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Particle collection efficiency of an inertial impactor with porous metal substrates

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Abstract

This study has investigated numerically the particle collection efficiency of an impactor with porous metal substrates. Two-dimensional flow field in the inertial impactor was simulated by solving the Navier–Stokes equations with the control volume method. Particle trajectories were then calculated to obtain the collection efficiency at different Reynolds numbers, which are based on nozzle diameter, and at different K, which is the resistance factor of the porous metal substrate. This study shows that some air may penetrate into the porous metal substrate resulting in different particle collection efficiency than that predicted by the traditional theory. The particle collection efficiency for the impactor with the porous metal substrate is higher than that with the flat plate substrate below the cutpoint, and numerical results are in good agreement with the experimental data. The dimensionless parameter $\phi = (\rho U_0/2K\mu t)(D_c/W)^{0.9}$ has been introduced to determine the excess particle collection efficiency, η_e, by the porous metal substrate in the limit of $\sqrt{\mathrm{St}} \to 0$. The theory explains the experimental data of the excess collection efficiency very well. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Collection efficiency; Porous metal substrate; Inertial impactors

1. Introduction

This study was conducted to investigate the effect of air penetration into the porous metal substrate on the particle collection efficiency of an impactor with porous metal substrates.

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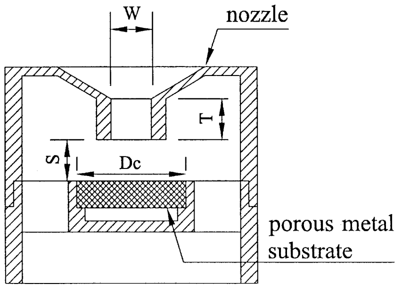

Fig. 1. The schematic diagram of an impaction stage with porous metal substrate (*S*: jet-to-plate distance; *T*: nozzle throat length; D_c: diameter of porous metal substrate).

Inertial impactors are widely used for size-fractionated sampling of aerosols. Theoretical analysis of the inertial impactors predicted the cutoff diameter and the shape of the collection efficiency curves reasonably well for the liquid particles. Hard solid particles may bounce off the collection substrates of the inertial impactors. Surface coating on the collection substrate is often used to reduce particle bounce. The porous metal disc impregnated with mineral oil has also been used as an impaction substrate to prevent particle bounce (Reischl & John, 1978; Marple & McCormack, 1983; Turner & Hering, 1987).

The use of uncoated substrate as a collection surface is suitable for subsequent chemical and elemental analysis of the collected particles because it is free of interference from coating materials (Biswas & Flagan, 1988). Newton, Carpenter, Cheng, Barr, and Yeh (1982) used the uncoated stainless steel substrates in the cascade impactor for sampling aerosols in the exhaust gas of the pressurized fluid bed coal combustion system at high temperature and pressure. However, the uncoated porous metal substrate has not previously been used as collection surface for inertial impactors, therefore, there is very little information available on the particle collection efficiency.

In our previous study (Tsai, Huang, Wang, & Shih, 2001), a 2 l/min personal denuder consisting of a two-stage impactor, and two denuder discs has been developed. The cutoff aerodynamic diameter is 9.5 and 2.0 μm, and the nozzle diameter is 0.72 and 0.19 cm for the first and second stages, respectively. The schematic diagram of one stage of the impactor is shown in Fig. 1. Uncoated porous metal discs (diameter: 1.2 cm, pore size: 100 μm, thickness: 0.317 cm, P/N 1000, Mott Inc., Farmington, USA) are used as the impaction substrates in the impactor. The experimental results indicate that the maximum particle loss by the downstream denuder is less than 9% for particle aerodynamic diameter smaller than 2.0 μm. Loss can be much higher for larger particle sizes. Since particles larger than 2.0 μm are removed by the cascade impactor, particles collected by the downstream denuder are not expected to interfere with gas concentration measurement. In the loading test, the experimental results indicated that the uncoated porous metal substrate prevents particle overloading problem because of its capillary action. If a flat plate substrate was used, impacted liquid particles were found to coalesce into a single droplet and subsequently reentrained.

