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The aerosol penetration through an electret fibrous filter*

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The aim of this paper is to present a theoretical study of the aerosol penetration through an electret fibrous filter, using a numerical approach. The aerosol sizes considered in this study were in the submicron range, and in the numerical model, the conventional mechanical mechanisms (impaction, interception, diffusion and gravitationally settling) were taken into consideration along with the electrostatic mechanisms, including the Coulombic and dielectrophoretic effects. The aerosol penetration through an electret fibrous filter is heavily dependent on the aerosol penetration of a single fibre. The aerosol penetration through a single electret fibre under various filtration conditions was calculated. The effects of aerosol diameter, aerosol and fibre charge state, face velocity, packing density and aerosol dielectric constant on the aerosol penetration were investigated.

Keywords: electrostatic mechanism, mechanical mechanism, aerosol penetration through an electret fibre

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1. Introduction

An electret fibre is made of permanently polarized dielectric materials. Electret filters are widely used in those conditions that demand high-efficient cleaning. Typically an electric fibre has circular cross-section and carries a high charge. Compared to a similar non-polarized fibre, the aerosol collection efficiency of an electret fibre can be significantly higher, even if the aerosol particles are uncharged. The fact that submicron particles can be easily captured is an important advantage of electret filters in comparison to mechanical ones in which fine nets with submicron meshes have to be used. The effectiveness of filtration of the submicron particles is of great importance, because such kind of particles constitutes a threat against human health. For an uncharged filter, collection efficiency increases as particles deposit. However, for the case of an electret filter, it is experimentally known to decrease with particle collection in the initial stage of the collection.[1] If it is needed to design a filter with improved service life, we need to acquire good understanding of the aerosol penetration through a single electret fibre under various filtration conditions.

Many investigators have studied the effects of different parameters on the collection efficiencies of the mechanical filters and the electret filters. Kuwabara[2] and Happel[3] have investigated independently the velocity field of a viscous flow. Their result has been accepted as fundamental to many theoretical studies of fibrous filtration. Based on the Kuwabara flow field approach, Lee and Liu[4] have discussed the combined effect of diffusion and interception. The theoretical studies on inertial impaction-dominated fibrous filtration with rectangular or cylindrical fibres have been conducted by Zhu *et al.*[5] In Ref.[5], analytical expressions of the single fibre collection efficiencies due to interception and inertial impaction of fine powders are derived based on the Kuwabara flow analysis around a cylinder. In Ref.[6], Lagrangian equations of motion of particles have been numerically solved and the effects of inertial impaction on particle collections studied. In order to account for the random nature of particle collection by Brownian diffusion, Ramarao *et al*[7] have presented a stochastic trajectory modelling approach in which some random numbers were introduced into

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the Langevin equations. Theoretical study on deposition of flexible and stiff fibrous aerosol particles on a cylindrical collector has also been studied.[8] The results of computation for the elongated particles were compared with those for spherical particles of the same volume. The thermal stability induced by organic coatings on nanoparticles have been investigated.[9]

A few experimental studies[10−13] have been undertaken to investigate the effects of particle charge, particle size, face velocity and fibre charge on the clean filter efficiency. Based on the experimental results, the collection mechanisms of an electret fibre and the most penetrating particle size have been discussed.[14] Walsh and Stenhouse[15] have found that the composition of the particles also has a significant effect on the loading behaviour, with titanium dioxide particles causing filtration efficiency to degrade much more rapidly than stearic acid particles. This may be due to the different permittivity of the two materials, and thus affecting the Coulombic and polarization collection mechanisms.

In our previous works,[16−18] the simulation model for split type fibres has been developed to study the filtration efficiency as well as the particle loading process. The filter was assumed to be composed of rectangular fibres arranged in staggered array in which the flow field, the electrostatic field and the collection mechanisms were determined by numerical simulation. As far as we know, less attention has been devoted to investigation of aerosol penetration through electret fibrous filter by taking into consideration both the conventional mechanical mechanisms (impaction, interception, diffusion and gravitationally settling) and the electrostatic mechanisms (including Coulombic and polarization forces). This is the aim of the present work. In this paper, an effort is made to understand the effects of aerosol and fibre diameter, aerosol and fibre charge state, face velocity, packing density and aerosol dielectric constant on the aerosol penetration through a single electret fibre based on the Kuwabara flow field. The aerosol penetration through a circular electret fibre is numerically determined, in which all of the important particle capturing mechanisms including inertial impaction, interception, gravitationally settling, Coulombic and polarization forces are considered. It should be mentioned that the simulation is based on the assumption of 'clean fibre', which represents the initial stage of a filtration process. The time-dependent blocking effect as deposition proceeds is excluded in this study.

