Sieving of aerosol particles with metal screens

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ABSTRACT

Metal screens with uniform micrometer-sized opening were employed to sieve aerosol particles by suppressing the adhesion of particles smaller than the openings. The collection efficiencies of monodispersed polystyrene latex (PSL) particles were experimentally determined using the metal screens with 1.2-, 1.8-, 2.5- and 4.2-μm openings at various filtration velocities. The particles smaller than the mesh opening adhered on the metal screen at a low filtration velocity, but the bounce-off of particles on the mesh surface suppressed the adhesion at a high velocity. As a result, we found that the adhesion of PSL particles larger than 0.3 μm mostly suppressed at a filtration velocity higher than 10 ms^{-1} and therefore we can sieve aerosol particles according to the opening size of metal screens. We also found that the particle number concentration could be determined by measuring the increase in pressure drop since the clogging of metal screen openings takes place by the individual particles.

1. INTRODUCTION

Filtration of aerosol particles is carried out by various mechanical collection mechanisms such as diffusion, inertia and interception. As a result, the collection efficiency curves of an air filter are always concave against the particle size at a given filtration velocity, i.e., there exists a most penetration particle size (MPPS) (Hinds 1982). The contribution of individual mechanical collection mechanisms for collecting certain size of particles varies according to the filtration velocity for a filter with a given fiber diameter. For example, the inertial effect enhances with the filtration velocity whereas the diffusion is suppressed at a high filtration velocity. Recently Otani et al. (2007) first applied an air filter to classify submicron aerosol particles, where they employed extremely high filtration velocity of around 40 ms^{-1} so that the inertial collection would be only the responsible collection mechanism of aerosol particles. At an extremely high filtration velocity, the particles are captured solely by inertia and the contribution of diffusion is negligibly small. The 'inertial filter' served as a classifier (low-pass filter) of aerosol particles with diameter of around 100 nm. However, particle bounce-off on the surface of fibers becomes significant at a high velocity, which degraded the classification performance of inertial filter. Such bounce-off phenomena were more significant when metal screen was used as a filter media.

Recently, metal screens with uniform micrometer-openings Metal Mesh Device (MMD, Murata Manufacturing Co., Ltd.) were manufactured by a precision plating techniques, and applied to the determination of PM2.5 (Seto et al., 2014). Although they obtained a good correlation between the mass of captured particles on the metal screen with 2.5-μm opening and that of PM2.5, the mass of particles collected on 2.5-μm opening metal screen does not always reflect the mass of PM2.5 because PM2.5 are composed mostly of submicron particles. [Seto et al. (2014) used a metal screen with the opening of 2.5 μm to measure PM2.5 and reported a correlation between the particle mass collected on the screen and PM2.5. This is probably because the mass of particles collected on the 2.5-μm opening screen reflected the mass of particles smaller than 2.5 μm since the particle size distribution was similar.]

By combining these two previous works, we came up with an idea of "sieving of aerosol particles with metal screen". If the bounce-off of particles is inevitable, we may enhance the particle bounce-off to achieve "no adhesion of particles". If we could achieve "no adhesion of particles" onto metal screen, we may "sieve" aerosol particles by using uniform-opening metal screen solely by the geometrical sizes of particles.

In this study, four metal screens with uniform openings of 1.2, 1.8, 2.5 and 4.2 μm were employed to “sieve” PSL standard particles at high filtration velocities.

2. METAL SCREEN

Figure 1 shows the SEM images of the metal screen used in this study. As shown in Figs. 1(a) and 1(b), the metal screens have uniform square openings prepared by metal plating and chemical etching of nickel thin film with 0.8 μm in thickness. The metal screens used in our experiments have a 3-μm thick support lattice under the 0.8-μm thick nickel lattice at about every 100 lattices. The uniform lattice composed of the bars with the width of D_f, (a) 0.6 μm and (b) 1.1 μm, is formed as a residue of etching process with photoresist. The average distances between the bars of each lattice, D_o, and their standard deviations are (a) 1.2 ± 0.02 μm and (b) 2.5 ± 0.04 μm, respectively. Table 1 shows the characteristic dimensions of four metal meshes used in this study. These uniform apertures should be effective to trap particles larger than D_o.

