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# Numerical simulation of aerosol particle aspiration in a passive sampler

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**Abstract.** A mathematical model and numerical calculations of the coefficient of aerosol aspiration into a passive sampler are realized. In the absence of the effect of particles influence on the gas flow the carrier medium is calculated in the approximation of an incompressible potential flow by the boundary element method. The equations of motion of the particles are calculated in the velocity field results to determine the coefficient of aspiration. The coefficient of the aspiration depending on the Stokes number and sampler angle is studied.

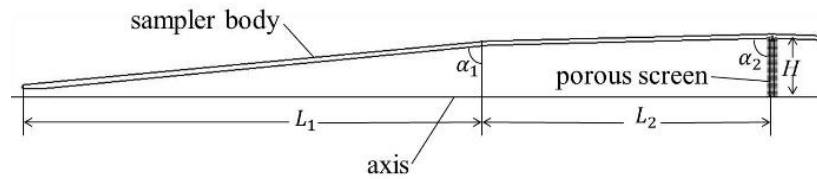
## 1. Introduction

Air pollution monitoring can be achieved using passive samplers on unmanned aerial vehicles [1]. In this work, a conical shaped aerosol sampler with an internal filter was developed, the flow in which is provided by the pressure of the incident flow. The sampler operates in the speed range of 70-120 km / h. Suspended particles are deposited on the filter inside the sampler. The air flow rate in the filter area is regulated by changing the permeability of the material. The conical expansion of the internal airflow reduces the air velocity in front of the filter. In work [1], radioactive aerosols with sizes of 0.1–1  $\mu\text{m}$  were studied. The described passive conical filter sampler can also be used for sampling coarse aerosols. In this case, the concentration of particles in the undisturbed flow and in the filter zone may differ due to the manifestation of their inertia. In this paper, a mathematical model of aerosol aspiration into a passive conical sampler of conical shape with a porous screen is proposed.

## 2. Formulation of the problem

The flow around a conical passive sampler with a porous screen (filter) inside is considered. The screen of radius  $H$  is located in the widest part of the apparatus, where the average flow velocity over the cross section will be the lowest. In figure 1 shows a diagram of the nose of the sampler. The flow is considered axisymmetric. The geometry of the body has two generators: a cone with a large inclination of the generatrix (with a corresponding angle between the generator and the base  $\alpha_1$ ) through which flow enters, and a cone with a small inclination of the generatrix (with an angle  $\alpha_2$ ) to level the flow ahead of the filter.





**Figure 1.** Schemes of the sampler fore part.

The tail part of the sampler can be of different shapes to ensure the flow of gas inside. For example, in work [1] a smoothly tapering channel with a sharp expansion at the end is used. The purpose of this paper is to analyze the aspiration of aerosol in a conical sampler under the assumption of unhindered gas ingress, therefore the shape of the tail section is not considered.

The problem is solved under the following assumptions. There is no developed turbulence, the boundary layer is thin, so the gas flow will be considered in the approximation of the absence of viscosity and compressibility. The concentration of the discrete phase in the environment of the sampler is considered small, without the interaction of particles with each other and with the stream.

It is required to determine the coefficient of aspiration of aerosol particles in a conical sampler for different values of the parameters of the problem. The second goal of the work is to establish the relationship between the parameters of the problem, such as the angle of the solution, the velocity of the apparatus and the permeability of the filter.

### 3. Models and methods

#### 3.1. Air flow model

The boundary value problem of air flow past the sampler is solved for the potential of velocity  $\varphi$  by the boundary element method [2] in the approximation of an inviscid incompressible axisymmetric flow. Such an approximation showed its viability in the problems of aerodynamics of flow past axisymmetric bodies [3-6].

The value of the potential velocity  $\varphi$  at point  $(x, r)$  has the form

$$\varphi(x, r) = U_{\infty} x - \sum_{i=1}^N \frac{q_i}{4\pi} \iiint \frac{dx_i dr_i d\theta}{\sqrt{(x-x_i)^2 + r^2 + r_i^2 - 2rr_i \cos \theta}}, \quad (1)$$

where  $U_{\infty}$  is vehicle speed (free stream),  $q_i$  is intensities of annular sources/sinks distributed over the surface of the sampler. The integration over the angle  $\theta$  is from 0 to  $2\pi$ , the  $x$  and  $r$  coordinates are axial and radial, respectively.