Two extra stages with the nozzle diameter of 0.26 and 0.36 cm, respectively, were later built and their particle collection efficiencies were also determined using monodisperse oleic acid test particles as described in Tsai and Cheng (1995). Test results indicated that discrepancy between the experimental data of Tsai et al. (2001) and theoretical results of Marple (1970) for solid substrates on particle collection efficiency exists as shown in Fig. 2, where the Stokes number $\mathrm{St} = \rho_p C d_p^2 U_0 / 9\mu W$

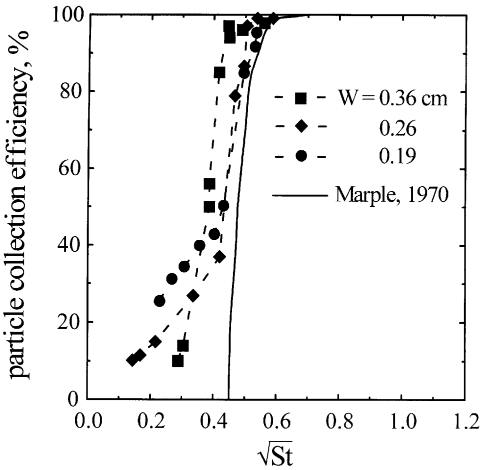

Fig. 2. Experimental data and theoretical results (Marple, 1970) of the particle collection efficiency.

(C: Cunningham slip correction factor; μ: air viscosity; ρ_p: particle density; d_p: particle diameter; U_0: air velocity at the nozzle; W: nozzle diameter). Instead of a sharp collection efficiency curve as predicted by Marple's theory, there are tails at the bottom of the curves. The collection efficiency does not seem to go to zero when the Stokes number goes to zero, especially for the small nozzle diameter of 0.19 cm. This disagreement was due to excess particle collection resulting from air penetrating into the porous metal substrates. This phenomenon was found by Rao and Whitby (1978) for the filter substrates. Their experimental results indicated that the performance of impactors was significantly affected by the nature of the collection surface. The glass fiber filter used as an impact collection surface reduced the particles bounce, but altered the shape of the efficiency curve. For example, at low stokes numbers for which the oil-coated glass plate had zero or low collection efficiency, the efficiency of the glass fiber filter was much higher than that of the oil-coated glass plate. One of the probabilities of the increase in the collection efficiency was thought to be attributed to the aerosol jet penetration into the filter surface.

To facilitate the design of the impactor with the porous metal substrates, the particle collection efficiency characteristic was investigated using numerical models which calculate flow field, particle trajectories and collection efficiency. The theoretical collection efficiency curves were then compared with the experimental data. An asymptotic theory was developed to describe the excess particle collection efficiency in the limit of $\sqrt{\mathrm{St}} \to 0$.

2. Numerical method

The flow field in the inertial impactor was simulated by solving the 2-D 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

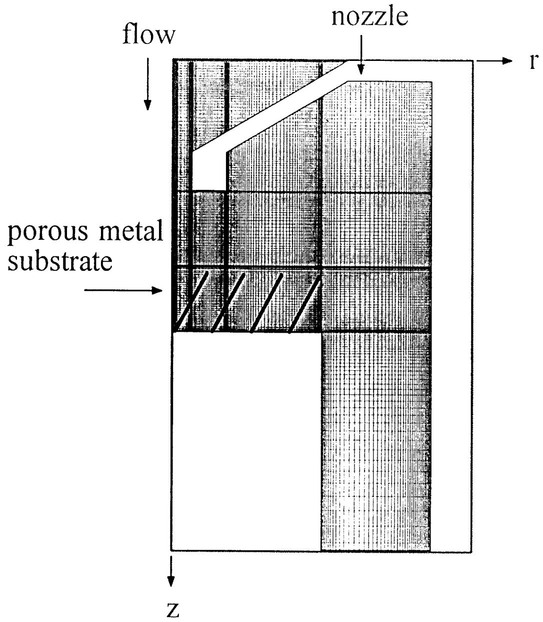

Fig. 3. Main control volume distribution for the flow field calculation in the present study. (Hatched area is the porous metal substrate.)