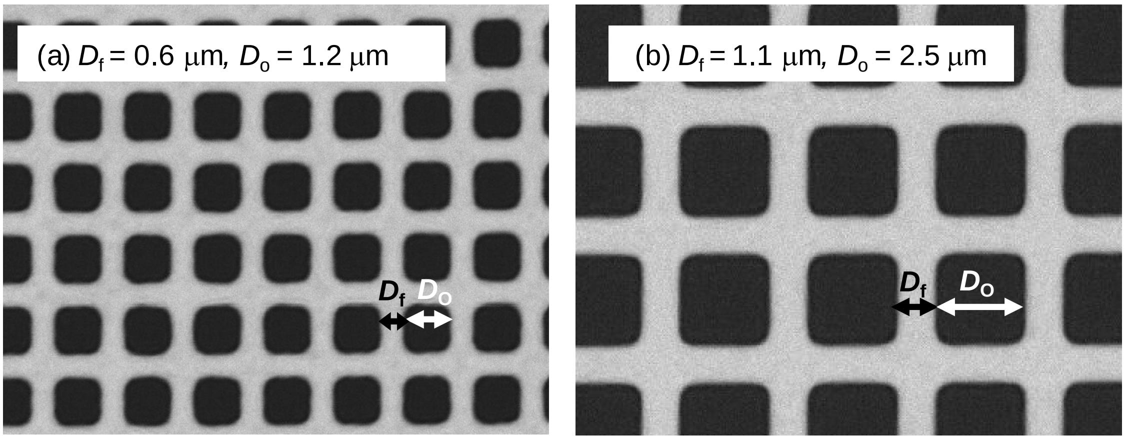

FIG. 1. SEM images of metal screens.

Table 1 Characteristic lengths of metal screens studied

Sample number	D_f [μm]	D_o [μm]	Photo
1	0.6 ± 0.02	1.2 ± 0.02	Fig. 1 (a)
2	0.8 ± 0.02	1.8 ± 0.03	—
3	1.1 ± 0.05	2.5 ± 0.04	Fig. 1 (b)
4	2.3 ± 0.15	4.2 ± 0.15	—

3. EXPERIMENTAL

Figure 2 shows the schematic diagram of experimental setup used for measuring the separation performance of metal screen. Monodispersed PLS standard particles (PSL, JSR Co.) in the size range from 0.31 to 5.12 μm were used as test particles. The PSL suspensions were aerosolized by a nebulizer (KG-02, Rion) and dried by a diffusion dryer. 241-Am neutralizer was used to electrically neutralize the charge of test particles. The test particles were then introduced to the metal screen. The metal screen was installed in a holder made of stainless steel, connected with the inlet/outlet pipes of inner diameter of 6 mm. The diameter of metal screen was 14 mm and the effective filtration area was 6 mm in diameter. In the case of the highest filtration velocity (10.6 m s^{-1}) studied in the present work, the metal screen with smaller effective filtration area (2 mm) was used to achieve high filtration velocity. Particle number concentrations at the inlet and outlet of the filter were measured by an optical particle counter (OPS 3330, TSI Inc.). The collection efficiency of the metal screen, E, was determined by

$$E = 1 - C_{out}/C_{in} \tag{1}$$

where C_{in} and C_{out} are the particle concentrations upstream and downstream of metal screen. The filtration velocity was varied from 0.6 to 10.6 m s^{-1}. The pressure drop of the metal screen was measured using a digital manometer (testo 510, testo AG).

