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Mechanism of Particle Impaction and Filtration by the Dry Porous Metal Substrates of an Inertial Impactor

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This study has investigated numerically the particle collection efficiency curves of inertial impactors with a dry porous metal substrate covering a wide range of particle diameters. The results show that the penetrating air causes higher inertial force for particles near the surface of the dry porous metal substrate than that of the flat plate, which increases the collection efficiency due to inertial impaction mechanisms. The calculated collection efficiency curve will be sharper than that assuming 100% filtration efficiency (ideal filtration) and there is a minimum value of <2% at $\sqrt{\mathrm{St}} = 0.05 \sim 0.07$ (corresponding to $d_p = 0.1 \sim 0.5\ \mu$m) for different Re and K. The collection efficiency increases to 15% for the ultrafine particles with a diameter of 0.01 μm when Re = 3,000 and K = 568,000 cm^{-2}. When $\sqrt{\mathrm{St}} \to 0$, the collection efficiency will approach the curve considering ideal filtration due to diffusion mechanisms.

INTRODUCTION

Using the dry porous metal substrate as the collection surface of an inertial impactor has the advantage that high concentration liquid particles can be sampled without an overloading problem because of its capillary action. However, the particle collection efficiency for the impactor with a porous metal substrate is higher than that with a flat plate substrate (Tsai et al. 2001). This is due to some air penetration into the dry porous metal substrate resulting in a different particle collection efficiency curve (Huang et al. 2001) than that predicted by the traditional theory (Marple 1970; Marple and Liu 1974; Marple and Willeke 1976; Rader and Marple 1985).

Rao and Whitby (1978) found this phenomenon for the impactor with filter substrates. Their experimental results indicated that the performance of impactors was significantly affected by the nature of the collection surface. Using the glass fiber filter as an impact collection surface reduced particle bounce, but altered the shape of the efficiency curve. At low Stokes numbers, the particle collection efficiency of the glass fiber filter was much higher than that of the oil-coated glass plate. One of the probabilities for the increase in the collection efficiency was attributed to the aerosol jet penetration into the filter surface (Rao and Whitby 1978). Turner and Hering (1987) indicated the glass fiber mats used in the impactor reduced bounce-off, but also collected a significant number of particles smaller than the critical particle size. This excess particle collection was due to the interception of particles on streamlines penetrating into the fiber mat.

In the previous study (Huang et al. 2001), the collection efficiency of the impactor with the dry porous metal substrates was obtained by assuming 100% filtration efficiency. That is, particles carried by the penetrating air into the dry porous substrate are assumed to be collected. The results showed that the excess particle collection efficiency increases with a decreasing resistance factor of the porous metal substrate, K, an increasing Reynolds number, which is based on the nozzle diameter, Re ($\mathrm{Re} = (\rho U_0 W)/\mu$, where U_0 is the air velocity at the nozzle, ρ is the air density, and μ is the air viscosity), and a decreasing nozzle diameter, W, when $\sqrt{\mathrm{St}} \to 0$ (St, Stokes number, $\mathrm{St} = (\rho_p C d_p^2 U_0)/9\mu W$, where C is the Cunningham slip correction factor, ρ_p is the particle density, and d_p is the particle diameter). The dimensionless parameter

$$\phi = \frac{\rho U_0}{2K\mu t}\left(\frac{Dc}{W}\right)^{0.9},$$

where t is the thickness of the porous metal substrate and Dc is the diameter of the porous metal substrate had been introduced to determine the excess particle collection efficiency by the porous metal substrate, and the theory predicted the numerical results very well. However, there is an additional filtration effect of penetrating aerosol particles by the porous metal substrate that was not included in the previous study. It is believed

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that if the filtration effect was considered, the particle collection efficiency of the impactor with dry porous metal substrate will be decreased.

To investigate the mechanism of particle impaction near the surface of the porous metal substrate and the effect of the particle filtration on the collection efficiency curves of the porous metal substrate, flow field and particle trajectories were simulated. The filtration efficiency of particles inside the porous substrate was calculated at different effective collector diameters, resistance factors of the porous metal substrate, and Reynolds numbers, which are based on the nozzle diameter, to obtain a complete particle collection efficiency curve covering a wide range of particle diameters.