by means of the finite volume method and solved by the SIMPLE algorithm (Patankar, 1980). One example of the calculation domain is shown in Fig. 3, where the number of grids is 40,000 (200 in r-direction $\times$ 200 in z-direction). The flow field is governed by

$$\rho(\mathbf{V}\cdot\nabla)\mathbf{V} = -\nabla P + \mu\nabla^2\mathbf{V} - K\mu\mathbf{V}, \tag{1}$$

where the last term of the right-hand side of the above equation is the additional pressure drop for the fluid flow through the porous metal substrate based on the Darcy's law. In Eq. (1) $\mathbf{V}$ is velocity vector in cm/s; P the pressure in dyne/cm^2; ρ the air density in g/cm^3; K the resistance factor of the porous metal substrate in cm^{-2} ($K = \frac{1}{k}$, k is the permeability).

After obtaining the flow field, the particle equations of the motion were solved numerically to obtain particle trajectories and collection efficiency. The particle equations of motion in r (radial) and z (axial) directions are

$$m_\mathrm{p}\frac{\mathrm{d}u_{\mathrm{p}r}}{\mathrm{d}t} = C_\mathrm{d}\mathrm{Re}_\mathrm{p}\frac{\pi\mu d_\mathrm{p}}{8C}(u_r - u_{\mathrm{p}r}), \tag{2}$$

$$m_\mathrm{p}\frac{\mathrm{d}u_{\mathrm{p}z}}{\mathrm{d}t} = C_\mathrm{d}\mathrm{Re}_\mathrm{p}\frac{\pi\mu d_\mathrm{p}}{8C}(u_z - u_{\mathrm{p}z}) + m_\mathrm{p}g. \tag{3}$$

In the above equations, C_d is the empirical drag coefficient; Re_p the particle Reynolds number; m_p and g the particle mass and the gravitational acceleration, respectively; $u_{\mathrm{p}r}$ and $u_{\mathrm{p}z}$ the particle velocities; u_r and u_z local flow velocities in the radial and axial directions, respectively.

The calculation involves integrating Eqs. (2) and (3) by means of the fourth Runge–Kutta method, applying an empirical drag law for the ultra-Stokesian regime and considering particle interception effect (Rader & Marple, 1985). As the particle equations of motion are integrated through the domain of interest, its initial velocity is given equal to the local flow velocity, and the initial position is set at the entrance of the nozzle. The new particle position and velocity after a small increment of time is calculated by numerical integration. The procedure is repeated until the particle hits the porous metal substrate or leaves the calculation domain.

If the particle concentration and velocity profiles are assumed to be uniform at the entrance of the nozzle, and particles are assumed to be collected when they hit the porous metal substrate, then the collection efficiency can be calculated as

$$\eta = (r_c/(W/2))^2, \tag{4}$$

where r_c is the critical radius across the nozzle within which particles will be collected. For comparison, the flow field and the particle collection efficiency for the impactor with flat plate substrates were also simulated.

3. Results and discussion

3.1. Effect of number of grids on the collection efficiency

Fig. 4 shows the particle collection efficiency curves for the porous metal substrate with $K = 568{,}000\ \mathrm{cm}^{-2}$ at the flow rate of 2 l/min based on different number of grids. As the number of the grids increases from 40,000 to 90,000, the collection efficiency curves do not change and almost overlap with each other. Hence in the subsequent simulation, 40,000 grids were used.