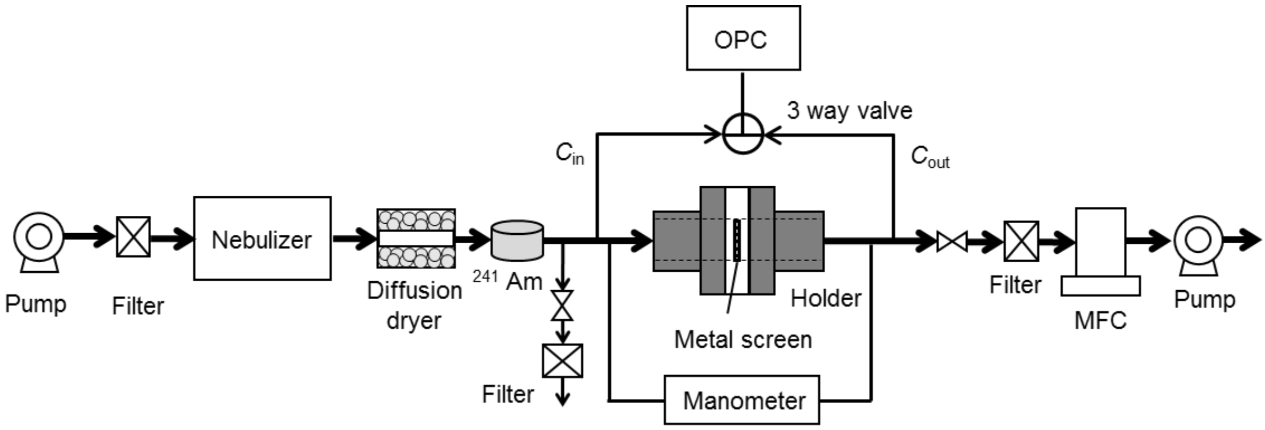

FIG. 2. Experimental setup.

4. RESULTS AND DISCUSSION

Figure 3 shows the collection efficiency of PSL particles through the metal screen with 2.5-μm opening at various filtration velocities. The stepwise solid line in this figure is the ideal separation curve if there would be no particle adhesion on the metal screen. The collection efficiencies of 2.5-μm and 3.3-μm PSL particles are equal to unity at any filtration velocity, indicating that the metal screen can completely trap PSL particles larger than the mesh opening. At the filtration velocity of 0.6 m s^{-1}, as the particle size decreases, the collection efficiency of particles smaller than the mesh opening decreases discontinuously at the particle size equal to the mesh opening and then decrease while having a small plateau at around 1 μm. At the filtration velocities of 3.0 and 10.6 m s^{-1}, the discontinuous drop in the collection efficiency at the particle size of mesh opening is more pronounced and then increases towards the broken line, without the difference in collection efficiency due to filtration velocity. The broken line in Fig. 3 is the collection efficiency curve predicted by considering the geometries of particle and mesh opening when the particles are collected by pure interception. As shown in Fig. 4, since the particles follow the streamline, they can penetrate through the mesh opening when the centers of particles pass through the square area with the side length of $D_o - D_p$. By assuming that the flow velocity is uniform in the mesh opening, the separation efficiency of particles is given by the following equation.

$$E = 1 - \frac{\left(D_o - D_p\right)^2}{D_o^2} \tag{2}$$

The agreement of experimental collection efficiencies of small particles with the predicted curve may suggests that PSL particles smaller than 0.5 μm completely adhere on the metal screen at the filtration velocity of 0.6 m s^{-1} when the particle contacts with the rim of bars without the velocity component in the direction transverse to the main motion. At the filtration velocity of 3.0 m s^{-1}, only 0.3-μm particles can completely adhere the metal screen.

Figure 3 also shows there is no difference in collection efficiency due to the filtration velocity of 3.0 and 10.6 m s^{-1}. This may be attributed to the multiple impingements of a particle on the metal screen. At the first collision of particles on the metal screen, particles with a higher velocity should readily bounce-off because of a larger momentum, but at the second impaction the collision velocity is considerably lower than the first impaction, resulting in the adhesion of particles regardless of the filtration velocity.

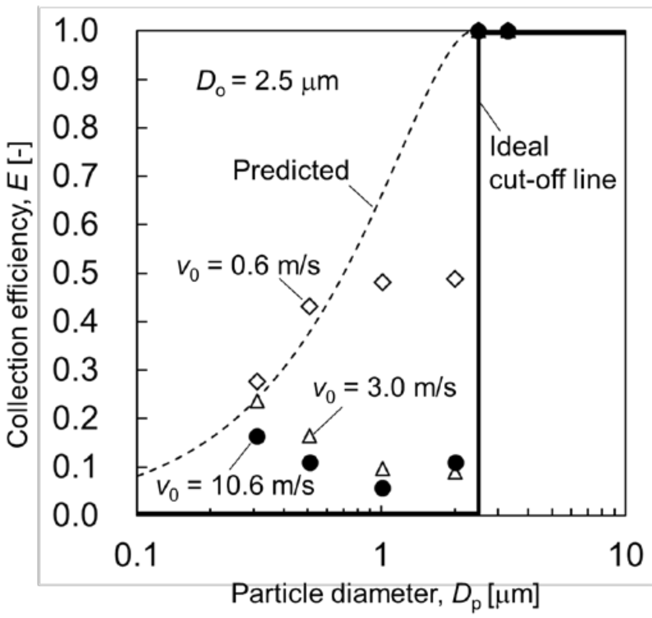

FIG. 3. Collection efficiency of PSL particles by metal screen.

