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# EFFECT OF DEPOSITED PARTICLES AND PARTICLE CHARGE ON THE PENETRATION OF SMALL SAMPLING CYCLONES

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**Abstract**—Effects of particle mass deposited in the cyclone and particle electrostatic charge on the particle penetration of the commonly used 10 mm nylon cyclone have been experimentally investigated in this study. The solid particle penetration of the cyclone has been found to decrease with an increase in particle mass deposited in the cyclone. This effect is most significant for particles near the cutoff aerodynamic diameter and when the deposited particle mass is low. The penetration of the cyclone has also been found to be influenced by particle electrostatic charge. This effect is also significant for particles near the cutoff aerodynamic diameter and when the number of elementary units of charge is greater than several thousands. To overcome these problems, a new cyclone made of conductive aluminum and with inner diameter nearly twice that of the 10 mm nylon cyclone has been designed and tested. Experimental results indicate that effects of both deposited particle mass as well as electrostatic charge on the penetration are reduced substantially in this cyclone. © 1999 Elsevier Science Ltd. All rights reserved

## INTRODUCTION

The definitions of respirable dust by the American Conference of Industrial Hygienist (ACGIH) and British Medical Research Council (BMRC) are the two most widely used criteria for respirable dust samplers. The cutoff aerodynamic diameters ($d_{ae}$) of ACGIH and BMRC criteria, 3.5 and 5.0 $\mu$m, respectively, are quite different. To avoid confusion between different criteria and facilitate future international exchange of sampling and risk assessment results, ACGIH (1993) has recently adopted a particle size-selective sampling criteria originally proposed by Soderholm (1989, 1991). The same criteria has also been adopted by ISO and CEN. The most significant change in the new ACGIH criteria for respirable dust sampler is the increase in the cutoff aerodynamic diameter from the original 3.5 to 4.0 $\mu$m.

The 10 mm nylon cyclone is widely used as a respirable dust sampler in the United States. In the literature, the particle penetration data of the 10 mm nylon cyclone have been different for different laboratories (Ettinger *et al.*, 1970; Seltzer *et al.*, 1971; Lippmann and Kydonieus, 1970; Caplan *et al.*, 1977a; Bartley and Breuer, 1982; Tsai and Shih, 1995). The flow rate of 1.7 L min$^{-1}$ is most commonly used to operate the cyclone. To match the new ACGIH criteria, an acceptable flow rate to match the new ACGIH criteria for the 10 mm nylon cyclone was recently determined to be 1.3 L min$^{-1}$ (Tsai and Shih, 1995) while Bartley *et al.* (1994) have suggested that the best operating flow rate be 1.7 L min$^{-1}$.

Several factors that influence the particle penetration contribute to the difference in penetration data obtained by different researchers. In the literature, effects of pump pulsation (Caplan *et al.*, 1977a; Blachman and Lippmann, 1974; Bartley *et al.*, 1984; Berry, 1991), sampler orientation (Blachman and Lippmann, 1974; Caplan *et al.*, 1977b; Marple and Rubow, 1983; Cecala *et al.*, 1983), particle material (Tsai and Shih, 1995), particle mass loading (Blachmann and Lippmann, 1974), and particle electrostatic charge (Blachman and Lippmann, 1974; Lippman and Kydonieus, 1970; Pickett and Sansone, 1973; Caplan *et al.*, 1977b; Vincent, 1989) on the penetration of the 10 mm cyclone have been discussed.

The effect of deposited particle mass in the cyclone has been investigated by Blachmann and Lippmann (1974) in detail. While sampling highly concentrated dust, the dust

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accumulated on the cyclone wall opposite to the inlet was claimed to gradually reduce the effective diameter of the cyclone. As a result, the cyclone penetration was decreased due to an increase in the velocity at the point of particle deposit. As the amount of particle deposit on the cyclone wall increases with sampling time, it eventually becomes heavy enough to detach and the penetration increases again since the effective diameter at the point of particle deposit increases.