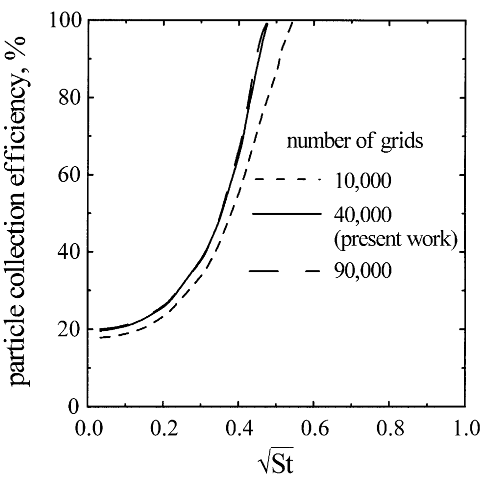

Fig. 4. The particle collection efficiency curves for the impactor with the porous metal substrate at different numbers of grids.

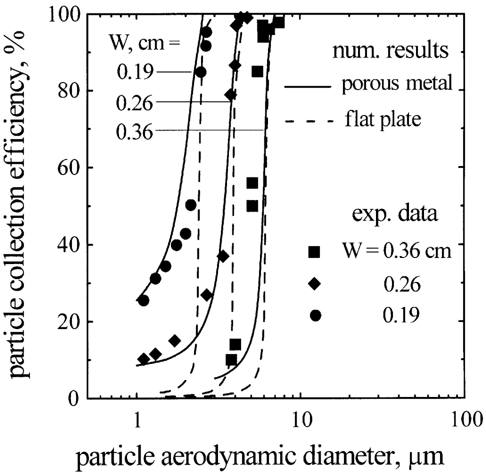

Fig. 5. Comparison of numerical results with experiment data (Tsai et al., 2001) for the collection efficiencies of oleic acid particles.

3.2. *Comparison of numerical results with experimental data*

The calculated collection efficiencies of the impactor with the porous metal and flat plate substrates are compared with the experimental data and shown in Fig. 5. It is seen that the particle collection efficiency for the impactor with the porous metal substrate is higher than that of the impactor with the flat plate substrate. The former is in much better agreement with the experimental data. In the limit of small particle diameter, the particle collection efficiency does not go to zero because some air flow penetrates into the porous metal substrate, as shown in both the experimental data and the present numerical study.

3.3. *Effect of Re on collection efficiency curves*

The particle collection efficiency curves of the impactor with porous metal substrate is shown in Fig. 6 at different Reynolds numbers, Re, where Re is based on the nozzle diameter. Also shown in Fig. 6 is the theoretical collection efficiency curve of Rader and Marple (1985). It is seen that the curve is in very good agreement with that calculated in this study assuming the flat plate substrate. Compared to the case of the flat plate, there is a substantial shift of collection efficiency curves to the left for the case of the porous metal substrates. As Re is increased, the curve becomes less sharp and deviates more from the traditional theory, which is based on the flat plate substrates. In the limit of $\sqrt{\mathrm{St}} \to 0$, the collection efficiency does not go to zero and is called the excess particle collection efficiency, η_e. When Re is increased, η_e increases and $\sqrt{\mathrm{St}_{50}}$ (Stokes number at 50% collection efficiency) decreases.

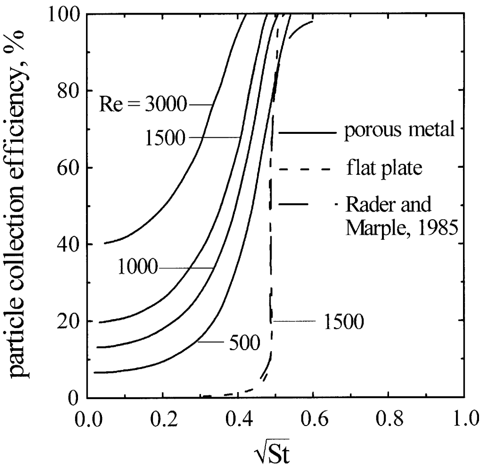

Fig. 6. The particle collection efficiency curves at different Reynolds numbers. Nozzle diameter = 0.19 cm, $K = 568{,}000\ \text{cm}^{-2}$.