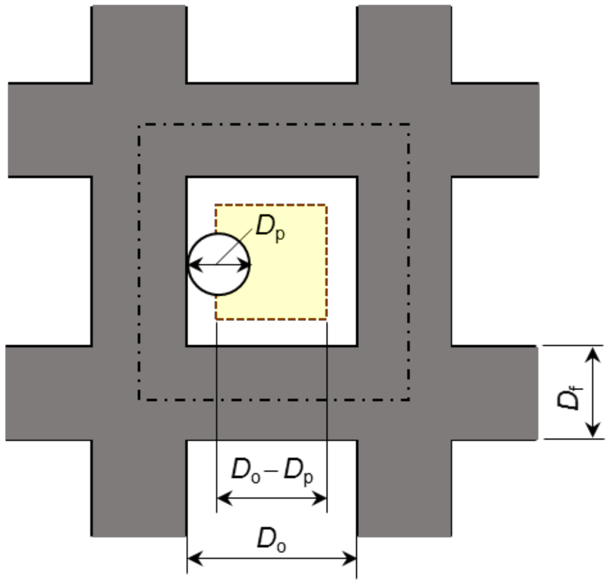

FIG. 4. Illustration of particle trap with diameter smaller than the mesh opening of metal screen.

Figure 5 shows the collection efficiencies of PSL particles through the metal screens with 1.2-, 1.8-, 2.5-, 4.2-μm openings at the filtration velocity of 3.0 m s^{-1}. We can see from these figures that the collection efficiencies of particles larger than the mesh opening are equal to unity, indicating that we can completely trap particles larger than the mesh opening and that the cutoff size can be varied by changing the mesh opening. Although the collection efficiencies of PSL particles smaller than the mesh opening are not equal to zero, i.e., we cannot completely suppress the adhesion of particles onto the metal screen, we can roughly "sieve" aerosol particles. The adhesion of small particles may be further suppressed by reducing the adhesion force between the particles and metal screen probably by a surface modification of metal screen or using other materials for metal screen. Incidentally, at the filtration velocity of 3.0 m s^{-1}, the collection efficiencies of 0.3-μm particles are in good agreement with the ~~broken line of complete adhesion of particles~~ curves predicted by pure interception without bounce-off for different mesh openings of metal screen~~, which supports that 0.3-μm PSL particles completely adhere on the metal screen~~. Based on this result, we may readily infer that the particles smaller than 0.3 μm should adhere onto the metal screen at a filtration velocity lower than 10 m s^{-1} and the collection efficiency could be predicted by the conventional filtration theory which accounts for diffusion and interception without the particle bounce-off.