METHOD

The particle collection efficiencies of the inertial impactors were simulated using the numerical models described in Huang et al. (2001). The flow field in the inertial impactor was simulated by solving the two-dimensional (2D) Navier–Stokes equations in the cylindrical coordinate. The fluid flow in the impactor was assumed steady, incompressible, and laminar, and air was assumed to be at 20°C and 1 atm. The governing equation was discretized by means of the finite volume method and solved by the SIMPLE algorithm (Patankar 1980). Grid independence checks were performed using different grid spacings. These checks revealed that approximately 40,000 grids were necessary to obtain a grid-independent solution. After obtaining the flow field, the particle equations of the motion were solved numerically to obtain particle trajectories and collection efficiency. If the particle concentration and velocity profiles are assumed to be uniform at the entrance of the nozzle, then the ideal collection efficiency (assuming 100% filtration efficiency) can be calculated as

$$\eta_{\text{ideal}} = \left(\frac{r_c}{(W/2)}\right)^2, \quad [1]$$

where r_c is the critical radius within which particles will be collected.

For calculating the filtration efficiency by the porous metal substrate, an analytical formula is required. The overall collection efficiency, E_T, of the porous metal substrate can be expressed as in Otani et al. (1989):

$$E_T = 1 - \exp\left(-\frac{3\alpha L \eta_S}{2(1-\alpha)D_f}\right), \quad [2]$$

where η_s stands for the collection efficiency of a single-collector, α is the solid volume fraction ($\alpha = 0.433$ for porous metal substrate; Poon et al. (1994), D_f is the effective collector diameter, and L is the particle traveling distance inside the porous metal substrate. The single-collector efficiency may be expressed by

$$\eta_S = \eta_D + \eta_G + \eta_R + \eta_I, \quad [3]$$

where η_D, η_G, η_R, and η_I represent the collection efficiencies by diffusion, gravity, interception, and impaction, respectively. The collection efficiency of a single collector may be estimated as in Otani et al. (1989). Since the porous substrate has a granular-like structure, the predictive equations of Otani et al., which are applicable in this structure for a wide range of filtration conditions, were used to calculate the collection efficiency of individual filtration mechanism.

$$\eta_D = ASc^B \mathrm{Re}_f^C, \quad [4]$$

$$\begin{cases} B = -\frac{2}{3} + \frac{\mathrm{Re}_f^3}{6(\mathrm{Re}_f^3 + 2.0\times 10^5)}, \\ A = 8.0,\ C = -2/3, \ \text{for } \mathrm{Re}_f < 30, \\ A = 40.0,\ C = -1.15, \ \text{for } 30 \le \mathrm{Re}_f < 100, \\ A = 2.1,\ C = -1/2, \ \text{for } \mathrm{Re}_f \ge 100, \end{cases} \quad [5]$$

$$\eta_G = \frac{G}{1+G}, \quad [6]$$

$$\eta_R = 16R^{2-\mathrm{Re}_f} \big/ \left(\mathrm{Re}_f^{1/3} + 1\right)^3, \quad [7]$$

$$\eta_I = \frac{\mathrm{Stk}_{feff}^3}{1.4\times 10^{-2} + \mathrm{Stk}_{feff}^3}, \quad [8]$$

where the parameters Sc, G, R, and Stk_{eff} are defined as

$$Sc = \frac{\mathrm{Pe}}{\mathrm{Re}_f}, \quad [9]$$

$$G = \frac{Cd_p^2(\rho_p - \rho)g}{18\mu u_0}, \quad [10]$$

$$R = \frac{d_p}{D_f}, \quad [11]$$

$$\mathrm{St}_{feff} = \mathrm{St}_f\left(1.0 + \frac{1.75\,(1-\alpha)\,\mathrm{Re}_f}{150\alpha}\right) \quad [12]$$

where Pe, Re_f, and St_f are the Peclet, Reynolds, and Stokes numbers, respectively, and are defined as

$$\mathrm{Pe} = \frac{u_0 D_f}{D}, \quad [13]$$

$$\mathrm{Re}_f = \frac{\rho u_0 D_f}{\mu}, \quad [14]$$

$$\mathrm{St}_f = \frac{\rho_p d_p^2 C u_0}{9\mu D_f}, \quad [15]$$

where D is the diffusion coefficient, u_0 is the average air velocity inside porous metal substrate, C is the Cunningham slip correction factor, and ρ_p is the particle density.

