Numerical study of aerosol sampling from high-speed flows

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Sampling aerosol particles from high-speed flows is modeled with the help of numerical solution of the Navier–Stokes equations. The effect of a coaxial shield mounted around the inlet tube of a sampler and the width of tube walls on aspiration distortions of the aerosol size spectrum is studied. Based on the calculated results, a device for sampling aerosol particles and separating them into two fractions has been designed. The obtained results can be used in the development of samplers for airborne studies of atmospheric aerosols.

Introduction

Studies of the size spectrum, physical, chemical, and biological properties of the particles of atmospheric aerosol are urgent for ecology, medicine, meteorology, and climatology. Atmospheric aerosols are usually sampled with the use of airborne samplers. Particles in this case are sucked in into a tube from a high-speed flow. The flow is decelerated before the inlet because the speed of air in the tube is lower than the speed of the flow. Due to inertia, particles cannot follow the flow that carries them and slip into the tube. Consequently, the concentration of particles in a sample is higher than in the ambient air, and the degree of increase depends on the particle size. If we are interested in the actual size distribution of atmospheric particles in a wide range, then the sampler should be designed in a way that diminishes this effect. Toward this end, a cylindrical shield can be mounted in front of and around the inlet tube; this shield fluently decelerates the flow and, additionally, smoothes its cross pulsations.[1]

On the other hand, investigators may be interested in particles of a certain size, for example, less than 10 or 2.5 μm. In this case, some device for separating particles into fractions is usually used. An example of such a device is an impactor, which is installed in series with a sampler. In the process of sampling, air is first decelerated at the tube inlet and then accelerated in the impactor. This leads to the loss of particles and extra energy consumption. It is likely more efficient to separate particles into fractions simultaneously with sampling. However, a device of such a kind does not exist by now.

One of the known devices is the counterflow virtual impactor,[2] in which air is blown from the tube in the direction opposite to the external flow. This air prevents penetration of fine particles into the tube, i.e., this device provides for sampling only the particles that are larger than some threshold size.

The aim of this paper is numerical study of the process of aspiration from a high-speed airflow and development of a device for simultaneous sampling and separating particles into fractions according to their size.

Numerical method

The process of aspiration of aerosol particles was modeled in two stages. First, the field of air speed at the entrance of a sampler was computed with the use of numerical solution of the Navier–Stokes equations written in the "eddy–stream function" variables. The equations were solved numerically using the Gauss–Siedel finite-difference iterative method.[3] It was assumed that the external flow is directed in parallel to the tube axis and its speed does not exceed 100 m/s, i.e., air compressibility can be ignored. For better approximation, the finite-difference grid had an irregular step with the grid densening near the walls and inlets, where the gradients of velocity and pressure are maximum.

The equations of particle motion written according to the Stokes laws were integrated in the obtained field of air velocity using the fourth-order Runge–Kutta method. The trajectories and flows of particles coming into the tube without contact with its walls or after colliding the inner surface of a wall were computed. The efficiency of aspiration defined as the ratio of the particle concentration inside the tube to the concentration in the unperturbed airflow was computed by the equation $A = S/S_0$, where S is the area of the region, from which particles penetrate into the tube; $S_0 = Q/W$ is the area of the region, from which air is sucked in into the tube with the volume flow Q; W is the speed of the external airflow. The coefficient of particle deposition onto the inner wall of the tube was computed in a similar way.

Aspiration of particles in the tube

Aspiration of aerosol particles into a thin-wall tube was simulated numerically for the following parameters: tube diameter $D = 1$ cm, mean air speed at

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the entrance to the tube $V = 2$ m/s, and the speed of the incident flow $W = 100$ m/s. Figures 1*a* and *b* show the calculated air streamlines at the tube entrance and trajectories of particles with the diameter $d_\text{p} = 4$ μm. It is seen that the air streamlines broaden sharply near the entrance; this leads to deposition of a large part of particles onto the inner wall. To fluently decelerate the flow before it enters the tube and to smooth the cross fluctuations of the flow, the entrance section of the tube can be encircled with a cylindrical shield.[1] Figures 1*c* and *d* show the air streamlines calculated for two versions of the tube with a shield.