Given the conditions on the surface of the sampler elements, we construct a system of linear algebraic equations for finding the unknown values  $q_i$ . After solving the system, the components of velocity at a point are determined by the relations:

$$\begin{aligned} u_x(x, r) &= \frac{\partial \varphi(x, r)}{\partial x}, \\ u_r(x, r) &= \frac{\partial \varphi(x, r)}{\partial r}. \end{aligned} \quad (2)$$

On the walls of the sampler, a no-flow condition of  $u_n = 0$  is set. The filter inside the sampler is treated as a porous screen. The pressure drop  $\Delta p$  is proportional to the flow through the filter [7]

$$\Delta p = \beta \rho U_{\infty} U_x, \quad (3)$$

where  $U_x$  is normal speed component on the filter surface,  $\rho$  is air density,  $\beta$  is parameter characterizing the properties of the porous screen, including its permeability. Cases  $\beta=0$  and  $\beta \rightarrow \infty$  correspond to absolute permeability (sampler without filter) and impermeable screen (solid wall).

We use the Bernoulli theorem for a stationary flow of an ideal incompressible fluid and relation (1), we write down for  $U_x$  the ratio

$$U_x = U_\infty \left( \sqrt{\beta^2 + 1} - \beta \right). \quad (4)$$

### 3.2. Particle motion model

In the approximation of the Stokes aerodynamic drag, the dimensionless equations of motion of a suspended particle have the form:

$$\begin{aligned} \frac{dv_x}{dt} &= \frac{u_x - v_x}{St}, \quad \frac{dx}{dt} = v_x, \\ \frac{dv_y}{dt} &= \frac{u_y - v_y}{St}, \quad \frac{dy}{dt} = v_y, \end{aligned} \quad (5)$$

where  $v_x, v_y$  are particle velocity components,  $St = U_0 \tau / r_c$  is Stokes number,  $\tau = \rho_p d_p^2 / 18\mu$  is spherical particle relaxation time,  $\rho_p$  is particle density,  $d_p$  is particle diameter,  $\mu$  is gas dynamic viscosity coefficient.

Solving the Cauchy problem for equations (5) with initial conditions  $t=0$ : we obtain  $v_x = 1, v_r = 0, x = x_0, r = r_0$  particle motion trajectories.

### 3.3. Aspiration rate

The constructed particle trajectories are used to calculate the aspiration coefficient  $A$ . The ratio of free flow velocities and at the inlet section of the sampler  $R_a = U_\infty / U_{in}$  is used as a parameter for trapping aerosol particles for thin-walled samplers.

In an undisturbed flow away from the sampler, particles move parallel to the  $x$  axis. Denote by  $S_p$  - the cross-sectional area in the free stream, limited by the limiting trajectory of the particles trapped in the sampler. The surface of the limiting trajectory divides the flow of particles in the medium into two parts: trapped in the tube and remaining outside the sampler. Knowing the area  $S_p$  and the flow rate through the inlet of the sampler  $Q = U_s \pi R_{in}^2$ , the aspiration coefficient can be expressed as

$$A = \frac{U_1 S_p}{Q} = \frac{\pi R_{p0}^2 U_\infty}{\pi R_{in}^2 U_s} = R_a R_{p0}^2, \quad (6)$$

where  $R_{p0}$  is the initial radial coordinate of the marginal trajectory in the free stream away from the sampler. In the case of passive sampling with a thin filter, the aspiration coefficient is estimated by the parameters  $\beta$  and  $\delta = (R_{ps} / R_{in})^2$ , ( $R_{in}, R_{ps}$  - radii of the input section of the sampler and the porous screen). Using the mass conservation ratio

$$U_{in} R_{in}^2 = U_x R_{ps}^2, \quad (7)$$

and the ratio (2) write the relationship between the parameters  $R_a$  and  $\beta$

$$R_a = \delta^{-1} / \left( \sqrt{\beta^2 + 1} - \beta \right). \quad (8)$$

By varying the parameters  $\beta$  and  $\delta$  you can find the values  $R_a$  that provide the required values, including the modes of isokinetic sampling.