The effective collector diameter, D_f, may be calculated by

$$D_f = \sqrt{\frac{16\alpha(1+2\xi)}{\varepsilon K K_h}}, \quad [16]$$

where ε, ξ, and K_h are the inhomogeneity factor (ε = 1.57 for the porous metal substrate; Poon et al. (1994)), slip coefficient, and hydrodynamic factor defined by

$$\xi = 0.998\left(\frac{2\lambda}{D_f}\right), \quad [17]$$

$$K_h = -0.25\alpha^2 + \alpha - 0.5\ln\alpha - 0.75 + \xi(0.5\alpha^2 - \ln\alpha - 0.5), \quad [18]$$

where λ is the air mean free path.

The particle collection efficiency of the impactor with porous metal substrate can be calculated as

$$\eta = \eta_{\text{ideal}} \times E_{T\text{ave}}, \quad [19]$$

where $E_{T\text{ave}}$ is the average of the filtration efficiency of a particle that is collected by the porous substrate. $E_{T\text{ave}}$ is calculated as

$$E_{T\text{ave}} = \sum_{i=1}^{r_c} Q_i \times \frac{E_{Tmi}}{Q_c}, \quad [20]$$

where Q_i denotes the flow rate represented by the *i*th radial position at the inlet of the nozzle; E_{Tmi} is the filtration efficiency of a particle entering at the *i*th radial position; and Q_c is the flow rate corresponding to the critical radius.

RESULTS AND DISCUSSION

Particle Trajectories

Figure 1 illustrates the particle trajectories inside the porous metal substrate at different $\sqrt{\text{St}}$ when $D_f = 126\ \mu$m and Re = 3,000 for the radial position at the nozzle inlet corresponding to 15% of the total flow. The figure only shows half of the impactor and the particles start at the radial position of the nozzle corresponding to 15% of the total flow. r_c is the critical radius across the nozzle which demarcates the starting radial position for a particle to be collected by the substrate or not. If a particle starts at a radial position smaller than r_c, then the particle will be collected. *Dc* is the diameter of the porous substrate while D_f is the effective collector diameter of the porous substrate. The diameter of the porous substrate is about 200 times the effective collector diameter. At a low Stokes number, $\sqrt{\text{St}} \leq 0.05$, the particle trajectories are close to the air streamlines. For particles with a greater Stokes number, e.g., $\sqrt{\text{St}} \approx 0.16$, the particle trajectories deviate from the corresponding streamlines due to the higher particle inertial force. The larger the Stokes number is,