2. Model setup

The simulation model for electret fibrous filter can be divided into several sub-models through which the flow field, the electrostatic field, and the aerosol penetration through a single electret fibre can be numerically solved.

2.1. Flow field setup

A fibrous filter with uniformly distributed identical fibres can be regarded as an assemblage of many identical cells where each cell surrounds one single fibre located at the centre of the cell. The cell model was originally developed by Kuwabara[2] and Happel.[3] The Kuwabara flow field[19] represents a solution of the two-dimensional viscous flow equation for a system of cylinders placed transverse to the flow. By drawing an imaginary coaxial boundary around a cylinder denoting the virtual surface, the filter solidity or the packing factor α is made equal to that of the coaxial cylinders. The relationship between r_f and b is chosen as follows:

$$\alpha = r_\mathrm{f}^2/b^2\,, \tag{1}$$

where r_f is the radius of the fibre and b is the radius of the outer cylinder or the boundary of the virtual surface. It can be proven that the velocity components of the flow field, U_x and U_y, can be expressed as (in Cartesian coordinates)

$$U_x = \frac{u}{2kr^2}\Big[r^2\ln\Big(\frac{r^2}{r_\mathrm{f}^2}\Big) + (y^2-x^2) + r^2\alpha + \frac{r_\mathrm{f}^2}{r^2}\Big(1-\frac{\alpha}{2}\Big)(x^2-y^2) - \frac{\alpha}{2}\frac{r^2}{r_\mathrm{f}^2}(3y^2+x^2)\Big], \tag{2}$$

$$U_y = \frac{xyu}{2kr^2}\Big[-2 + 2\frac{r_\mathrm{f}^2}{r^2}\Big(1-\frac{\alpha}{2}\Big) + \frac{r^2}{r_\mathrm{f}^2}\alpha\Big]. \tag{3}$$

2.2. Electrostatic field setup

In order to obtain the aerosol penetration through an electret fibrous filter, it is necessary to know the electrostatic field around each electret fibre. For small packing density, the interaction between electrostatic fields generated by individual fibres can be neglected.[20] The electric field at a distance r from a charged fibre that carries a uniform charge λ (Coulomb/m) per unit length acts purely in the radial direction and has a magnitude expressed as follows:[21−23]

$$\boldsymbol{E} = \frac{\lambda}{2\pi\varepsilon_0}\frac{1}{r}\boldsymbol{r}_0, \tag{4}$$

where ε_0 is the permittivity of free space, $\boldsymbol{r}_0$ is the unit vector in the radial direction. The Coulombic force $\boldsymbol{F}_{\mathrm{C}}$ and the polarization force $\boldsymbol{F}_{\mathrm{P}}$ can be expressed as

$$\boldsymbol{F}_{\mathrm{C}} = \frac{N_{\mathrm{p}} e\lambda}{2\pi\varepsilon_0}\frac{1}{r}\boldsymbol{r}_0, \tag{5}$$

$$\boldsymbol{F}_{\mathrm{P}} = -\frac{\varepsilon_{\mathrm{P}}-1}{\varepsilon_{\mathrm{P}}+2}\frac{D_{\mathrm{P}}^3\lambda^2}{8\pi\varepsilon_0}\frac{1}{r^3}\boldsymbol{r}_0, \tag{6}$$

where N_{p} is the number of elementary charges on each particle, e is the charge on the elementary particle, i.e. -1.6×10^{-19}C, ε_{P} is the relative dielectric constant of a particle, D_{P} is the particle diameter. In Cartesian coordinates, the components of Coulombic and polarization forces $F_{cx(y)}$ and $F_{\mathrm{p}x(y)}$ can be given by

$$f_{cx(y)} = \frac{F_{cx(y)}}{m} = \frac{1}{m}\frac{N_{\mathrm{p}} e\lambda}{2\pi\varepsilon_0}\frac{x(y)}{r^2}, \tag{7}$$

$$f_{\mathrm{p}x(y)} = \frac{F_{\mathrm{p}x(y)}}{m} = \frac{1}{m}\frac{\varepsilon_{\mathrm{p}}-1}{\varepsilon_{\mathrm{p}}+2}\frac{D_{\mathrm{p}}^3\lambda^2}{8\pi\varepsilon_0}\frac{x(y)}{r^4}. \tag{8}$$

Coulombic force acts when both the particle and fibre have a charge, while polarization force occurs on both uncharged and charge particles. The image force due to the fibre charge is neglected owing to their relatively small magnitudes.