However, so far there have been no data available to asses the effect of different amounts of deposited particle mass on the cyclone penetration. Tsai and Shih (1995) have found that the penetration of 10 mm nylon cyclone to be lower for liquid particles than for solid particles since a solid particle bounces from the cyclone wall opposite to the inlet. It was suspected that the effect of deposited solid particle mass on the penetration of the cyclone may be as important as that of the impactor and hence further investigation of this effect was then recommended.

Notably, the effect of deposited particles on the penetration of an impactor has been studied by Tsai and Cheng (1995). The initial solid particle penetration has been found to be high in an impactor with uncoated substrate because solid particles bounce easily from the substrate. As the amount of deposited particles gradually increases, more incident particles will impact on previously deposited particles. Part of the incident kinetic energy is spent moving deposited particles away from their initial positions. This increases the likelihood of particle collection upon impaction. Also, the particle rebound velocity will more likely have a downward component when particle-to-particle collision occurs, which also tend to increase the collection efficiency. This explains why particle penetration decreases with an increasing particle mass loading. However, as deposited particles become thick enough under the nozzle, the incident particles always impact on the same particle bed, then the penetration will remain nearly constant unless the particle mound becomes too high to get re-entrained (Tsai and Cheng, 1995). Whether or not a similar relationship between the particle penetration and the deposited particle mass exists in small sampling cyclones is worth investigating.

Particles in workplaces may carry electrostatic charge and influence the penetration of sampling cyclones. Johnston *et al.* (1985) has measured particle charge in many workplaces in The United Kingom extensively. In their study, median particle charge, $q_{\mathrm{m}}$, was approximated as a function of particle diameter ($d$) as

$$\left|\frac{q_m}{e}\right| = Kd^n, \tag{1}$$

where $e$ is the charge on an electron, $K$ and $n$ are constants. $K$ can also be viewed as the median number of elementary units of charge carried by a 1 $\mu$m diameter particle. Charge levels were found to vary considerably between workplaces. For compact airborne dusts, $K$ varies from 2.1 to 49.8 while $n$ varies from 0.8 to 1.84. Typically, the median number of elementary charge is less than several hundreds as found by Johnston *et al.* (1985).

Lippmann and Kydonieus (1970) have found that the penetration of the 10 mm nylon cyclone is lower for particles carrying 440 elementary units of charge than that for the charge-neutralized particles, especially at conditions where the penetration is high for charge-neutralized particles. Blachman and Lippmann (1974) have also drawn similar conclusions. However, Caplan *et al.* (1977b) found no significant effect of particle charge on the particle penetration, for the particles carrying several hundred to two thousand elementary units of charge. In general, the problem of electrostatic effects in relation to sampler performance is only significant for samplers made of insulating material (Vincent, 1989). It is therefore believed to be still pertinent to determine at what charge level and particle size the particle charge affects the penetration of different sampling cyclones.

The experimental system used to determine the effects of particle mass loading and particle charge on the penetration is first described in the following. Both the 10 mm nylon and the new cyclone, which was made of conductive aluminum with twice the inner diameter as that of the 10 mm nylon cyclone, have been tested. The experimental results obtained by using the new cyclone are compared with those for the 10 mm nylon cyclone.

## EXPERIMENTAL

The experimental set-up is shown in Fig. 1. Monodisperse solid ammonium fluorescein particles (density: $1.35\,\mathrm{g\,cm^{-3}}$) with the aerodynamic diameter ranging from 1 to 10 $\mu$m were generated by a TSI Model 3450 vibrating orifice monodisperse aerosol generator (VOMAG), based on the techniques of Vanderpool and Rubow (1988). The aerosols were neutralized using a TSI Model 3054 Kr-85 charge neutralizer and dried in a drying column before being introduced into a stainless-steel test chamber. The diameter of the test chamber was 15 cm and the height was 30 cm. Flow straighteners were installed both at the top and bottom of the chamber. In the test chamber, the total air flow rate, which comprised $1\,\mathrm{L\,min^{-1}}$ dispersed air and $10\,\mathrm{L\,min^{-1}}$ dilution air from VOMAG, was $11\,\mathrm{L\,min^{-1}}$ and the average air velocity was about $1\,\mathrm{cm\,s^{-1}}$. The flow rates were controlled by mass flow controllers.

