found by extrapolating their values from inside the calculation region.

The equations of motion of the particles, written in conformance with Stokes' law, were integrated using a fourth-order Runge–Kutta method. The starting positions of the trajectories were chosen in a plane perpendicular to the velocity vector of the incident flux located far enough from the sampler that the flux could be taken to be unperturbed. A particle was taken to have fallen inside the sampler if it got inside a cylindrical surface inside the gap whose diameter was equal to $D/3$. Particles that touched the surface of the disk were taken to be lost, i.e., rebound of the particles and their secondary aspiration were neglected. The entrance cross section of the gap cannot serve as a control boundary since the inertial particles under certain conditions can fly clear across the gap. Let S be the area of the region of starting positions, starting from which the particles fall into the device. The particle flux concentration inside the sampler is equal to the ratio of the particle flux through the area S to the volume flow rate of air through the sampler. Thus, by definition of the aspiration efficiency

$$A = WS/Q \,. \tag{3}$$

The area S was calculated by summing up the areas of the elementary cells containing starting points, starting from which the particles fell inside the sampler. The value of S was refined by decreasing the size of the cells located along the boundaries of this region.

3. Results of calculations

We calculated the aspiration efficiency of a sampler with the following parameters $D = 0.1$ m, $h = 0.01$, 0.005 m, air flow $Q = 0.02$ m^3/s, $V = 6.4$ and 12.7 m/s. The outer flow velocity $W = 1$, 2, 5, 7, 10, 15 m/s.

In the course of preliminary calculations we chose the dimensions of the calculation region $R = 0.3$ m , $m_0 = 0.06$ m. Further increase of these values did not affect the solution. We found the optimal number of grid points to be 60 in the radial direction, and 25 or 35 (for $h = 0.01$ or 0.005 m , respectively) along the z axis, and 40 in angle. The results that follow were obtained using the indicated parameter values of the region and grid.

Figure 2 shows an isometric portrait of individual particle trajectories, calculated for $W = 2$ m/s, Stk = = 0.01, and $h = 0.01$ m. The calculations showed that the particles can fall into the gap from the windward side or be deposited on the surface of the disk or fly over the disk and be drawn into the gap from the leeward side.

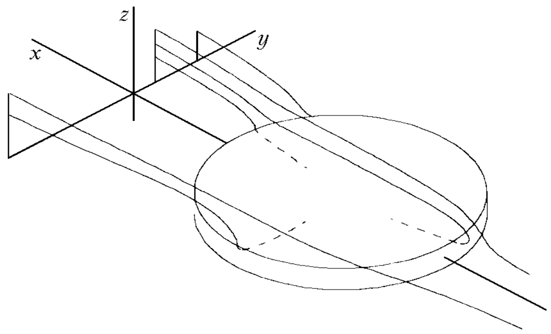

Fig. 2. Particle trajectories calculated for $W = 2$ m/s, Stk = 0.01, $h = 0.01$ m.

Figure 3 shows the region of starting points, starting from which the particles fall into the sampler, calculated for Stk = 0.4, $W = 2$ m/s, $h = 0.01$ m, D=0.1 m, and $k = 3.2$. For ease of visualization, the projection of the annular slit is superimposed on the indicated region. The gaps inside this region correspond to starting points, starting out from which the particles do not fall into the sampler but are deposited on the outer surface of the disk.

Fig. 3. Region of starting points, starting from which the particles fall into the sampler (Stk = 0.4, $W = 2$ m/s, $h = 0.01$ m).

Results of calculations of the dependence of the aspiration efficiency on the velocity ratio k are plotted in Fig. 4. It can be seen that the values of the aspiration efficiency A calculated for $L = 10$ and 20 are quite close for Stk ≤ 0.1. Here $A > 0.85$. Thus, the condition Stk ≤ 0.1 can be used as a criterion of smallness of the aspiration distortions for the investigated values of D/h. The nature of the dependence of the aspiration efficiency is the same for the entire region of Stk values, namely A reaches a maximum for $k \cong 1$. For $k > 1$ ($W < V$) the particles begin to be deposited on the outer surface of the disk, and for $k < 1$ ($W > V$), to jump clean across the gap. Therefore, the aspiration efficiency is lowered, and the influence of these factors depends on the ratio of the characteristic dimensions of the sampler L.

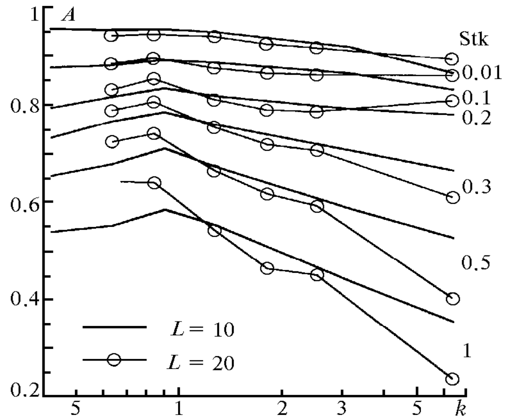

Fig. 4. Results of calculations of the efficiency of aspiration of aerosol particles into the slit sampler.

In our further investigations we plan to study the dependence of the aspiration efficiency on L and to check the sufficiency of the used similarity criteria (Stk, k, L).

References

1. S.P. Belyaev, N.K. Nikiforov, V.V. Smirnov, and G.I. Shchelchkov, *Optoelectronic Methods of Studying Aerosols* (Energoizdat, Moscow, 1981), 232 pp.
2. A.R. McFarland, J.B. Wedding, and J.E. Cermak, Atmos. Environ. **11**, No. 3, 535–539 (1977).
3. G.N. Lipatov, G.L. Shingarev, S.A. Grinshpun, and A.G. Sutugin, Izv. Akad. Nauk SSSR, Fiz. Atmos. Okeana **23**, No. 3, 320–324 (1987).
4. V.T. Kustov, Trudy Inst. Eksp. Meteorol. [Proceedings of the Institute of Experimental Meteorology, in Russian], No. 7(112), 87 (1984).
5. P.G. Romankov and M.I. Kurochkina, *Hydromechanical Processes of Chemical Technology* (Khimiya, Leningrad, 1982), 288 pp.
6. S.P. Belyaev and L.M. Levin, Trudy Ins. Eksper. Meteorol., No. 20, 3–33 (1971).
7. D.J. Rader and V.A. Marple, Aerosol Sci. Technol. **8**, 283–299 (1988).
8. A.A. Medvedev, N.N. Trusova, S.G. Chernyi, and S.V. Sharov, Atmos. Oceanic Opt. **11**, No. 9, 879–882 (1998).
9. Yu.A. Gryazin, S.G. Chernyi, S.V. Sharov, and P.A. Shashkin, Dokl. Ros. Akad. Nauk **353**, No. 4, 478–483 (1997).