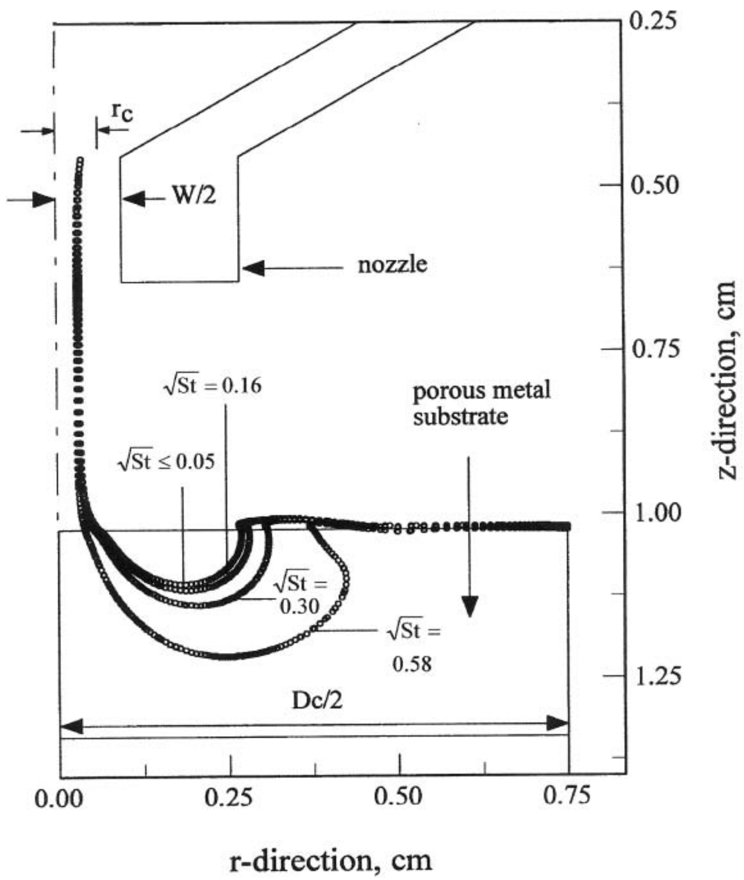

Figure 1. Particle trajectories inside the porous metal substrate at $D_f = 126\ \mu$m and Re = 3,000 at the radial position of the nozzle corresponding to 15% of the total flow.

the larger the distance that the particle trajectory deviates. The particles will be collected inside the porous metal substrate by the inertial impaction, diffusion, interception, and gravitational settling mechanisms.

Particle Impaction Near the Substrate Surface

Once the penetrating air enters the porous metal substrate at a high velocity, the controlling collection mechanism is inertial impaction for large particles. Figure 2 shows the particle collection efficiency as a function of Stokes number, St_f, at different radial positions corresponding to 5, 15, 25, and 35% of the total flow assuming the penetrating depth of 0.1 cm. It is seen that impaction occurs near the surface with 100% efficiency for particles with a Stokes numbers >0.1, as shown in Figure 2a. When the effective collector diameter is increased and the Reynolds number is decreased, the efficiency decreases to $82 \sim 87\%$ for $St_f = 0.1$, as shown in Figure 2b.

Particle Diffusion inside the Substrate

The penetrating air has the lowest velocity when it is about to exit the porous metal substrate when Brownian diffusion is the dominant mechanism for fine particles. Figure 3 shows the particle collection efficiency as a function of Peclet number, Pe, at different radial positions corresponding to 5, 15, 25, and 35%