A TSI Model 3310A aerodynamic particle sizer (APS) was used to measure the aerosol number concentrations at the inlet and outlet of the cyclone, to determine the particle collection efficiency. The aerosol number concentration ($N_1$) in the chamber was sampled at the flow rate of $1.7\,\mathrm{L\,min^{-1}}$ by a vertical sharp-edged thin brass tube (ID: 1.0 cm), the opening of which was kept at the same height as that of the cyclone inlet. Additional $3.3\,\mathrm{L\,min^{-1}}$ of clean air, controlled by a mass flow controller was added to the tube to make the total flow rate equal to $5.0\,\mathrm{L\,min^{-1}}$, which was the sampling flow rate in the APS. $N_1$ was measured by APS when the valves $V_1$ and $V_4$ were closed and $V_2$ and $V_3$ were open, and was taken as the inlet concentration at the cyclone. The experiment commenced only when the variation in $N_1$ was less than 5%.

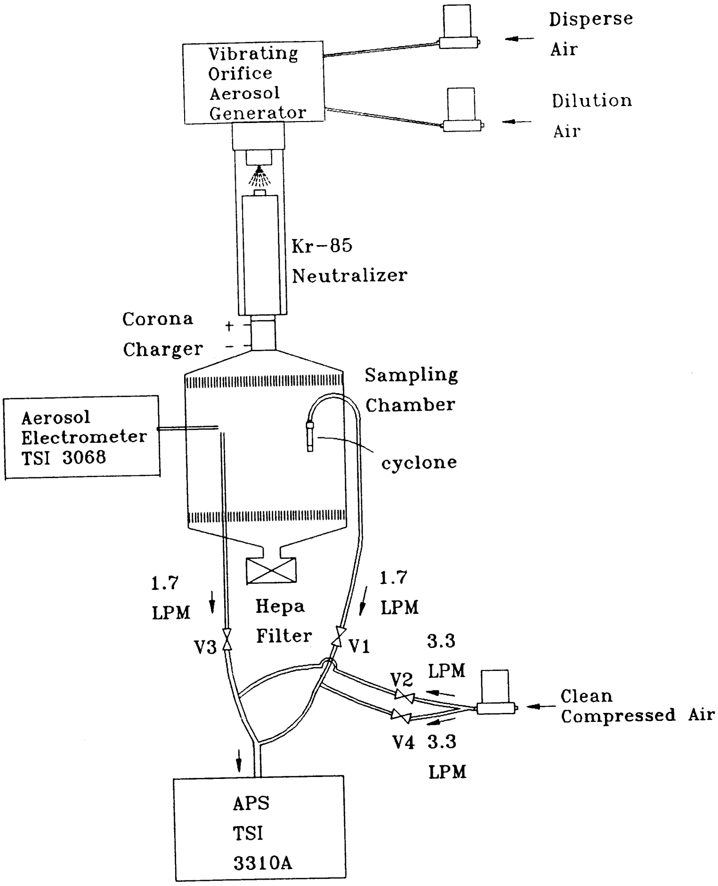

Fig. 1. Schematic diagram of the experimental set-up.

The outlet of the cyclone was connected to a brass tube (ID: 1.0 cm) with a large bend radius from the top to avoid particle transport losses. The outlet aerosol number concentration was measured by the APS at any time interval $i$ (denoted as $N_{2i}$) by keeping the valves $V_1$ and $V_4$ open and $V_2$ and $V_3$ closed. The duration of each time interval was kept constant at 20 s. The flow rate through the cyclone was also kept 1.7 $\mathrm{L\,min^{-1}}$, while additional 3.3 $\mathrm{L\,min^{-1}}$ of clean air was added to make the flow rate equal to 5.0 $\mathrm{L\,min^{-1}}$.

