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Investigation of the aerosol particle deposition formation due to the capture of the filter fiber

O V Soloveva[1,*], S A Solovev[2,3], R Sh Misbakhov[1], R R Yafizov[1]

[1]Institute of Heat Power Engineering, Kazan State Power Engineering University, Krasnoselskaja st. 51, Kazan, 420066, Russia

[2]Institute of Mechanics and Engineering – Subdivision of the Federal State Budgetary Institution of Science "Kazan Scientific Center of the Russian Academy of Science", Lobachevsky st. 2/31, Kazan, 420111, Russia

[3]Institute of Mathematics and Mechanics, Kazan Federal University, Kremlevskaja st. 18, Kazan, 420008, Russia

rara_avis86@mail.ru

Abstract. In this paper, an iterative model is constructed for the formation of a sediment of inertial aerosol particles on the surface of a cylindrical fiber, taking into account its effect on the gas flow and further settling of the particles. Parametric calculations are carried out for various values of the porosity of a number of fibers and the Stokes number, which determines the inertia of the particles. The shape of the sediment varies depending on the particle size. For strongly inertial particles, the thickness of the layer of settled particles is close to uniform. For weakly inertial particles with a small porosity of a number of fibers, a nonuniform distribution of the thickness of the deposited layer along the streamlined surface is observed.

Introduction

Aerosol filters are used in many devices to purify air from suspended particles. For a typical low flow rate through a filter, the deposition mechanism depends on the particle size [1, 2]. The fine particles settle on the filter elements by diffusion. Inertial precipitation and gravitation are the main processes of precipitation of large particles. The particle motion and deposition efficiency also depend on the structure of the filter. Typically, aerosol filters are a porous medium consisting of solid elements, for example, fibers [3-5] or granules [6-8], or an open cell foam material [9-12].

For small particles or in the nanosized region, the contribution of diffusion deposition increases, the intensity of which is determined by the Brownian diffusion coefficient. Investigations of diffusion deposition are discussed in [3, 8, 13]. It was shown in [14] that Brownian diffusion plays a decisive role for particles with a diameter less than 0.2 μm. For the problem of the diffusion deposition of polydisperse aerosol particles [15], analytical formulas for the efficiency of precipitation are obtained.

One of the most investigated is the inertial deposition of particles in porous media [1]. Early work on inertial deposition was devoted to the problem of flow past a gas suspension and the deposition of particles on a single cylinder. The main parameter influencing the inertial deposition is the Stokes number, therefore, in all studies, the dependence of the inertial sedimentation of suspended particles on the Stokes number is investigated [16, 17]. The notion of an effective Stokes number was

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introduced in [18, 19]. This made it possible to reduce the S-shaped curves of the inertial capture efficiency for the sphere and the cylinder into one universal curve in terms of the effective Stokes number. The authors of [19] obtained extended dependences not only for the efficiency of inertial capture of a cylinder in a potential flow, but also for the rates of subsidence, the concentration of particles on the cylinder surface, and the angular distribution of the quantities of interest. In [20] at Reynolds numbers of order unity, the fiber resistance forces and the trapping coefficients of inertial particles are determined. For identical values of the Stokes number, the capture coefficient is larger, the larger the Reynolds number.

In addition to inertial deposition, an important role is played by the effect of meshing particles (direct tangency), in which contact with the obstacle is determined by the geometric size of the particle and does not require that the trajectory of the particle's center cross the surface of the obstacle. Precipitation of particles due to the linkage was investigated in [21-24].

The solid elements of the filter can themselves have a porous structure. The motion of particles in a series of parallel porous cylinders was considered in [25, 26]. It was shown that the use of porous cylinders as elements of aerosol filters significantly increases the efficiency of diffusion deposition of aerosol particles. In [27], numerical calculations show that particles trapped in a porous cylinder can pass through the fibers.

During the operation of the filter and the trapping of particles on the surface of the fibers, a layer of settable particles is formed, which at the initial stage is a dendritic structure. With the further settling of the particles, the layer becomes denser and tends to a dense porous package.