## 4. Results

### 4.1. The results of the comparative calculations of the cylindrical sampler

We will compare the calculations according to the proposed method on the example of a cylindrical sampler  $\delta = 1$ . Consider different values  $R_a$  in comparison with the known approximate formulas: work [8]

$$A(\text{St}) = 1 + \lambda(R_a - 1),$$

$$\lambda = 1 - \frac{1}{(1 + (2 + 0.62 / R_a)\text{St})}, \quad (9)$$

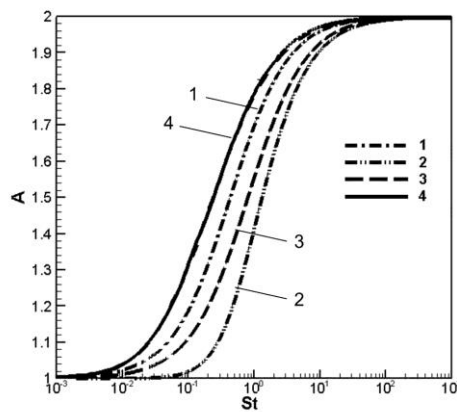
work [9]

$$\lambda = 1 - \frac{1}{1 + \text{St} / (1 + 0.418 / \text{St})}, \quad (10)$$

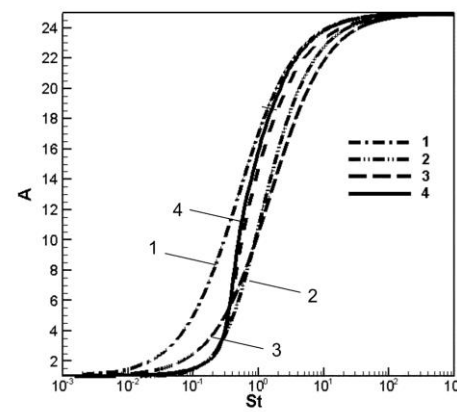
work [10]

$$\lambda = 1 - \frac{1}{1 + (2 + 0.62 / R_a - 0.9R_a^{0.1})\text{St}}. \quad (11)$$

The results are shown in figure 2-3.



**Figure 2.**  $A(\text{St})$  for  $R_a = 2$  and  $\delta = 1$ : 1 – [8], 2 – [9], 3 – [10], 4 – proposed method calculations.



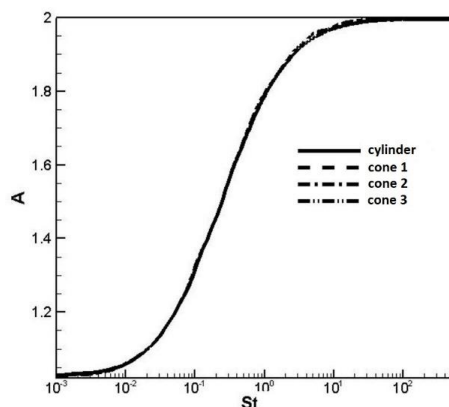
**Figure 3.**  $A(\text{St})$  for  $R_a = 25$  and  $\delta = 1$ : 1 – [8], 2 – [9], 3 – [10], 4 – proposed method calculations.

It can be seen that the calculations by the proposed method are close to the curves of the approximate formulas of the experimental works [8–10], in particular, they repeat the nature of the increase in the aspiration coefficient with increasing Stokes number.

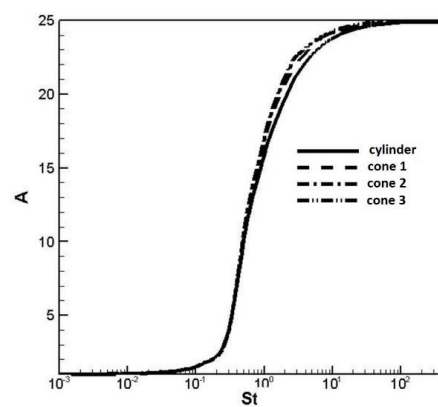
### 4.2. The results of the calculations of the conical sampler

Next, the aspiration curves of particles for a conical sampler with different values of the angle of the solution were constructed.

Comparison of the dependences of the aspiration coefficient  $A$  on the Stokes number  $St$  for various parameters of the passive conical sampler  $R_a$  and  $\delta$  is shown in figure 4-5.



**Figure 4.**  $A(St)$  for  $R_a = 2$  and  $\delta$ : 1 –  $\delta=1$ , 2 –  $\delta=3.323$ , 3 –  $\delta=4.207$ , 4 –  $\delta=48.025$ .



**Figure 5.**  $A(St)$  for  $R_a = 25$  and  $\delta$ : 1 –  $\delta=1$ , 2 –  $\delta=3.323$ , 3 –  $\delta=4.207$ , 4 –  $\delta=48.025$ .

With a small aspiration rate, the curves  $A(St)$  practically coincide for cylindrical and conical samplers with a different angle of the cone solution. At sufficiently large values of the aspiration rate, there are differences in operation between cylindrical and conical samplers in the range of inertial particles. At the same time, the differences in the aspiration coefficient for different angles of the cone solution are insignificant.

### Acknowledgments

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