In order to check the occurrence of particle losses in the outlet transport tube of the cyclone, concentrations $N_1$ and $N_2$ were compared when the cyclone was disconnected from its outlet tube. The corresponding results showed that the ratio $N_1/N_2$ varied from 0.98 to 1.03 as $d_{ae}$ varied from 1.31 to 9.4 $\mu$m, i.e. the sampling efficiencies were nearly the same for both inlet and outlet transport tubes of the cyclone. The penetration of the cyclone, $P(\%)$, at any sampling time was calculated as

$$P(\%) = \frac{N_{2i}}{N_1} \times 100\%. \tag{2}$$

After $n$ time intervals, the particle mass deposited in the cyclone, $m$, was calculated as

$$m = \sum_{i=1}^{n} \frac{\pi}{6} \rho_p d_p^3 (N_1 - N_{2i}) Q t_i, \tag{3}$$

where $\rho_p$ is the particle density; $d_p$ is the particle diameter; $Q$ is the flow rate in the cyclone; and $t_i$ is the duration of each sampling interval $i$. In equation (3), the overall sampling efficiency of solid particles by the APS is assumed to be 100%. Although the overall sampling efficiency is shown to be low for large liquid particles (Kinney and Pui, 1995), it is considerably higher for solid particles (Blackford *et al.*, 1988). However, there have been no accurate data for overall sampling efficiency of solid particles in the literature. Once the data become available, the particle mass loading can be corrected.

When the effect of particle charge was to be determined, a corona charger, as shown in Fig. 2, was installed after the dilution and charge-neutralization column. The diameter and

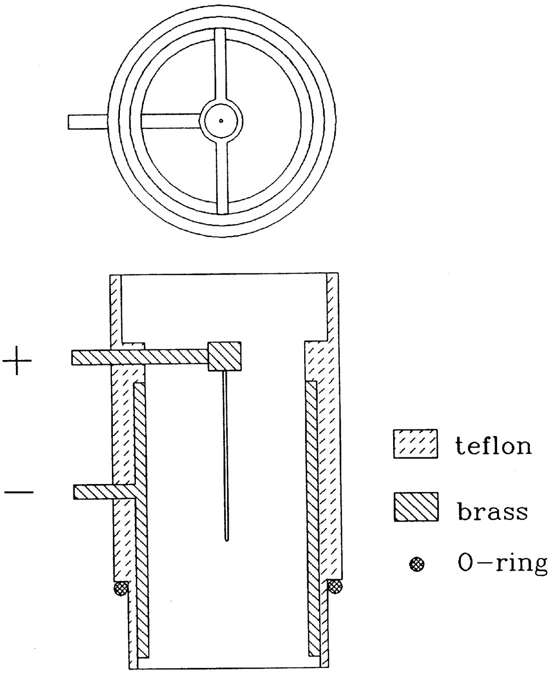

Fig. 2. Schematic diagram of the corona charger. The diameter and length of the central electrode is 0.1 and 30 mm, respectively.

length of the electrode was 0.1 and 30 mm, respectively, and the critical voltage for corona discharge was calculated to be 1.27 kV (Taylor and Secker, 1994). The amount of particle charge was controlled within the range of several tens to thousands of elementary units of charge by varying the voltage from 1.5 to 2.5 kV. The average particle charge, $n_p$, in terms of the number of elementary units of charge, was calculated as

$$n_p = \frac{I}{Q_a N_1 e}, \tag{4}$$

where $I$ is the electric current measured by an electrometer (TSI Model 3068), $Q_a$ is the air flow rate through the electrometer, $N_1$ is the aerosol number concentration.