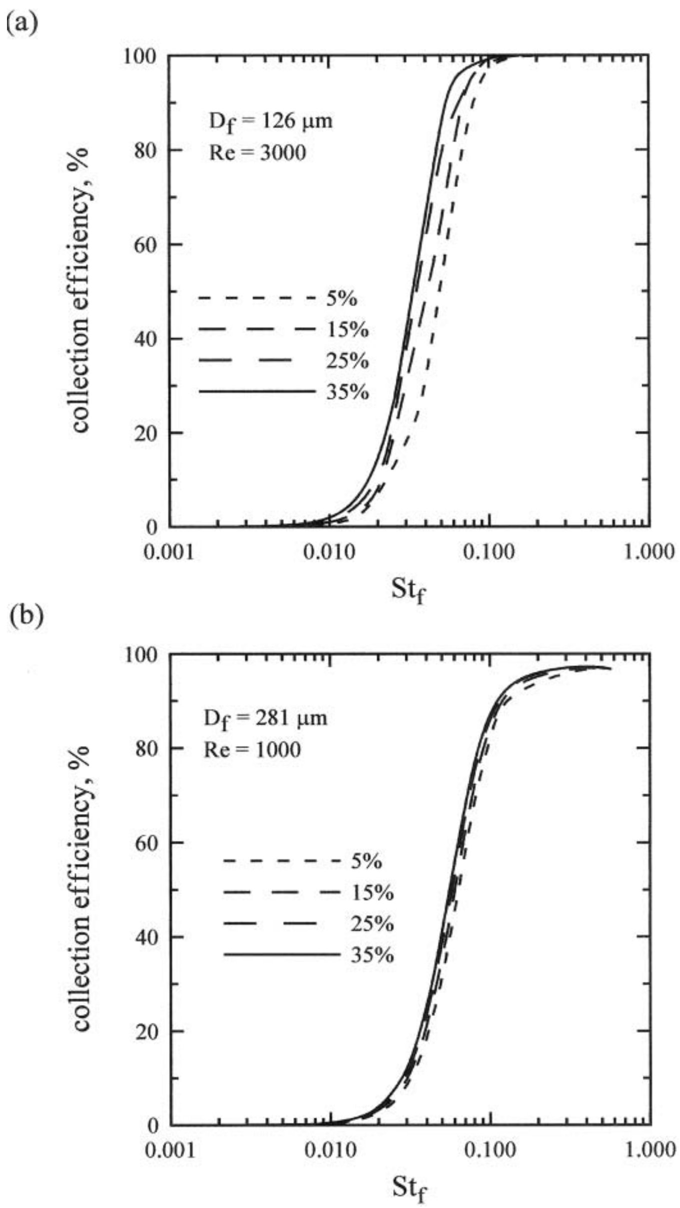

Figure 2. Particle impaction efficiency at different radial positions of the nozzle corresponding to 5, 15, 25, and 35% of the total flow. (a) $D_f = 126\ \mu$m, (b) $D_f = 281\ \mu$m.

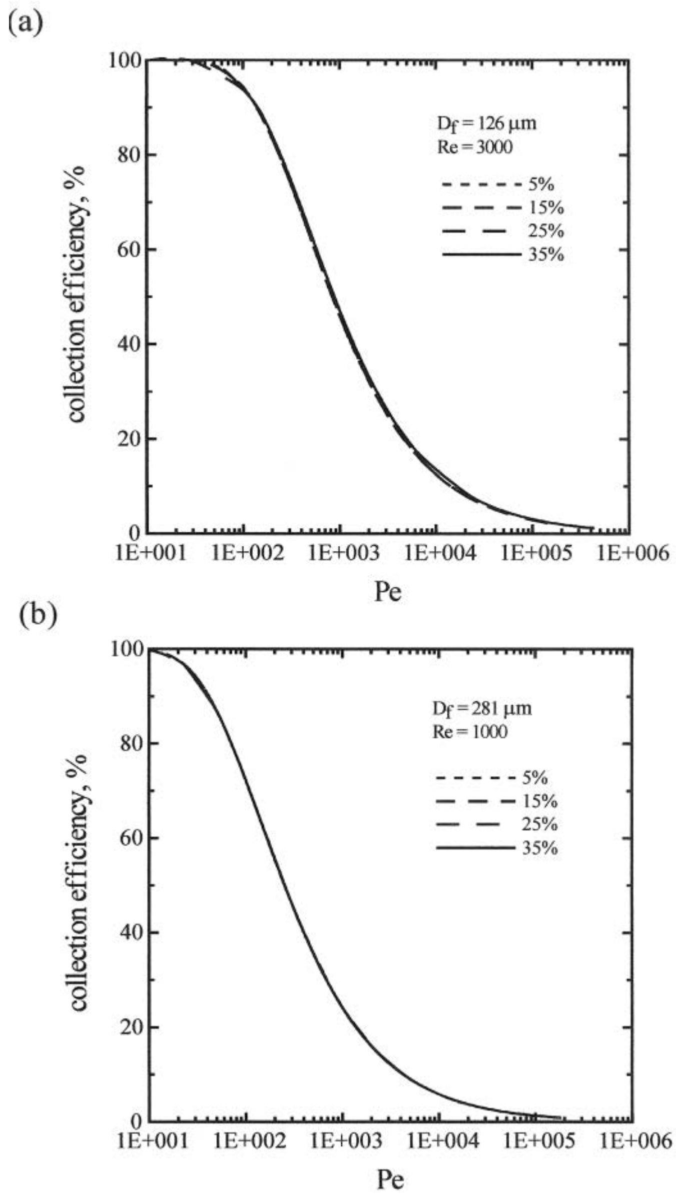

Figure 3. Particle diffusion efficiency at different radial positions of the nozzle corresponding to 5, 15, 25, and 35% of the total flow. (a) $D_f = 126\ \mu$m, (b) $D_f = 281\ \mu$m.

of the total flow for the thickness of 0.1 cm near the air outlet from the porous metal substrate. It is seen that the particle collection efficiency is 100% due to the diffusion mechanism when Pe is >40, as shown in Figure 3a. When the effective collector diameter is increased and the Reynolds number is decreased, the efficiency decreases to 90% for Pe = 40, as shown in Figure 3b.