The change in the form of the filter catching element affects the hydrodynamics of the flow between the fibers and the deposition of particles. In [28], the fractal form of the deposited layer, which is characteristic of the initial period of filter operation, is taken into account. Studies based on the assumption of a uniform porous layer of deposit particles on the surface of the element were carried out in [12, 29] and for cases of asymmetric precipitation in [30]. At the same time, the shape of the deposited layer can vary considerably depending on the deposition mechanism and depending on the hydrodynamics of the flow in the filter and the parameters of the particle phase [28, 31]. In the case of diffusion deposition, dendrites are formed over the entire surface of the fiber, and for the engagement mechanism, they are located on the frontal surface of the fiber. In the case of inertial collision, the particles will mainly settle near the front critical point.

In the present paper, an iterative model is constructed for the formation of a layer of inertial aerosol particles that settle on the surface of the filter fiber, taking into account its effect on the gas flow and further settling of the particles. The model includes a model of the flow of a carrier medium, the equations of motion of particles. At each iteration, the shape of the streamlined body is calculated as a result of subsidence. The thickness of the deposited layer depends on the porosity of a number of cylindrical fibers and the inertia of the particles. Parametric calculations were carried out.

Sludge formation model

We will assume that the motion of suspended particles does not affect the motion of the gas. We consider the flow past a fiber with a radius R_c of a viscous incompressible gas flow in a two-dimensional plane formulation [27, 32, 33]

$$\nabla \cdot \bar{U} = 0,$$
$$\varepsilon_c^{-2} \rho \bar{U} \cdot \nabla \bar{U} = -\nabla P + \frac{\mu}{\varepsilon_c} \nabla^2 \bar{U} - \beta \frac{\mu}{k} \bar{U}, \quad (1)$$

where $\bar{U}$ is the gas velocity, ρ is the gas density, μ is the dynamic viscosity of the gas, P is the pressure, ε_c is the porosity, k is the permeability of the porous medium, β is the coefficient determining the resistance to movement of gas in a porous medium. When calculating the external flow past a fiber ($\varepsilon_c = 1, \beta = 0$), the system of equations (1) becomes Navier-Stokes equations. When calculating the gas motion inside a porous region, the system (1) goes over into the extended Darcy-Brinkman equations. Let us choose the characteristic dimensionless parameters: for the outer flow around the fiber gas it is the Reynolds number $\mathrm{Re} = \rho U_0 2R_c / \mu$, for the gas motion inside the porous region it is the Darcy number $\mathrm{Da} = k / R_c^2$.

In Fig. 1 shows the considered region of gas flow with particles. In view of symmetry, we choose a periodic cell of height H and length $2H$. Then the packing density of cylindrical fibers is defined as $\alpha = \pi / 4h^2$, where $h = H / R_c$. To solve the system (1), we set the following boundary conditions: on the left boundary, we set the velocity of the free gas flow U_0, on the right boundary it is $\partial P / \partial n = 0$, at the upper and lower boundaries it is the symmetry conditions. The gas flow problem was solved by the finite volume method using the Fluent computational package.

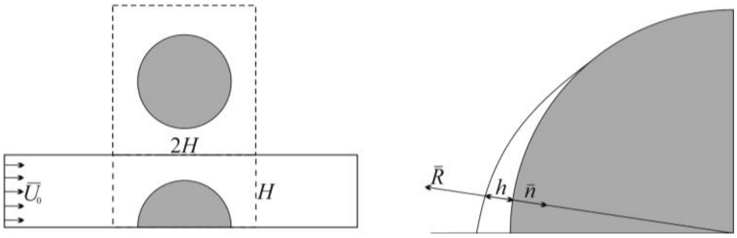


Figure 1. Scheme of calculation domain

The motion of suspended spherical particles will be considered against the background of a gas flow in the Stokes aerodynamic drag approximation

$$\frac{d\bar{V}}{dt} = \frac{\bar{U} - \bar{V}}{\tau}, \qquad \frac{d\bar{R}}{dt} = \bar{V}, \tag{2}$$

where $\bar{V}$ is the velocity of the suspended particle, $\bar{R}$ is the radius vector of the particle coordinate, $\tau = \rho_p D_p^2 / 18\mu$ is the relaxation time of the spherical particle, ρ_p is the particle density, D_p is the particle diameter. The system (2) is solved numerically by the Runge-Kutta method of the fourth order, taking into account the gas flow velocity obtained from the solution of the system (1). The characteristic dimensionless parameter in the study of particle motion is the Stokes number $\mathrm{St} = U_0 \tau / R_c$.