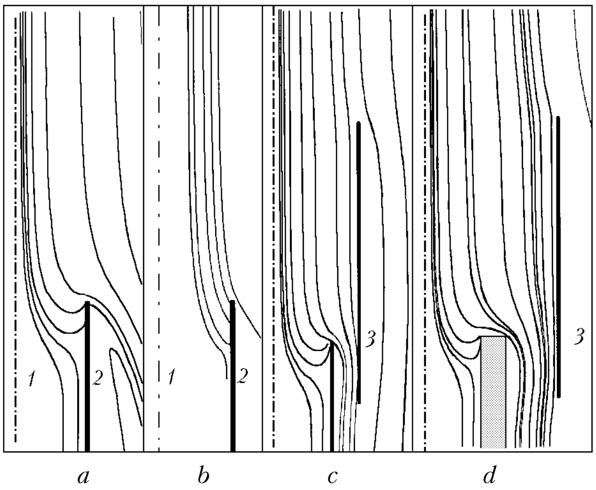

Fig. 1. Air streamlines (*a*, *c*, *d*) and trajectories of particles (*b*); symmetry axis *1*, tube wall *2*, shield *3*.

Figure 2 shows the computed dependence of the aspiration efficiency on the particle diameter for tubes with different thickness of walls at various assumptions on the character of interaction between particles and the wall surface: particles touched with the inner wall jump off and are sucked into the sampler or stick to the wall and, consequently, are ignored.

It is seen that for all the computed versions the aspiration efficiency increases with the particle size and tends to some limit equal to the ratio of the external flow speed to the mean air speed at the tube entrance. Due to installation of a shield for the thin-wall tube, the aspiration efficiency calculated with the allowance made for the particles touched with the inner wall decreases a little bit for small particles but increases for particles with the diameter larger than 5 μm.

The aspiration efficiency computed assuming that particles touched with the inner surface of the tube are lost decreases for all particle diameters. This can be explained by the fact that because of the shield the flow before the inlet moves along a more straight line and a part of large particles entering the sampler increases; however, many particles touch the inner wall and are considered differently in different versions of our calculations. Due to the increase in thickness of the tube walls up to 0.25 cm, the flow inside the shield is decelerated before the tube end, and this leads to an extra decrease of the aspiration efficiency.

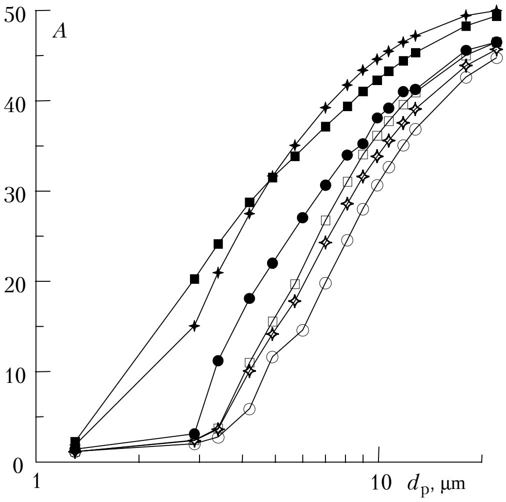

Fig. 2. Calculated aspiration efficiency for different configurations of the sampler at the following assumptions: particles touched with the inner surface are thought (1) falling into the sample: thin-wall tube (■), thin-wall tube with a shield (✦), thick-walled tube with a shield (●) and (2) are thought lost: thin-wall tube (□), thin-wall tube with a shield (✧), thick-wall tube with a shield (○).

Thus, the computations showed that combination of a shield with a thick-wall tube provides for smallest distortions of the particle size spectrum.

Selective sampler

Then we have developed and numerically studied the scheme of a sampler for simultaneously sampling aerosol particles from a high-speed flow and separating them into fractions.

The air streamlines and particle trajectories calculated for aspiration into the tube show that the airflow in the entrance section of the tube splits into two parts, of which the smallest one comes farther into the tube and the largest turns back and leaves the tube. As this takes place, the air velocity is directed to the wall, and this causes deposition of particles of a certain size, because large particles fly inside the tube by inertia, whereas small particles come out with the flow. Based on this observation, we have proposed the design shown in Fig. 3*a*.

The device includes a body *1*, whose entrance section is made as a truncated cone. A tube *2* is installed coaxially inside the body. The tube diameter should be larger than or equal to the diameter of the body inlet. A cylindrical shield *3* encircles the entrance section of the body.