Filtration Efficiency Curve of the Porous Metal Substrate

Figure 4 shows the filtration efficiency of the impactor with porous metal substrate including inertial impaction, diffusion, interception, and gravitational settling mechanisms at different radial positions corresponding to 5, 15, 25, and 35% of the total flow based on the average air velocity and the particle traveling distance inside the porous metal substrate. It is seen that there is a substantial shift of filtration efficiency curves to the left for the case of a larger initial radial position (corresponding to higher flow rate) compared to the smaller radial position, as shown in Figure 4a. When the effective collector diameter is increased and the Reynolds number is decreased, the filtration curves have a similar trend, as shown in Figure 4b.

Figure 5 shows the average filtration efficiency, $E_{T\text{ave}}$, of the impactor with porous metal substrate for different particle sizes at Re = 3,000 and $K = 568{,}000$ cm^{-2}. There is a minimum filtration efficiency of about 5% at the particle size of 0.1 μm

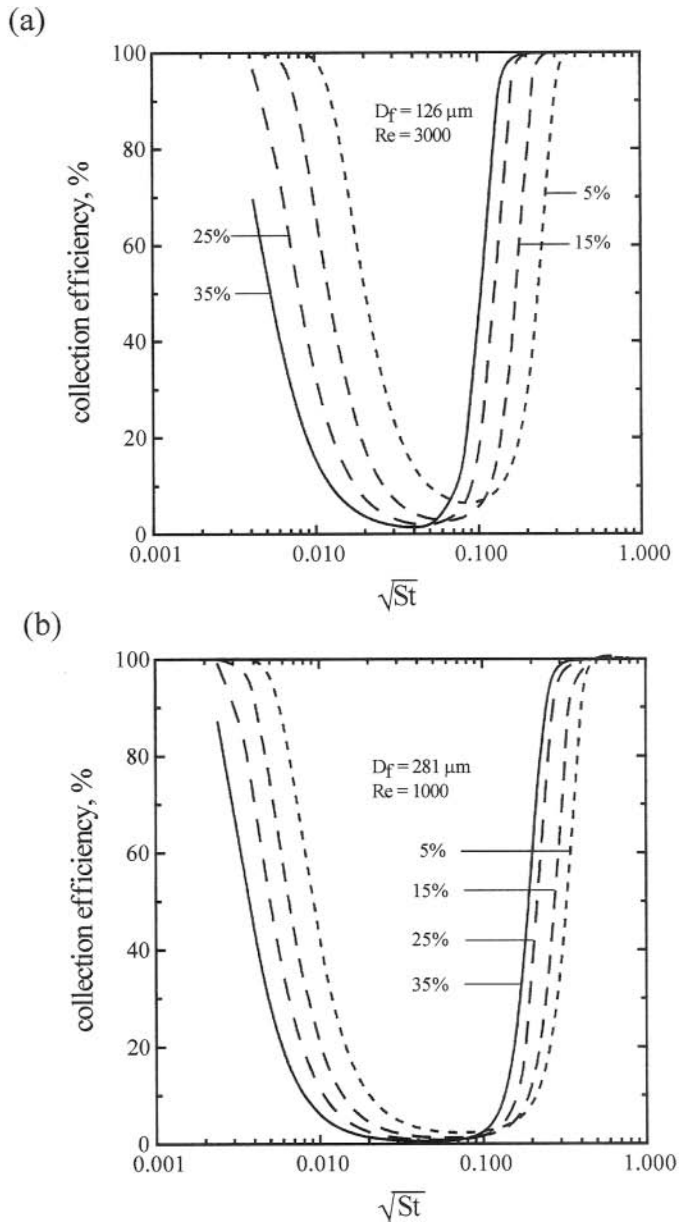

Figure 4. Filtration efficiency of the impactor with the porous metal substrate at different radial positions corresponding to 5, 15, 25, and 35% of the total flow. (a) $D_f = 126\ \mu$m, (b) $D_f = 281\ \mu$m.

(corresponding to $\sqrt{\mathrm{St}} = 0.05$) in the curve. When the particle size is smaller, the filtration efficiency increases due to the diffusion mechanism. Beyond the particle size of minimum efficiency, the filtration efficiency increases with increasing particle size due to the interception and impaction mechanism. When the particle is as large as 1 μm, the collection efficiency increases to 97%.