The original 10 mm nylon cyclone and the new cyclone, shown in Fig. 3, were tested in the above set-up. The diameter of the original 10 mm nylon cyclone was 10 mm and the inlet opening was close to a square cross-section with a side length of 2.2 mm. The new cyclone was 18 mm in diameter and was made of conductive aluminum. It was expected that the much larger inner diameter of the new cyclone would be able to reduce the particle mass loading effect, since the collected particles can be distributed over a wider inner surface compared to the 10 mm nylon cyclone. While the dimension of the inlet of the new cyclone was kept the same as that of the 10 mm nylon cyclone, the other dimensions were designed according to the Stairmand's high efficiency cyclone type (Cooper and Alley, 1990). Both the cyclones were operated at 1.7 L min$^{-1}$.

The typical sampling time for obtaining the relationship between particle penetration and deposited particle mass, lasted for 1–2 h for each test. The inlet mass concentration ranged from 0.3 to 4.2 mg m$^{-3}$ and the deposited particle mass ranged from 0.007 to 3.0 mg, which increased with increasing particle size as well as sampling time. For comparison, the deposited particle mass was 0.8 mg in the cyclone after 8 h of sampling at 1.7 L min$^{-1}$ at

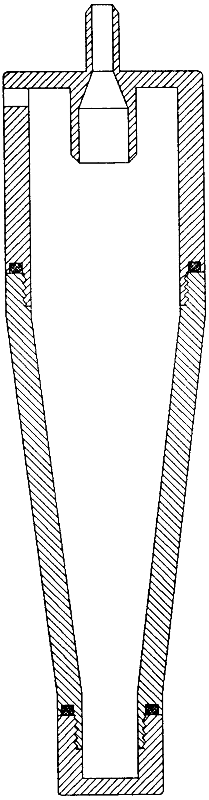

Fig. 3. Schematic diagram of the new cyclone. The inner diameter is 18 mm and the total length of the cyclone is 86 mm.

a workplace where the total dust concentration was 2.0 mg m$^{-3}$ and 50% of the mass concentration was respirable. That is, the range of deposited particle mass in this study covers that typically found in the workplace.

## RESULTS AND DISCUSSIONS

### *Penetration for monodispersed particles*

Experimental data on the penetration of monodispersed particles of a given aerodynamic diameter as a function of deposited particle mass, containing particles of the same aerodynamic diameter, were first obtained. Observation of the particle deposition region inside the 10 mm and new cyclones indicated that most of the particles larger than the cutoff aerodynamic diameter were collected near the inner wall opposite to the inlet opening. Some particles were rebound and were recollected at other locations on the inner surface. When the deposited particle mass became excessively high, the particles were found to slough off from the particle mound in the form of aggregates and dropped to the bottom of the cyclone.

The effect of deposited particle mass on penetration is shown in Fig. 4a and b for the 10 mm nylon and new cyclones, respectively. It can be seen that for the 10 mm nylon cyclone, the effect of deposited particle mass on particle penetration is significant, especially for particles near the cutoff aerodynamic diameter, 4.0 $\mu$m. This effect is less pronounced in the new cyclone. For example, the penetration for 3.06, 3.53, 4.04 and 4.7 $\mu$m particles decreases from 97.1 to 71.1%, 75.9 to 31.1%, 62.3 to 25.2% and 31.4 to 8.7% as the deposited particle mass increases from 0 to 0.028 mg, 0.3 mg, 0.27 mg and 0.40 mg,