2.3. Governing equation of particle motion

The trajectory of a particle can be obtained by solving the following equation of particle motion satisfying Newton's second law:

$$m\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = \boldsymbol{F}_{\mathrm{C}} + \boldsymbol{F}_{\mathrm{P}} + \boldsymbol{F}_{\mathrm{D}} + \boldsymbol{F}_{\mathrm{R}} + \boldsymbol{F}_{\mathrm{G}}, \tag{9}$$

where $\boldsymbol{v}$ is particle velocity, m and t are mass of particle and time, respectively. $\boldsymbol{F}_{\mathrm{C}}$, $\boldsymbol{F}_{\mathrm{P}}$ and $\boldsymbol{F}_{\mathrm{G}}$ represent respectively the Coulombic force, the polarization force, and the gravity force. $\boldsymbol{F}_{\mathrm{D}}$ is the drag force due to the relative slip between the particle and the fluid. $\boldsymbol{F}_{\mathrm{R}}$ is the Brownian force:

$$\boldsymbol{F}_{\mathrm{G}} = \frac{1}{6}\pi D_{\mathrm{P}}^3\rho_{\mathrm{P}}\boldsymbol{g}, \tag{10}$$

where ρ_{P} is density of the particle, $\boldsymbol{g}$ is gravity acceleration vector of the particle.

$$\boldsymbol{F}_{\mathrm{D}} = \frac{18\mu}{\rho_{\mathrm{P}} D_{\mathrm{P}}^2 C_S}(\boldsymbol{u}-\boldsymbol{v}), \tag{11}$$

where C_{S} is the Cunningham slip factor, μ is the gas viscosity, $\boldsymbol{u}$ is the face velocity.

For a spherical particle within the Stokes regime, in Cartesian coordinates Eq.(9) can be rewritten as

$$\frac{\mathrm{d}v_x}{\mathrm{d}t} = \frac{18\mu}{\rho_{\mathrm{p}} D_{\mathrm{p}}^2 C_s}(u_x - v_x) + f_{cx} + f_{\mathrm{p}x} + n_x(t), \tag{12}$$

$$\frac{\mathrm{d}v_y}{\mathrm{d}t} = \frac{18\mu}{\rho_{\mathrm{p}} D_{\mathrm{p}}^2 C_s}(u_y - v_y) + f_{cy} + f_{\mathrm{p}y} + n_y(t) - g, \tag{13}$$

where $n_i(i = x, y)$ are the Brownian motion components for unit mass. They are modelled as a Gaussian random process,[18,24] similar to that for generating the white noise process with their spectral intensity of the noise given by

$$n_i(t_j) = Z_i\sqrt{\frac{2\pi S_0}{\Delta t}}, \tag{14}$$

where

$$S_0 = \frac{216\mu\, kT}{\pi^2 D_{\mathrm{p}}^5 \rho_{\mathrm{p}}^2 C_s},$$

the distribution of Z_i has zero mean and unit variance and the two random numbers form an independent white noise process with a constant spectral intensity S_0. T is the fluid absolute temperature. k is the Boltzmann constant. Δt should be much larger than the molecular time scale and much smaller than the particle relaxation time. Here, the Brownian force is treated like any other force and the coupling between different forces can be conveniently accommodated in the numerical calculation. In this paper, the Brownian force is considered only for neutral particle ($N_{\mathrm{p}} = 0$), while, for charge particles, the Brownian force is relatively small in magnitude and thus neglected.