Collection Efficiency Curves at Different Re and K

Figure 6 shows the particle collection efficiency curves of the impactor with porous metal substrate for the different Reynolds numbers at the resistance factor of 568,000 cm^{-2}. Considering the surface impaction and ideal filtration mechanism only, dotted lines show that there is a large shift of the collection efficiency curve of the impactor with the porous metal substrate to the left of the flat-plate impactor. This is because the penetrating air causes a higher inertial force for particles near the surface of the porous metal substrate than that of the flat plate. However, as the penetrating air carries the particles into the porous metal substrate, the filtration effect of the porous metal substrate must be considered when calculating the overall particle collection efficiency. Solid lines show that the collection efficiency curves, although less sharp than those of the flat plate substrate, have left

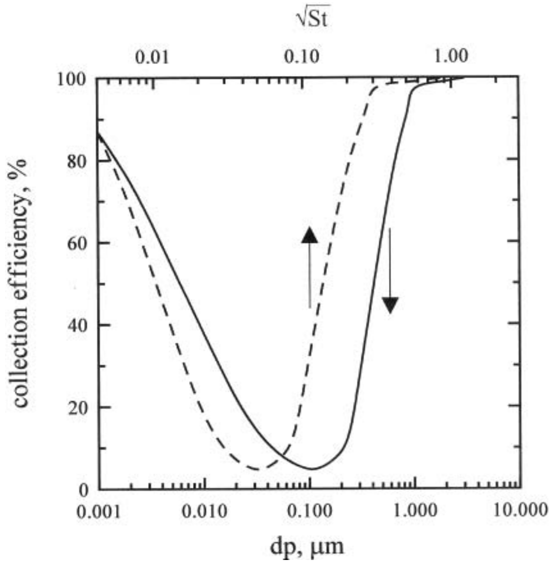

Figure 5. Average filtration efficiency of the impactor with the porous metal substrate for different particle sizes at $\mathrm{Re} = 3{,}000$ and $K = 568{,}000\ \mathrm{cm}^{-2}$.

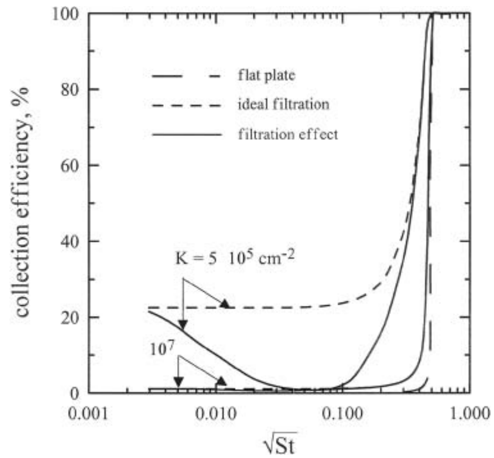

Figure 7. Particle collection efficiency curve of the impactor with the porous metal substrate for different K at $\mathrm{Re} = 1{,}500$.

tail ends that are close to zero collection efficiency. These collection efficiency curves resemble those that appeared in Kavouras and Koutrakis (2001) and hence are more realistic.

For $\mathrm{Re} = 3{,}000$, it is seen that for larger particles with $\sqrt{\mathrm{St}} = 0.24$ (corresponding to $d_p = 0.8\ \mu$m), the particle collection efficiency is close to the case of ideal filtration because of the inertial impaction and interception mechanisms by the porous metal substrate. There is a minimum value of about 2% at $\sqrt{\mathrm{St}} = 0.05$ (corresponding to $d_p = 0.1\ \mu$m), which corresponds to the most difficult particle size to collect during the impaction process. For ultrafine particles with $\sqrt{\mathrm{St}} = 0.013$ (corresponding to $d_p = 0.01\ \mu$m), the collection efficiency increases to 15%. In the case of $\mathrm{Re} = 500$, the minimum efficiency is about 0.3% at $\sqrt{\mathrm{St}} = 0.06$ (corresponding to $d_p = 0.5\ \mu$m) and for an ultrafine particle with $\sqrt{\mathrm{St}} = 0.0127$ (corresponding to $d_p = 0.05\ \mu$m), the collection efficiency increases to 2%. For both cases, when $\mathrm{Re} = 500$ and 3,000 the collection efficiency will approach the ideal filtration curve due to the diffusion mechanism in the limit of $\sqrt{\mathrm{St}} \to 0$.