It is assumed that the particles settle upon contact with the surface of the fiber. For the considered problem of the motion of inertial particles, the value of the deposition efficiency E is calculated as the ratio of the number of particles reaching the surface to the total number of particles in the cross section of the cylinder far from the surface.

In this paper, we use a stationary model of gas flow. To determine the influence of build-up on the gas flow, we construct an iterative model for the formation of sediment. Let one iteration correspond to a maximum build-up thickness equal to 1% of the diameter of the cylindrical fiber. Solving the system (2), we determine the values V_n of the normal component of the velocity of the settled particles whose trajectories finish on the cylinder. Then determine the maximum thickness of the build-up as $h_{max} = 0.01R_c$, at the point where $V_n = V_{n,max}$. In other points $h = h_{max}(V_n / V_{n,max})$. The values h are plotted along the normal to the fiber surface at the first iteration, to the current boundary of the build-up at subsequent iterations.

The normal component of the velocity of the particle V_n was chosen as the determining parameter of precipitate formation. Inertial particles colliding with a fiber can rebound [34, 35]. In the absence of electrostatic forces and the mechanism of engagement at high speeds, the particles will settle on the porous fiber at the maximum value of the normal velocity component.

Result and discussion

In the present work, calculations were made for cylindrical filaments of radius $R_c = 500$ µm, which corresponds to the fiber sizes of typical aerosol filters. The value of the velocity U_0 of the oncoming stream corresponds to the value $\mathrm{Re} = 1$. To calculate the deposition efficiency E, the start of the particles in the undisturbed flow is carried out at a distance $x = 250R_c$ from the porous cylinder. To test the calculations, gas-suspension flows were studied in a periodic row of solid cylinders. The efficiency curves for a solid-state solid cylinder at different values α of the packing density are calculated. Comparison of the obtained particle deposition efficiency curves with the efficiency curves calculated in [36] shows good agreement.

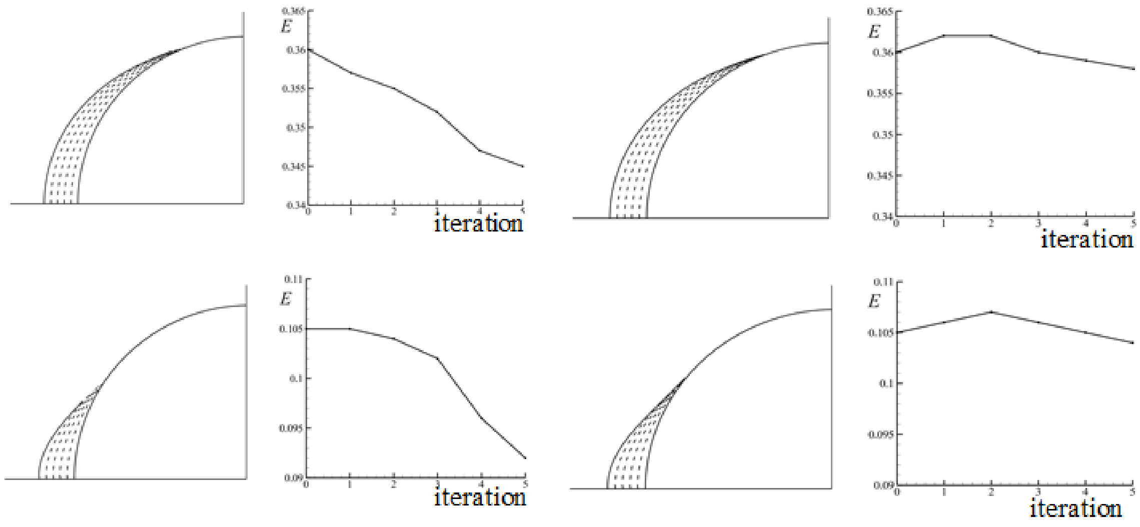
The dependence of the efficiency E on the Stokes number for various Darcy numbers for the fiber packing density parameter $\alpha = 0.01$, obtained using numerical calculations, is analyzed. The case $\mathrm{Da} = 0$ corresponds to an impermeable cylinder. In this case, the efficiency of inertial deposition decreases to very small values (close to zero) for small Stokes numbers [5]. For a porous cylinder, for sufficiently small values St, the value E remains finite. This means that we can provide a significant flow of particles to the porous cylinder, increasing its porosity. The authors of [13] used the range of Darcy numbers $\mathrm{Da} \le 0.1$ to calculate the flow of gas through a porous layer.