2.4. Calculation of aerosol penetration through a single electret fibre

For particle collections by the mechanical and electrostatic mechanisms in fibrous filtration, there is no rigorously derived analytical solution for the aerosol penetration through the electret fibrous filter. However, an approximate expression can be obtained. If a time interval t is chosen such that fluid velocity and external force experienced by a particle are nearly constant for a given time interval, one can obtain the following equations by integrating Eqs.(12) and (13) for a very short time interval[7,21]

$$v_x = v_{x0}\mathrm{e}^{-\beta t} + u_x(1-\mathrm{e}^{-\beta t}) + \frac{f_x}{\beta}(1-\mathrm{e}^{-\beta t}), \tag{15}$$

$$v_y = v_{y0}\mathrm{e}^{-\beta t} + (u_y - \frac{g}{\beta})(1-\mathrm{e}^{-\beta t}) + \frac{f_y}{\beta}(1-\mathrm{e}^{-\beta t}), \quad (16)$$

$$x = x_0 + \frac{v_{x0}}{\beta}(1-\mathrm{e}^{-\beta t}) + u_x\Big[t - \frac{1}{\beta}(1-\mathrm{e}^{-\beta t})\Big] + \frac{f_x}{\beta}\Big[t - \frac{1}{\beta}(1-\mathrm{e}^{-\beta t})\Big], \quad (17)$$

$$y = y_0 + \frac{v_{y0}}{\beta}(1-\mathrm{e}^{-\beta t}) + \Big(u_y - \frac{g}{\beta}\Big)\Big[t - \frac{1}{\beta}(1-\mathrm{e}^{-\beta t})\Big] + \frac{f_y}{\beta}\Big[t - \frac{1}{\beta}(1-\mathrm{e}^{-\beta t})\Big], \quad (18)$$

where

$$f_{x(y)} = f_{\mathrm{c}x(y)} + f_{\mathrm{p}x(y)} + n_{x(y)}$$

and $\beta = 18\mu/\rho_{\mathrm{P}} D_{\mathrm{P}}^2 C_{\mathrm{S}}$.

A particle in the gas stream will be captured once its trajectory ends on the fibre surface or its trajectory approaches the fibre surface within a distance equal to the particle radius. Hence, the single fibre collection efficiency is calculated as

$$\eta = \frac{y_{\mathrm{c}}}{r}, \quad (19)$$

where $r = \sqrt{x^2 + y_{\mathrm{c}}^2} = r_{\mathrm{f}} + r_{\mathrm{p}}$ $(x = -\sqrt{b^2 - y_{\mathrm{c}}^2})$; and y_{c} is critical y value at which the particle can be captured. Then, the aerosol penetration through the electret fibre is as follows:

$$P = (1-\eta) \times 100\%. \quad (20)$$

3. Results and discussion

In this paper, the particle diameter varies from 0.1 to 1.0μm, the gas viscosity is 1.83×10^{-5} kg/ms, the dielectric constant of aerosol is $\varepsilon_{\mathrm{p}} = 5.9$ (NaCl) and $\varepsilon_{\mathrm{p}} = 9.2$ (Al_2O_3). The temperature is $T = 293.15$ K.

Figure 1 shows the simulation of aerosol (NaCl) penetration through the electret fibrous filter for neutral particles ($N_{\mathrm{p}} = 0$) and singly charged particles ($N_{\mathrm{p}} = 1$), and also for charged fibre with $\lambda = 5.15 \times 10^{-9}$ C/m. The penetration is a function of particle diameter, in Fig.1 particle diameter is in the range from 0.1 to 1.0 μm, for packing density $\alpha = 0.041$ and filtration velocity $U = 0.1$ m/s. The aerosol penetration curve in Fig.1 increases with particle diameter until a maximum value is reached and then decreases with further increase of particle diameter. The decreasing part reflects that the polarization force, impaction and interception effect are dominating while the increasing portion reflects the diffusion effect on neutral particles, and Coulombic force and diffusion effect on charged particles. There is a region of maximum aerosol penetration on each curve where these effects are weak. These results can be explained because larger particles can be polarized to higher level, and they are subjected to stronger polarization force which will enhance the capture due to polarization effect, and at the same time inertial impaction and interception become important for large particles ($D_{\mathrm{p}} > 0.5$ μm).[5] For small charged particle, Coulombic force is stronger than diffusion effect and begins to dominate. So the penetration of charged particle is lower than that of neutral particle.