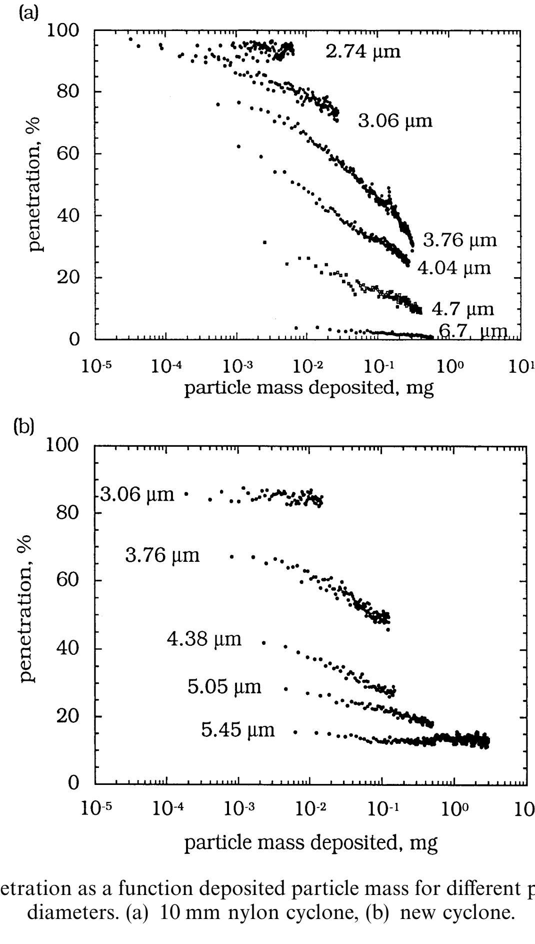

Fig. 4. Particle penetration as a function deposited particle mass for different particle aerodynamic diameters. (a) 10 mm nylon cyclone, (b) new cyclone.

respectively. The decrease in penetration with increasing deposited mass is due to the fact that fewer particles rebound or rebound with less kinetic energy from the particle mound as these particles impact on previously collected particles, rather than on a clean surface (Tsai and Cheng, 1995). Such a decrease is more significant for particles near the cutoff aerodynamic diameter as these particles fly closer to the inner wall than smaller particles.

A drastic decrease in the penetration was found to occur when deposited particle mass is low. As deposited particle mass increases such that several layers of particles are deposited on the inner surface, the penetration was still found to decrease but much less drastically.

The particles near or smaller than the cutoff aerodynamic diameter were found to deposit on a much wider inner area and penetration remained high. For example, the experimental data show that the penetration remains at about 95 to 90% as deposited particle mass increases from 0 to 0.007 mg for 2.74 $\mu$m particles. For particles much larger than the cutoff aerodynamic diameter, e.g. 6.7 $\mu$m, the penetration of the 10 mm nylon cyclone remained lower than 5% and was nearly independent of mass loading. This is as expected, since the larger particles, no matter whether they rebound upon impaction or not, often experience higher centrifugal force and thus result in a higher collection efficiency.

For the new cyclone, Fig. 4b shows that the effect of deposited particle mass on penetration still exists for particles near the cutoff aerodynamic diameter but is much less significant than that for the 10 mm nylon cyclone. For example, the penetration for 3.76, 4.38 and 5.05 $\mu$m particles decreases from 67.1 to 48.0%, 41.9 to 28.0% and 28.4 to 18.4% as the deposited particle mass increases from 0 to 0.12, 0.15, 0.27 and 0.50 mg, respectively. Observation of the particle-deposited area inside the new cyclone showed that the particles larger than the cutoff aerodynamic diameter were also collected near the opposite inner wall of the inlet but distributed over a larger area compared to the 10 mm nylon cyclone. As a result, the effect of deposited particle mass on the penetration is greatly reduced over the range of deposited mass tested.

For particles much smaller and larger than the cutoff aerodynamic diameter, the penetration remains nearly constant, the same as that of the10 mm nylon cyclone. For example, for 5.45 $\mu$m particles, the penetration remained nearly constant at 15% when the deposited particle mass increased from 0 to 3.0 mg during the 8 h experiment.

### *Penetration curve and cutoff aerodynamic diameter*

In order to investigate the effect of different amounts of deposited particle mass on the cutoff aerodynamic diameter and the penetration curve, the cyclones were loaded to 0.0 (cyclone with a clean inner surface), 0.3, 0.6 and 3.0 mg, respectively, with 6.7 $\mu$m particles. The corresponding results are shown in Fig. 5a and b, wherein each measurement ran for a short period of time to avoid a significant increase in the loaded particle mass, and repeated three times for a better accuracy.