Calculations of sediment formation were carried out for the packing density value $\alpha = 0.01$. The buildup of buildup of inertial particles according to the proposed model for large numbers St will occur over the entire front surface of the cylinder with a uniform increase in the cross-sectional area of the fiber. Therefore, cases of small number St, where subsidence is observed only on a part of the front surface, may be of greatest interest. In Fig. 2 (a) shows the results of calculations after five iterations for the parameters $\mathrm{St} = 3$, the permeability of the cylinder $\mathrm{Da}_c = 0$, and the permeability of the deposition layer $\mathrm{Da}_h = 0$.

Five iterations determine 10% of the radius of the cylinder in the section of the greatest thickness of the sediment. The growth is formed almost on the entire front surface of the cylinder. In this case, the relative efficiency of particle capture is reduced by 4.17%. This corresponds to a decrease in the ordinate of the particle settling section.

In Fig. 2 (a) shows the calculations for the parameters of numbers $\mathrm{St} = 1.6$, $\mathrm{Da}_c = 0$, $\mathrm{Da}_h = 0$. It is seen the formation of a small growth in the front of the fiber. In this case, the deposition efficiency of the suspended particles decreases as well as in the case. On the growth, it is more clearly visible that the sediment layer at the fifth iteration is much lower in ordinate than the layer at the first iteration. This indicates the influence of build-up on the hydrodynamics of the gas flow and the motion of the particles. The relative efficiency of particle capture decreased by 12.38%. Thus, if one considers both the fiber and the resulting sediment impenetrable, that the build-up of particles results in a decrease in the efficiency of inertial deposition. Qualitatively, the pattern of formation of the build-up corresponds to [28, 31].

Let us consider the cases of the formation of a permeable build-up $\mathrm{Da}_h = 0.05$ on an impermeable fiber $\mathrm{Da}_c = 0$. We also choose the numbers $\mathrm{St} = 3$ and $\mathrm{St} = 1.6$ (Fig. 2 (b)). The formation of the build-up has a similar picture with the case $\mathrm{Da}_h = 0$. At the same time, the values E of deposition efficiency are almost unchanged in both cases. There are small increases E in the second and third iterations and the subsequent decrease. Since the permeability of the build-up is sufficiently large, the flow of gas freely passes through it, obtaining a flow similar to that of an impermeable fiber. Obviously, for the case $\mathrm{Da_h} = \mathrm{Da_c} > 0$ of formation of a built-up edge, it makes almost no contribution to the change in efficiency E.



(a) (b)

Figure 2. Calculation of deposition layer formation and particle deposition efficiency at: (a) $\mathrm{Da_c} = 0$, $\mathrm{Da_h} = 0, \mathrm{St} = 3$ and $\mathrm{St} = 1.6$; (b) $\mathrm{Da_c} = 0$, $\mathrm{Da_h} = 0.05$, $\mathrm{St} = 3$ and $\mathrm{St} = 1.6$.

Let us consider the case of a flow past a strongly permeable fiber $\mathrm{Da_c} = 0.1$. In this case, the build-up built-up edge has a permeability $\mathrm{Da_h} = 0.01$ that is less than the permeability of the cylinder. The calculation result for $\mathrm{St} = 1.6$ after one iteration shows the build-up on almost the entire front surface of the fiber. In this case, after the formation of the build-up, the relative efficiency of particle capture decreased by 59.17%. That is, the built-up edge has brought the efficiency of particle capture to the efficiency of a cylinder without a build-up of the same permeability $\mathrm{Da_c} = 0.01$.

Conclusion

Analysis of the results shows that the deposition efficiency is slightly reduced in cases where the permeability of the cylinder is less than or equal to the permeability of the precipitate. Thus, even large sediment (about 10%) of inertial particles formed during long-term operation does not greatly affect the efficiency of the filter. In this case, the situation changes in the case when strongly permeable fibers are used, which are more effective, and the build-up of sedimented particles has less permeability. Numerical calculations show that a denser (but sufficiently thin) sediment changed its efficiency and brought it closer to the values, as if the entire cylinder had permeability of the deposited layer.

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