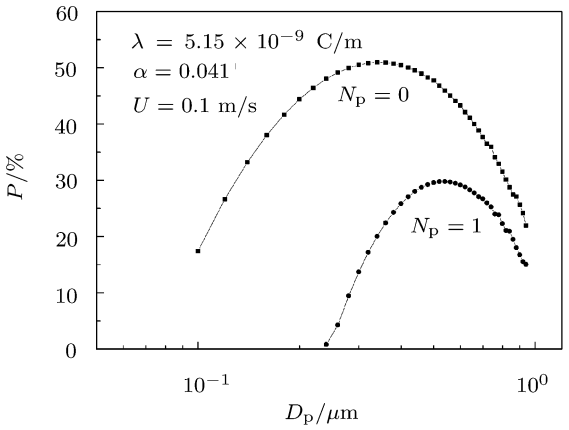


Fig.1. Aerosol penetration through an electret fibrous filter versus particle diameter for neutral ($N_{\mathrm{p}} = 0$) and single charged ($N_{\mathrm{p}} = 1$) particles.

Effects of the flow velocity and the filter packing density are illustrated in Figs.2 and 3, respectively.

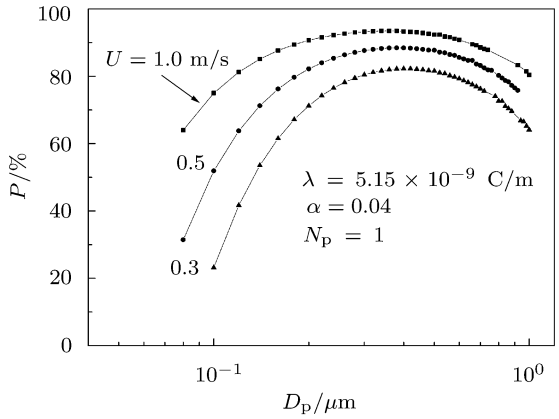


Fig.2. Aerosol penetration through an electret fibrous filter versus aerosol size for different face velocities.

Figure 2 shows the simulated singly charged particle penetration through an electret fibrous filter versus particle diameter for different face velocities. The fibre charge is set at $\lambda = 5.15 \times 10^{-9}$ C/m and the face velocities considered are 0.3, 0.5 and 1.0 m/s. Because of the particle charge and higher filtration velocity, the

diffusion effect is neglected due to their relatively small magnitudes. As shown in Fig.2, the aerosol penetration increases with the increase of face velocity. There is a region of maximum aerosol penetration on each curve where it is approximate 0.4 μm for face velocity of 0.5 m/s. The increasing part in the figure represents where Coulombic force dominates and the decreasing part reflects where the polarization force, impaction and interception effects are dominant. Figure 3 shows the effect of filter packing density on the penetration of singly charged particle through an electret fibrous filter for three different particle sizes. When particle diameter equals to 0.4 μm, the aerosol penetration is higher than that of the two others. This result is in agreement with that in Fig.2.

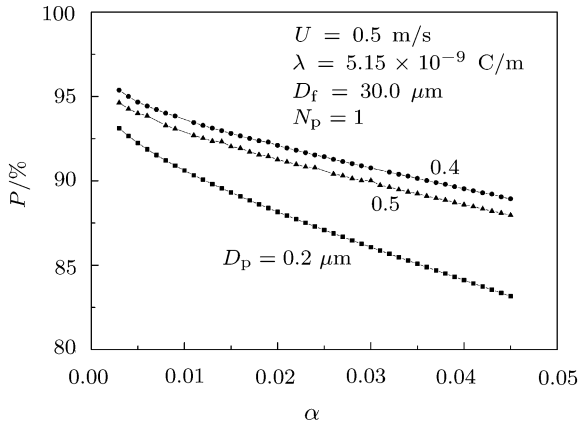


Fig.3. Aerosol penetration through an electret fibrous filter versus packing density for different particle sizes.