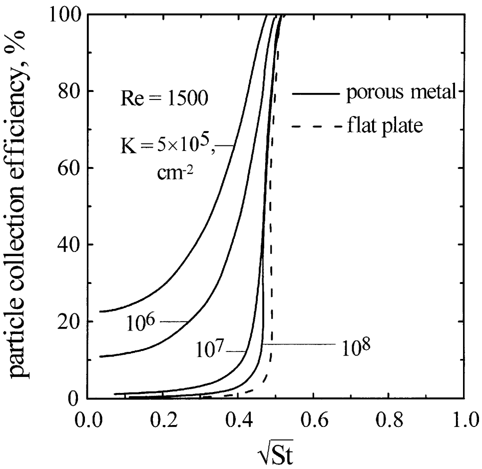

Fig. 7. The particle collection efficiency curves at different K. Nozzle diameter = 0.19 cm, Re = 1500.

3.4. Effect of K on collection efficiency curves

Fig. 7 shows the influence of K on the particle collection efficiency for the impactor with the porous metal substrates at Re = 1500, nozzle diameter $W = 0.19$ cm. It is seen that the particle collection efficiency increases as K is decreased at the same $\sqrt{\text{St}}$. In the limit of $\sqrt{\text{St}} \to 0$ the excess particle collection efficiency also increases with a decreasing K. This is because that more air penetrates into the porous metal substrate when K is smaller. As K is as large as $10^8\ \text{cm}^{-2}$, the

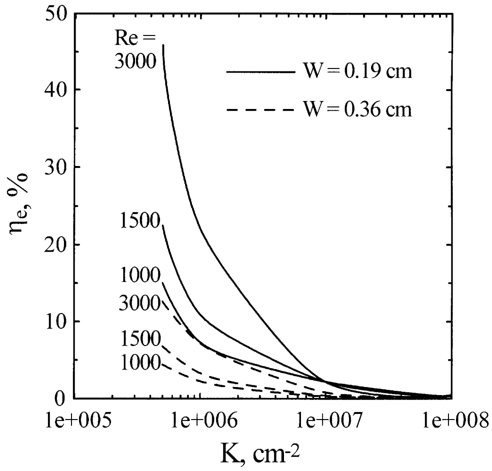

Fig. 8. The influence of Re, K and W on the excess particle collection efficiency.

collection efficiency curve is close to that of the flat plate substrate, and the excess particle collection by the porous metal substrate can be neglected. For the porous metal substrate, the resistance factor increases with decreasing nominal pore size. For example, the resistance factor of porous metal substrate with 5 μm pore size and 0.157 cm thickness will be as high as $1.2 \times 10^9\ \mathrm{cm}^{-2}$ (Heikkinen & Harley, 2000). Therefore, there will be negligible excess particle collection efficiency in this case.

Fig. 8 shows the effect of the Reynolds number, resistance factor and nozzle diameter on the excess particle collection efficiency for the impactor with the porous metal substrate. Beside the factor K which influences η_e very much, it is seen that both Re and W are also important factors influencing η_e. When Re is larger, the thickness of the boundary layer over the substrates is thinner, the air flow penetrate into the porous metal substrate more easily resulting in a higher particle collection efficiency at any fixed K and W. When K is smaller than $10^7\ \mathrm{cm}^{-2}$, η_e increases drastically with a decreasing K at any fixed Re and W. The excess particle collection efficiency is found to be smaller for the case with a larger nozzle diameter at any fixed Re and K. At the same Re, the dynamic air pressure will be larger for the case of a smaller nozzle diameter than that of a larger nozzle diameter. The area over which air penetrates into the substrate relative to the nozzle area becomes larger for the case of the smaller nozzle diameter, leading to a higher excess collection efficiency.