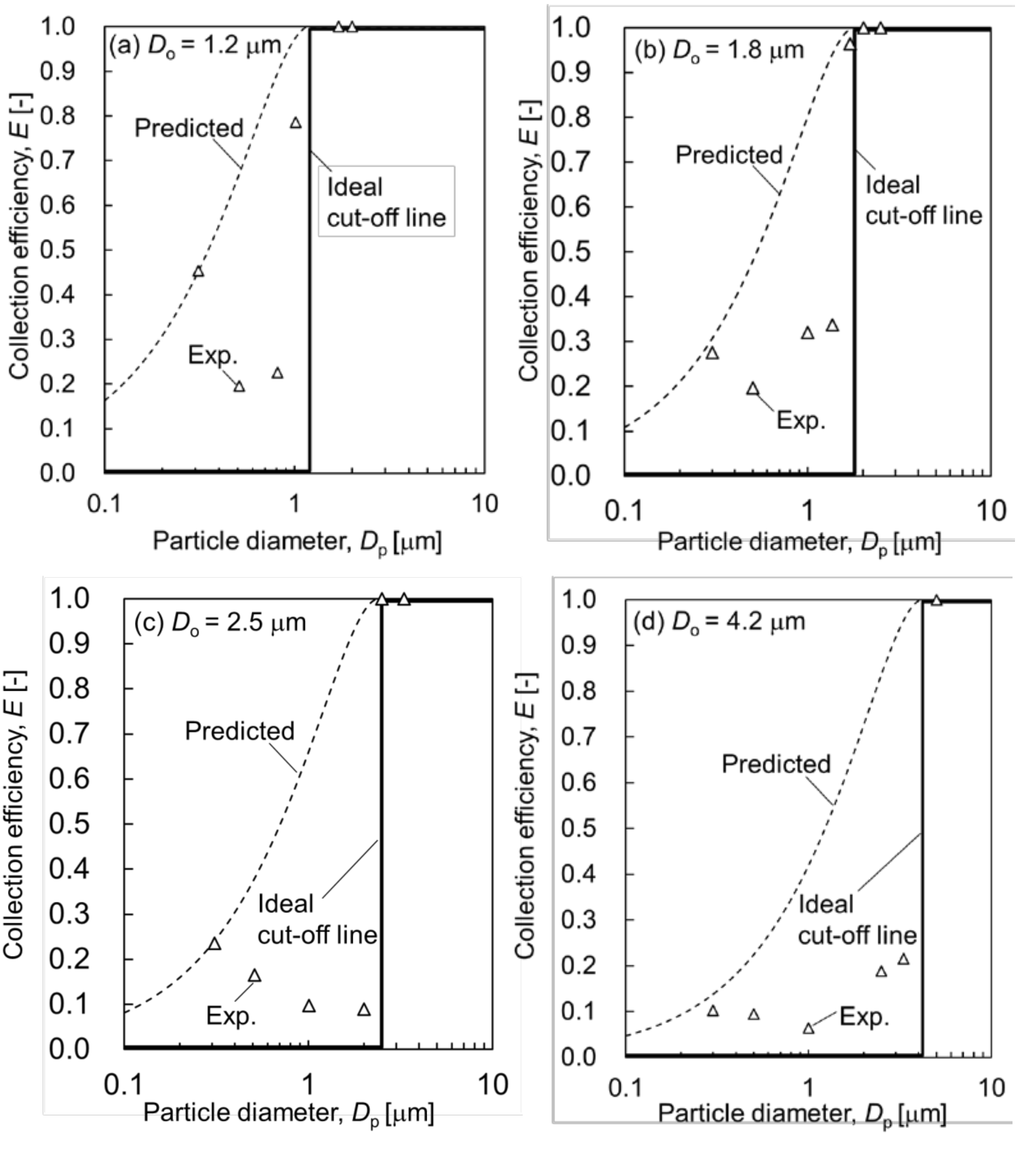

FIG. 5. Collection efficiencies of PSL particles through metal screens with different openings.

Figure 6 shows the dependence of collection efficiency of PSL particles with different sizes ($D_p < D_o$) filtration velocity. The metal screen had the opening of 2.5μm. At the filtration velocity of 0.3 m s^{-1}, the collection efficiency is higher for larger particles, suggesting that the interception is dominant collection mechanisms of particles. As the filtration velocity increases, the difference in collection efficiency due to particle size becomes smaller and eventually at the filtration velocity of 10.6 m s^{-1} there is almost no difference in collection efficiency due to the particle size, except 0.31-μm particles. This implies that the interception is no longer the dominant collection mechanisms at a high filtration velocity but the bounce-off of particles may determine the penetration. For 0.31-μm particles, the particles essentially adhere on the metal screen upon the collision over the filtration velocity studied in the present work so that the interception remains as the main collection mechanisms giving a small dependency on the filtration velocity. Loeffler et al. (1974) reported that the adhesion efficiency of fibrous filter is a function of kinetic energy of particles. However, in the present study, since the collection efficiency at a high filtration velocity does not depends on the particle size, it is obvious that the adhesion efficiency is not a function of kinetic energy of particles, probably because of multiple impaction of particles onto the metal screen.

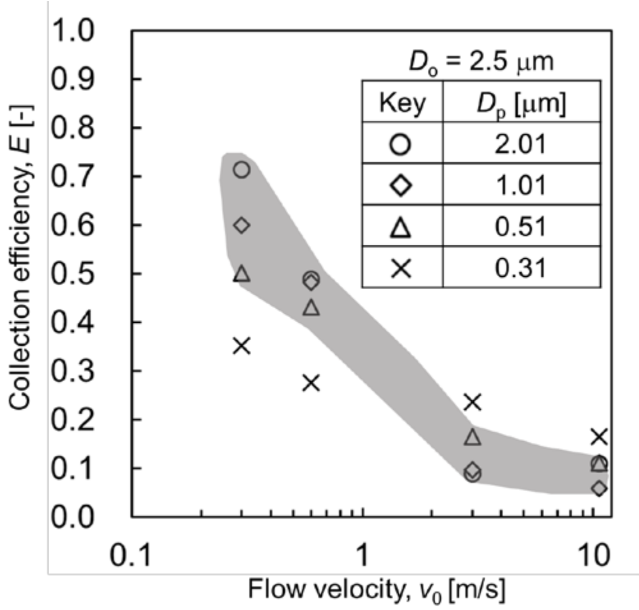

FIG. 6. Influence of filtration velocity on collection efficiency of PSL particles through metal screen with 2.5-μm openings.