The combined effects of fibre charge density and fluid velocity on aerosol penetration through an electret fibrous filter are studied in detail in Fig.4. The penetration of singly charged particles is shown in Fig.4(a) as a function of particle size, using fibres in three charge states: 3.06×10^{-9}, 5.15×10^{-9}, and 6.23×10^{-9} C/m. Likewise, the penetration of singly charged particles is plotted in Fig.4(b) as a function of fibre charge density, for fluid velocities of 0.5 and 0.8 m/s and for particles of 0.2 and 0.6 μm. The three simulated curves in Fig.4(a) show the same trend. Each curve increases with particle diameter until a maximum value is reached and then decreases with further increase of particle diameter. Under the same parameters, the higher the fibre charge density, the lower the penetration. On the other hand, Fig.4(b) indicates that, there exists a crossover at the intersection of curves with different particle diameters of 0.2 and 0.6 μm with the same fluid velocity of 0.5 m/s or 0.8 m/s. The result can be explained as follows: Smaller particles are subjected to stronger Coulombic force while larger particles are subjected to stronger polarization force and inertial impaction and interception effects. When the fibre charge density is weaker, the penetration of the smaller particles are lower than that of the larger ones due to the dominating Coulombic force effect for both smaller (0.2 μm) and larger (0.6 μm) particles. When the fibre charge density is stronger, the penetration of the smaller particles are higher than that of the larger ones because the polarization force and the inertial impaction and interception effects begin to dominate for both smaller (0.2 μm) and larger (0.6 μm) particles. The value of the fibre charge density at the crossover decreases as fluid velocity increases. A higher fluid velocity will result in shorter resident time of a particle around the fibre, which generally results in a higher penetration due to lower electrostatic force effects acting on the particle. There may be an optimum combination of the fluid velocity and the charge fibre density for different particle size under which the penetration has a minimum value.

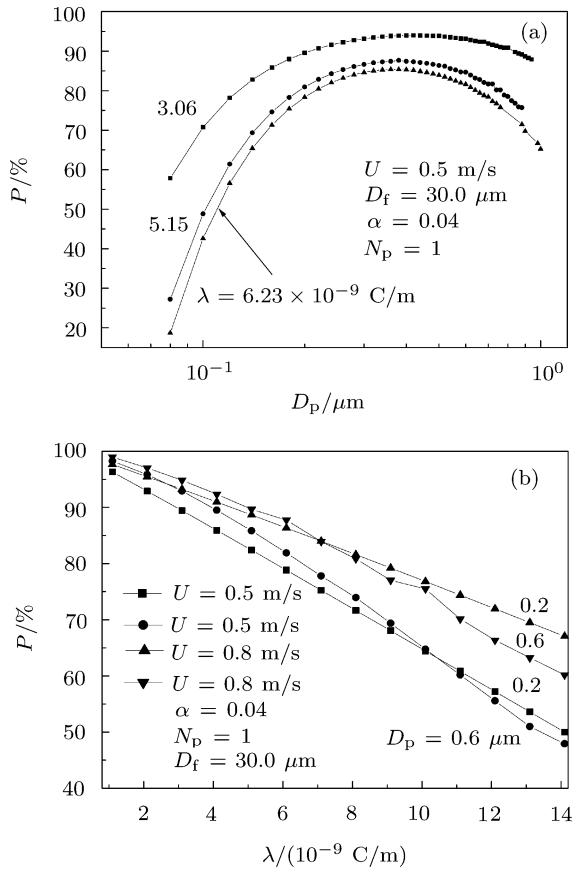


Fig.4. Effect of fibre charge on aerosol penetration through an electret fibrous filter. (a) as function of particle size, (b) as function of fibre charge density.

Except for the parameters mentioned in the above paragraphs, the physical properties of the particles also strongly affect the aerosol penetration through an electret filter. Figure 5 plots the aerosol penetration through the filter with a charge density of 5.15×10^{-9} C/m and at a face velocity of 0.5 m/s versus aerosol size in three charge states. The numbers (N_p) on the curves are the number of elementary charges on each particle. It can be observed that the aerosol penetration declines with the increase of N_p. The vertical distance between the curves is larger for the small particles than that for the larger particles. From Eqs.(7) and (8), one can find that the effect of the aerosol charge state on Coulombic force is greater than that on polarization. Figure 6 plots the aerosol penetration through the filter with a charge density of 5.15×10^{-9} C/m and at a face velocity of 0.5 m/s versus aerosol size for singly charged NaCl ($\varepsilon_p = 5.9$) and Al_2O_3 ($\varepsilon_p = 9.2$) particles. The results reveal that the aerosol penetration with Al_2O_3 particles exceeds that of NaCl for the larger particles. The data demonstrate that penetration through an electret filter declines as the dielectric constant of the aerosol increases. The principal electrostatic capture force between singly charged particles and an electret fibre is the Coulombic force and the polarization force. A larger particle with a higher dielectric constant has a higher polarization force than that of a smaller particle. The predicted results of particle penetration through the filter agree with those of Ref.[25].