3.5. *Asymptotic theory of excess particle collection by porous metal substrate*

To model the effect of various factors on the excess particle collection by the porous metal substrate, the pressure drop for the air penetrating through the porous metal substrate is assumed to be proportional to the dynamic pressure of the fluid flow in the nozzle as

$$K\mu t U_1 = \alpha \tfrac{1}{2}\rho U_0^2, \qquad (5)$$

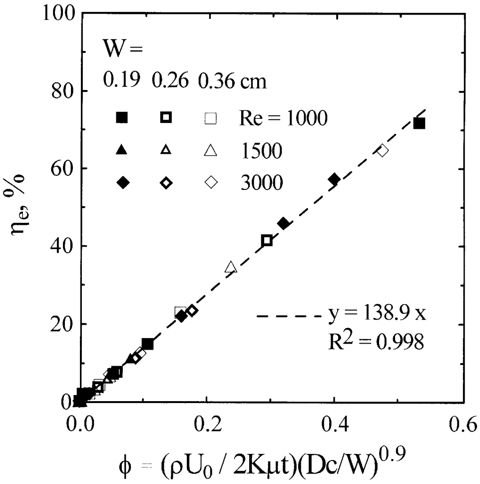

Fig. 9. The relationship between the excess particle collection efficiency and the dimensionless parameter ϕ. Symbols represent numerical results and the dashed line is the fitted curve.

where α is a proportionally constant, t the thickness of the porous metal substrate, U_1 the average air velocity penetrating into the porous metal substrate.

Assuming that the particle concentration over the substrate surface is the same as that at the nozzle, the excess collection efficiency of particles can be defined as

$$\eta_e = \frac{U_1 A_1}{U_0 A_0}, \tag{6}$$

where A_1 is the part of the substrate area where air is penetrating, and A_0 is the nozzle area. Substituting Eq. (5) into (6), the excess collection efficiency of particles can be calculated as

$$\eta_e = \alpha \frac{\rho U_0}{2K\mu t}\left(\frac{D_c}{W}\right)^n = \alpha\phi, \tag{7}$$

where the dimensionless parameter $\phi = (\rho U_0/2K\mu t)(D_c/W)^n$. The ratio of A_1 and A_0 is assumed to be proportional to $(D_c/W)^n$, due to the fact that the area over which air penetrates into the substrate is related to the nozzle area for the different nozzle diameter. Exponent n is obtained from the best fitting of the numerical results with experimental data and found to be 0.9. Fig. 9 shows the relationship between the excess particle collection efficiency and the dimensionless parameter ϕ. It is seen that the excess particle collection efficiency increases linearly with an increasing ϕ, and the asymptotic theory fits with the numerical results very well. However, there is an additional complication due to filtration effect of the penetrating aerosol particles by the porous metal substrate. This effect is not included in this study. It is believed that if the filtration effect is considered, the excess particle collection efficiency of the impactor with porous metal substrate will be decreased. For collecting particles upstream of a denuder, the sharp cutoff collection efficiency curves is desired. Thus, if the excess particle collection efficiency for the impactor is to be kept smaller than 10%, the theory predicts that ϕ must be smaller than 0.07.

4. Conclusions

Using the porous metal substrate as the collection surface of an inertial impactor, it has the advantage that high concentration liquid particles can be sampled without overloading problem because of its capillary action. However, some air may penetrate into the porous metal substrate such that extra particles are collected in the substrate resulting in different particle collection efficiency than that predicted by the traditional theory. A numerical study has been conducted to calculate the collection efficiency of the impactor and the calculated results agree with the experimental data very well. The particle collection efficiency of the porous metal substrate depends on the resistance factor of the porous metal substrate K, flow Reynolds numbers Re, and nozzle diameter W. In the limit of $\sqrt{\mathrm{St}} \to 0$, the excess particle collection efficiency increases with a decreasing K, an increasing Re and a decreasing W.

An asymptotic theory has been developed to determine the excess particle collection efficiency and the theory predicts the numerical results very well. If the excess particle collection efficiency for the impactor is to be kept smaller than 10%, the theory predicts that the dimensionless parameter ϕ must be smaller than 0.07.

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