Figure 7 shows the influence of filtration velocity on collection efficiency through the metal screen with 1.2-μm openings, which is about a half of that in Fig. 6. The interpretation of this figure is more complicated than that of Fig. 6. For 0.31-μm particles, the particles basically adhere onto the screen so that the collection efficiency has a weak dependence on the filtration velocity because the interception is the dominant collection mechanism, like in Fig. 6. For 0.81- and 0.51-μm particles, there is no significant difference in the collection efficiency due to the particle size over the whole filtration velocity, indicating that the bounce-off of particles may determine the penetration, which is the same as in Fig. 6. However, for 1.0-μm particles, since the collection efficiency of 1.0-μm particles is much higher than that of 0.81- and 0.51-μm particles, the interception plays important role in the particle collection while the bounce-off of particles is much severer than that of 0.81- and 0.51-μm particles. The ratio of particle size to mesh opening is 0.80 for 2.01-μm particles in Fig. 6 and that for 1.01-μm particles is 0.84 for 1.01-μm particles in Fig. 7, indicating that the interception effect is about the same for 2.01-μm particles in Fig. 6 and 1.01-μm particles in Fig. 7. However, the ratio of pore length (equal to the screen thickness $T = 0.8$ μm) to the particle size is 0.40 ($T/D_p = 0.8/2.01$) for 2.01-μm particles in Fig. 6 and it is 0.79 ($T/D_p = 0.8/1.01$) for 1.01-μm particles in Fig. 7, since the thickness of metal screen is the same for both 2.5- and 1.2-μm metal screens. Therefore, 1.01-μm particles in Fig. 7 might have a chance higher than 2.01-μm particles in Fig. 6 to hit the pore wall, which may result in the adhesion of particles upon the subsequent impaction on the pore wall.

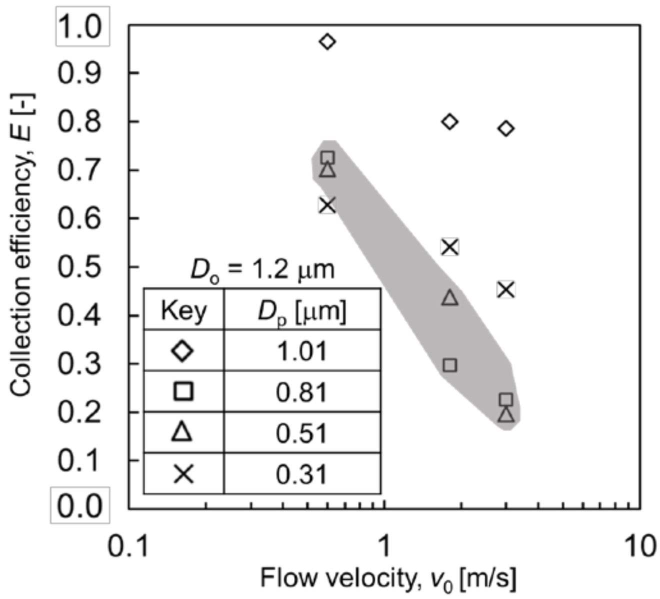

FIG. 7. Influence of filtration velocity on collection efficiency of PSL particles through metal screen with 1.2-μm openings.

Figure 8 shows the SEM images of captured particles on metal screens with different opening when the ratio of particle size to mesh opening is nearly equal to 0.8. As seen in these figures, most of particles are collected in pores of metal screen (Fig. 8(a)), while all the particles are trapped on the frontal surface of metal screen (Fig. 8(b)). In case of Fig. 8(a), PSL particles may collide repeatedly on the walls of pores because the ratio of pore length to the particle diameter is as high as 0.8. Therefore, the particles have a higher chance to stick on the sidewalls of pores after losing kinetic energy by the previous impaction. On the other hand, in case of Fig. 8(b), the ratio of pore length to the particle diameter is as small as 0.4. Therefore, the particles tend to penetrate metal screen without the collision on the sidewall of pores after the first collision.