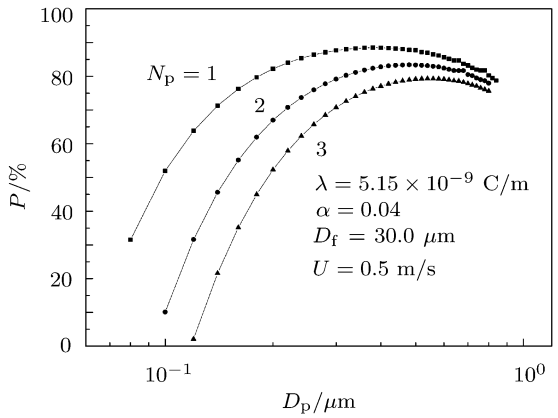


Fig.5. Effect of charged particle state on aerosol penetration through an electret fibrous filter. The number on the curve is the number of elementary charges on each particle.

The singly charged NaCl aerosol penetration through the filter with fibre charge density of 6.23×10^{-9} C/m and a face velocity of 0.1 m/s is plotted in Fig.7. The inserted plot is the Fig.7 in Ref.[25]. The physical properties of the electret fibre and aerosol particles used are the same as those of Fig.7 (curve of charged aerosol-0.08 M SO pretreated filter labelled number (1)) in Ref.[25]. In comparison, the two curves reveal the same trends and the maxima of aerosol penetration agree with each other. These data indicate that the Coulombic effect is significant for smaller aerosol and becomes weaker as the aerosol size increases, which are consistent with those of Kanaoka *et al*[14] and Romay *et al.*[26] Hence, the simulated results obtained in this paper can be accepted.

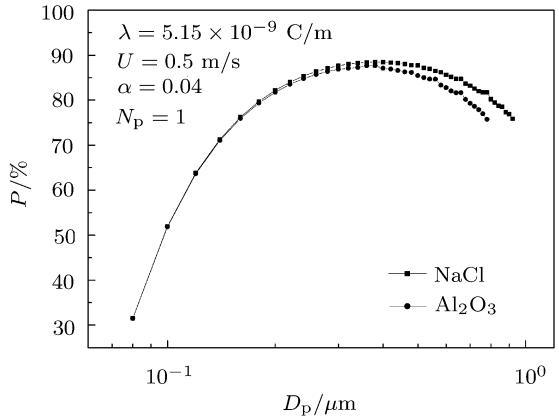


Fig.6. Aerosol penetration through an electret fibrous filter versus particle diameter for NaCl and Al_2O_3 aerosol.

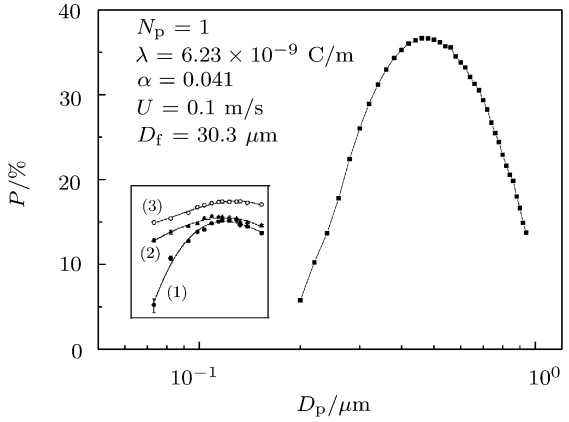


Fig.7. Aerosol penetration through an electret fibrous filter versus particle diameter for single charged particle. Inset picture is Figure 7 of Ref.[25].

4. Conclusions

In the present paper, based on the Kuwabara flow field, the effects of several influential factors on the initial stage of aerosol penetration through an

electret filter have been investigated, including particle size and charge state, fibre charge, filter packing density and fluid velocity. The conventional mechanical mechanisms (impaction, interception, Brownian diffusion and gravitationally settling) and the electrostatic mechanisms (including Coulombic and dielectrophoretic) have been coupled in the numerical model. Simulation reveals that particles larger than 0.5 μm are mainly subjected to the polarization force, as well as the impaction, and interception effects; while Coulombic force effect becomes prevailing as the particle size decreases. The fibre charge state is found to be a critical factor affecting the aerosol penetration through electret fibres. The higher the fibre charge density, the lower the penetration. The results also indicate that there exists a crossover for different particle diameters with the same fluid velocity. In addition, the packing density and particle dielectric constant have significant influence on the penetration, for example the penetration through an electret fibre declines as the dielectric constant of the aerosol increases.

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