Figure 7 shows the influence of K on the particle collection efficiency for the impactor with the porous metal substrates at $\mathrm{Re} = 1{,}500$. It is seen that the collection efficiency curve will be sharper than that assuming 100% filtration efficiency (dotted lines) and there is a minimum value of about 1% at $\sqrt{\mathrm{St}} = 0.07$

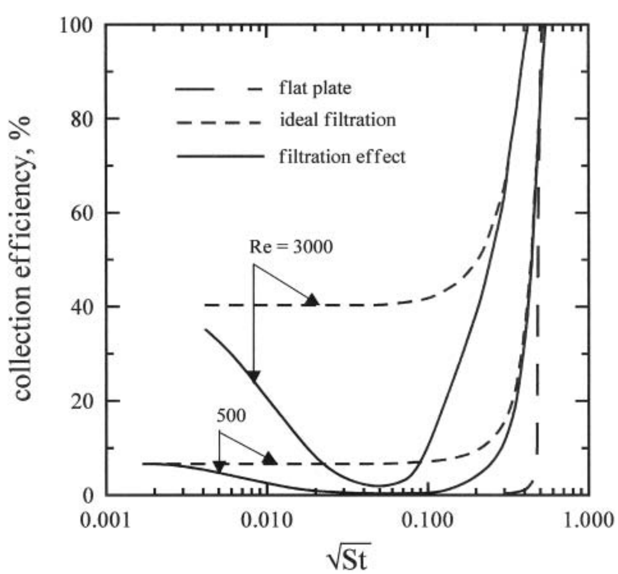

Figure 6. Particle collection efficiency curve of the impactor with the porous metal substrate for different Re at $K = 568{,}000\ \mathrm{cm}^{-2}$.

(corresponding to $d_p = 0.3\ \mu$m) when $K = 500{,}000\ \text{cm}^{-2}$. When the resistance factor of the porous metal substrate is increased to $10^7\ \text{cm}^{-2}$, the collection efficiency curve becomes close to that of the ideal filtration assumption. In this case, the excess particle collection by the porous metal substrate can be neglected. Also, in the limit of $\sqrt{\text{St}} \to 0$, the collection efficiency will approach the ideal filtration curve due to the diffusion mechanism when the asymptotic theory developed by Huang et al. (2001) can be used to predict the excess particle collection efficiency by the porous metal substrate.

CONCLUSIONS

As the penetrating air carries particles into the dry porous metal substrate of the inertial impactor, the effect of particle filtration by the dry porous metal substrate on the particle collection efficiency must be considered. This study shows that the particle trajectories inside the dry porous metal substrate are different for different particles' Stokes numbers. The collection efficiency curves of inertial impactor with porous metal substrate considering filtration effect are less sharp than those of the flat plate substrate, and the curves are still *S*-shaped when the low tail ends approach a zero collection efficiency.

For larger particles, the penetrating air causes a higher collection efficiency near the porous metal substrate surface due to the inertial impaction mechanism. There is a minimum value of about 0.3 ~ 2% at the particle diameter of 0.1 ~ 0.5 μm when $\text{Re} = 500 \sim 3{,}000$ and $K = 5 \times 10^5 \sim 10^7\ \text{cm}^{-2}$. In the case of $\text{Re} = 3{,}000$ and $K = 568{,}000\ \text{cm}^{-2}$, the collection efficiency increases to 15% for ultrafine particles with a diameter of 0.01 μm. For different Re and *K*, the collection efficiency will approach the ideal filtration curve (assuming 100% filtration efficiency) due to the diffusion mechanism in the limit of $\sqrt{\text{St}} \to 0$.

Although dry porous substrates have the advantage that solid particle bounce can be minimized, caution should be observed when designing a cascade inertial impactor with porous substrates because ultrafine particles will be collected on the upper stages, resulting in a bias to particle size distribution measurement. Thus the collection efficiency of ultrafine particles must be measured when designing this kind of inertial impactor.

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