What follows from Figs. 6 and 7 is that the collection efficiency of metal screen is determined by the combination of interception and bounce-off of particles accounting for the multiple impactions.

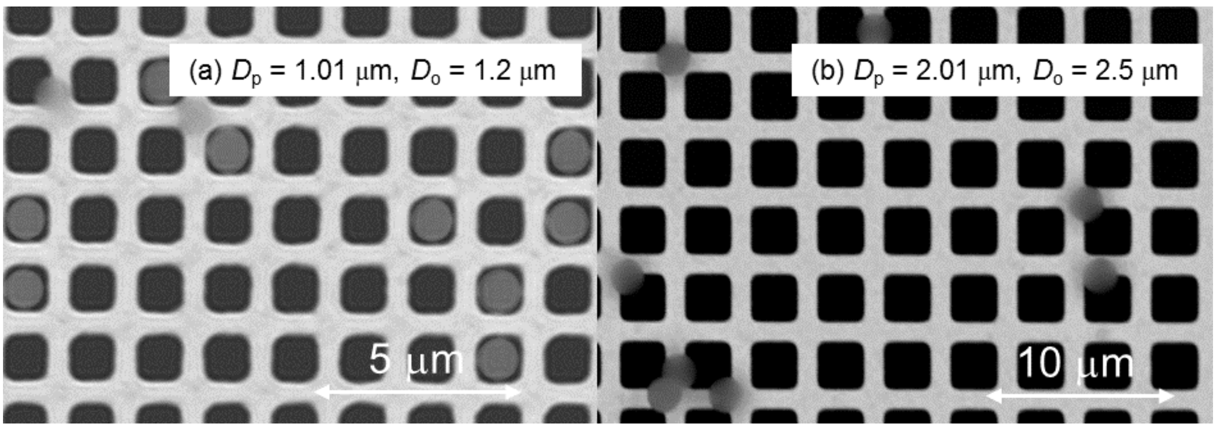

FIG. 8. SEM images of captured particles on metal screens with different opening when the ratio of particle size to mesh opening is nearly equal to 0.8.

Figure 9 shows the initial pressure drops of metal screens with various openings as a function of flow velocity. The pressure drops linearly increases with the filtration velocity, indicating that the flow is in viscous flow regime.

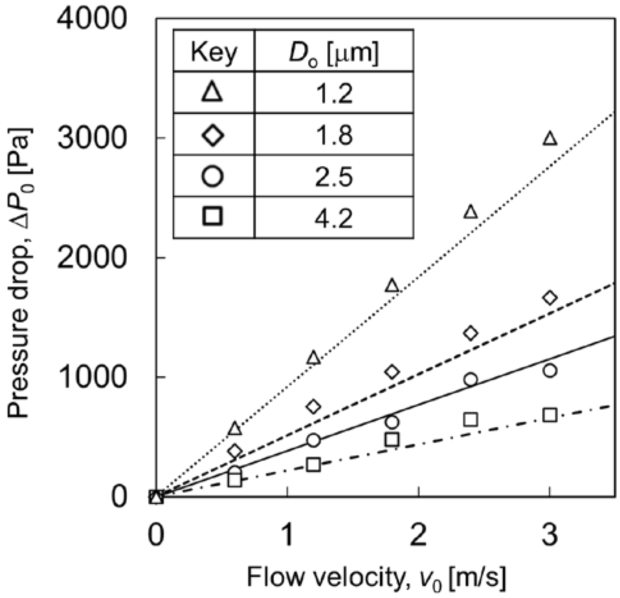

FIG. 9. Initial pressure drops of various metal screens as a function of filtration velocity.

Figure 10 shows the evolution of pressure drop with the accumulation of particles when 2.5-μm PSL particles are collected by the metal screen of 2.5-μm opening. The abscissa of this figure is the clogging ratio which is equal to the ratio of the number of particles collected per unit metal screen area, N_p, to the number of openings in unit metal screen area, N_o. [The clogging ratio was determined as the ratio of number of particles fed to the screen over the number of metal screen openings.] The data shown in Fig. 10 are those when the particles and the pores are about the same in size. The solid and broken lines are the predicted curves of pressure drop using Fig. 9, where the clogging of openings of metal screen simply brings an increase in filtration velocity. Although one particle does not always clog one opening of the metal screen as shown in the inset picture of Fig. 10, the predicted curves at two different filtration velocities are in good agreement with the experimental data. Since the pressure drop increase is a function of number of collected particles on the metal screen, we may obtain the particle number concentration by measuring the pressure drop increase.