The major part of air (80%) coming to the sampler (this part carries fine particles) is sucked in into the gap between the tube *2* and the inner surface of the body *1*, the rest part with the coarse fraction of aerosol particles comes out through the tube *2*.

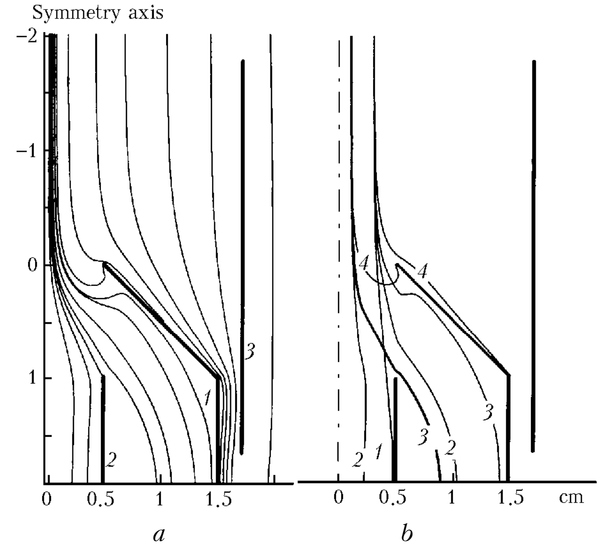

Fig. 3. Design of a selective sampler and field of airflow (*a*): body *1*, tube *2*, and shield *3*; trajectories of particles with the following diameters (*b*): 8 (*1*), 5.7 (*2*), 4.3 (*3*), 1.8 µm (*4*).

The computations were made for the following parameters: diameter of the tube and the body inlet – 1 cm, diameter of the cylindrical part of the body – 3 cm, distance from the inlet cross section to the tube cross section – 1 cm, length of the conical section along the axis – 1 cm, mean air speed at the entrance to the tube – 2 m/s, speed of the external flow – 100 m/s. The calculated field of the airflow near and inside the sampler is shown in Fig. 3*a*. The trajectories of particles of different diameter are shown in Fig. 3*b*.

It is seen that large particles (5.7 and 8 µm) come into the tube *2*, small particles (1.8 µm) deposit onto the outer surface of the conic part of the body *1*, and medium particles (4.3 and 5.7 µm) are sucked in into the gap between the tube *2* and the body *1*. The efficiency of aspiration of fine and coarse particles as a function of the particle size is shown in Fig. 4 for two versions of the sampler (with and without the shield). One can see that the sampler allows one to separate two fractions of particle: with the size from 1 to 15 and larger than 5 µm. The calculated results showed also that the shield installed around the entrance section of the body markedly increases the efficiency of aspiration of fine particles due to the effect of smoothing the flow and pressing it to the sampler axis before the inlet (this effect was mentioned above for the tube).

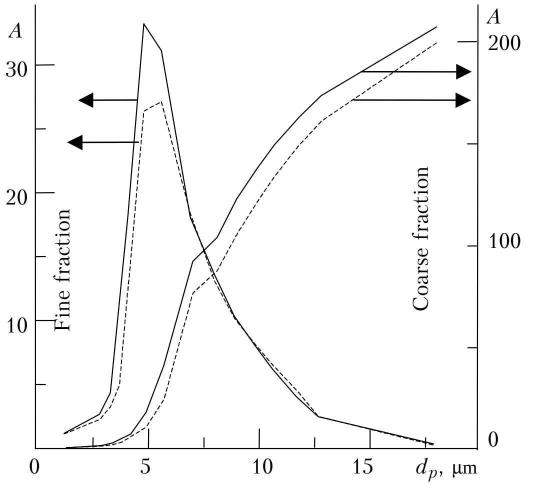

Fig. 4. Aspiration efficiency for the fine and coarse aerosol fractions calculated for the selective sampler: sampler with (—) and without (- - -) shield.

Conclusion

Our numerical studies showed that increasing the thickness of the tube walls and mounting a cylindrical shield in front of the inlet could decrease the distortion of the aerosol particle size spectrum at sampling.

Based on the calculated results, we have proposed the design of a sampler for simultaneous sampling aerosol particles from a high-speed airflow and separating them into two fractions by the particle size. The choice of the optimal geometry of the sampler, as well as modeling of sampling at higher speeds, at which it is necessary to take into account air compressibility, may be the subject of our further studies.

References

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