As can be seen in Fig. 5a and b, the deposited particle mass on the 10 mm nylon cyclone influences the cutoff aerodynamic diameter as well as the penetration curves to a much greater extent than the new cyclone. When the deposited mass is 0.0, 0.3, 0.6 and 3.0 mg, the corresponding cutoff aerodynamic diameter is 4.31, 3.72, 3.55 and 3.47 $\mu$m, respectively, for the 10 mm nylon cyclone, while it is 4.29, 4.10, 3.96 and 3.91 $\mu$m for the new cyclone. The cutoff aerodynamic diameter of both the cyclones decreased with an increase in deposited particle mass, the decrease being more significant for the 10 mm nylon cyclone than for the new cyclone. The deviation of the cutoff aerodynamic diameter from the designated value in the new ACGIH criteria, i.e. 4.0 $\mu$m, is also much larger for the 10 mm nylon cyclone.

An obvious shift of the entire penetration curve to the left of the graph occurs with increasing deposited particle mass, as the mass increases from 0 to 0.3 mg for the 10 nylon cyclone. A further increase in the deposited mass from 0.3 mg only decreases the penetration for the particles smaller than cutoff aerodynamic diameter. For the 10 mm nylon cyclone, Fig. 5a shows that the penetration curve at any deposited mass does not match very well with the new ACGIH curve (ACGIH, 1993). On the other hand, Fig. 5b indicates that all the penetration curves match much better with the new ACGIH curve for the new cyclone.

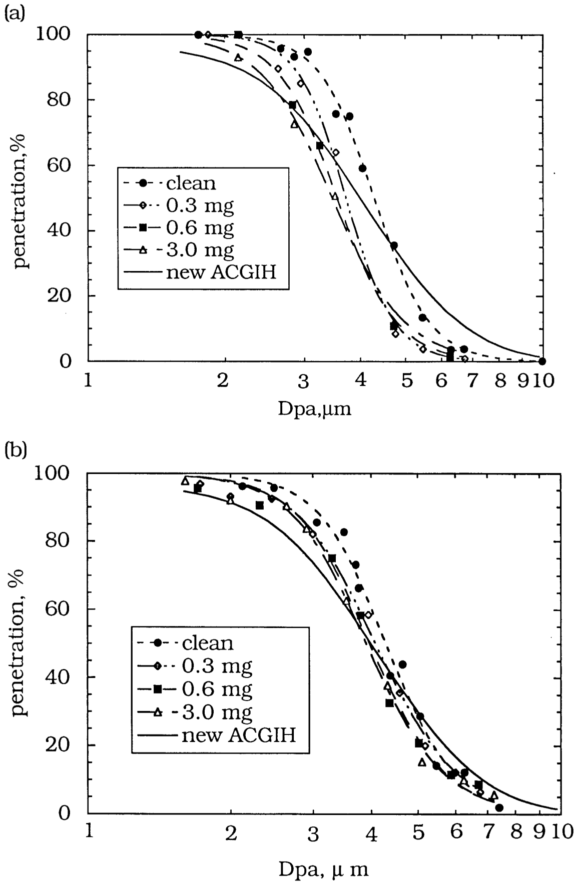

Fig. 5. Particle penetration curve versus particle aerodynamic diameter for different amounts of deposited particle mass containing monodispersed particles of 6.7 $\mu$m in aerodynamic diameter. (a) 10 mm nylon cyclone, (b) new cyclone.