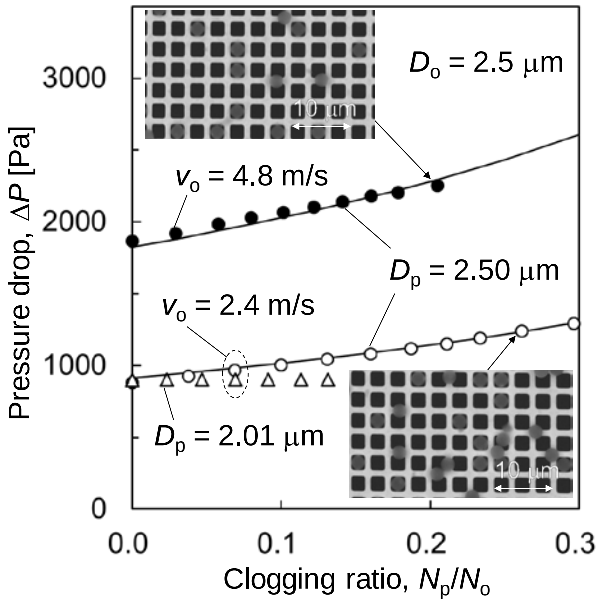

FIG. 10. Evolution of pressure drop by clogging the metal screen.

Figure 11 shows the change in collection efficiency with the particle load. Even when the metal screen is clogged up to 20% of the openings, there is a very small change in the collection efficiency. This is probably because the bounce-off of particles becomes more significant due to an increase in approaching velocity of particles against an increase in collection efficiency due to already-captured particles.

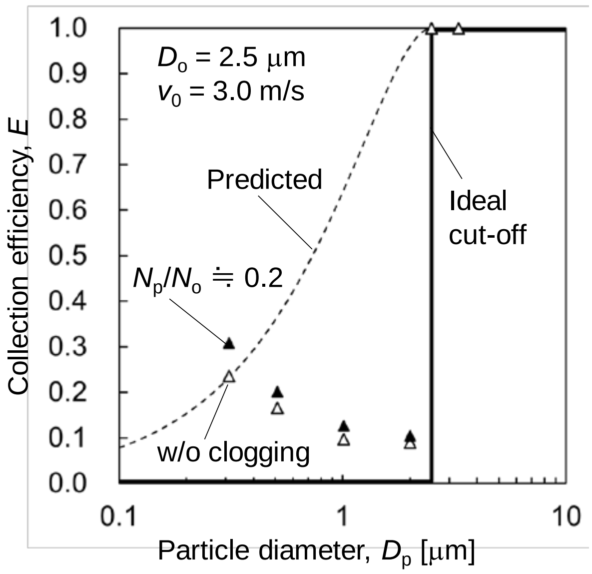

FIG. 11. Effect of clogging on collection efficiency.

5. CONCLUSION

Metal screens with uniform micrometer-sized opening were employed to sieve aerosol particles by suppressing the adhesion of particles smaller than the openings. The collection efficiencies of monodispersed PSL particles were experimentally determined using the metal screens with 1.2-, 1.8-, 2.5- and 4.2-μm openings at various filtration velocities. The particles smaller than the mesh opening adhered on the metal screen at a low filtration velocity, but the bounce-off of particles on the mesh surface suppressed the adhesion at a high velocity. As a result, we found that the adhesion of PSL particles larger than 0.3 μm mostly suppressed at a filtration velocity higher than 10 m s^{-1} and therefore we can sieve aerosol particles according to the opening size of metal screens. However, for 1.0-μm particles through the metal screens with 1.2-μm opening, since the collection efficiency of 1.0-μm particles is much higher than that of 0.81- and 0.51-μm particles, the interception plays important role in the particle collection while the bounce-off of particles is much severer than that of 0.81- and 0.51-μm particles.

We also found that the particle number concentration could be determined by measuring the increase in pressure drop since the clogging of metal screen openings takes place by the individual particles.

This work was confined with the experimental data of PSL particles so the conclusions are limited only for spherical hard particles. In case of irregular particles such as atmospheric aerosol, particles easily adhere the metal screen. The influences of particle’s shape and physical property as well as the screen’s physical property onto the bounce-off phenomena are of our future work. Surface modification of metal screen may reduce the sticking probability.

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