At a fixed flow rate of 1.7 L min$^{-1}$, quantitative evaluation of the sampling accuracy of both the cyclones, based on the new ACGIH criteria, is determined by $\phi$, which can be calculated as (Bartley and Breuer, 1982)

$$\phi = \int_0^\infty [(\eta - \eta_A) f_3(d_{ae})]^2 \, \mathrm{d}d_{ae}, \tag{5}$$

where $\eta$ and $\eta_A$ are the penetration of the cyclone and ACGIH criteria, respectively; and $f_3(d_{ae})$ is the normalized mass distribution function of the aerosol particles. A smaller $\phi$ value represents a better match with the new ACGIH criteria. Here a normalized log-normal distribution function is assumed for $f_3(d_{ae})$ as

$$f_3(d_{ae}) = \frac{1}{d_{ae}\sqrt{2\pi}\ln\sigma_g} \exp[-(\ln d_{ae} - \ln \mathrm{MMAD})^2 / 2\ln^2\sigma_g)], \tag{6}$$

where MMAD is the mass median aerodynamic diameter, and $\sigma_g$ is the geometric standard deviation, GSD.

Figure 6a and b compares the $\phi$ values, assuming different MMADs and GSDs, for the new and 10 mm nylon cyclones for deposited mass of 0.0 and 3.0 mg, respectively. These figures show that the effect of the particle mass loading is to reduce $\phi$ values or increase the sampling accuracy of the cyclones. When the deposited particle mass is 3.0 mg, and the

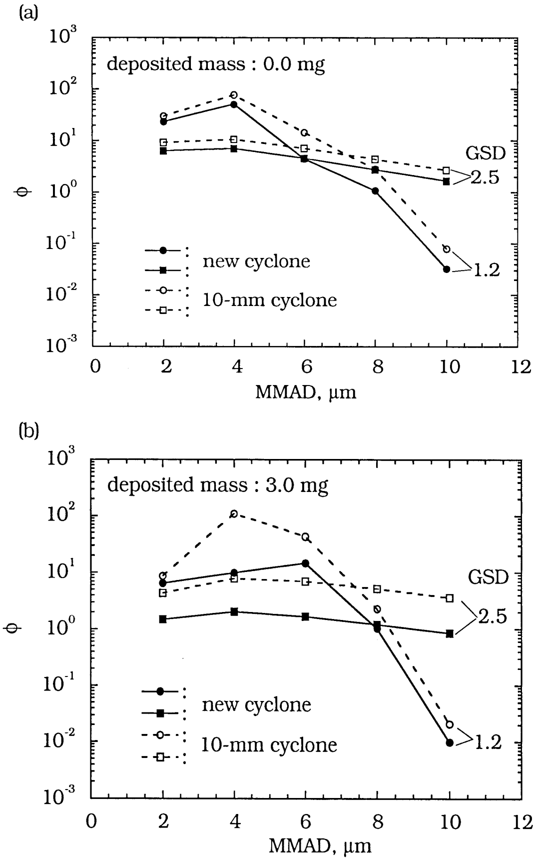

Fig. 6. Comparison of $\phi$ values. (a) 10 mm nylon cyclone, (b) new cyclone.

particles are smaller than 7–8 $\mu$m in aerodynamic diameter, sampling accuracy for nearly monodispersed particles (GSD = 1.2) is worse than the more polydispersed particles (GSD = 2.5) by both the cyclones. In all cases, nevertheless, the new cyclone outperforms the 10 mm nylon cyclone.

At the same deposited particle mass, the effect of deposited mass on penetration may be different when the diameter of the initially loaded particles is different. Figure 7 compares the penetration curves for two initially loaded particle diameters: *viz.* 3.76 and 6.7 $\mu$m, respectively, at the same deposited mass, 0.06 mg, for the 10 mm nylon cyclone. As the initially loaded particles are smaller, the decrease in particle penetration for the particles smaller than cutoff aerodynamic diameter is seen to be more significant than that for larger loaded particles. Such an increase is mainly due to a wider deposition area for the smaller loaded particles, which enables more efficient capturing of the incoming or rebounding particles.

### *Effect of particle electrostatic charge*

All the data presented so far were obtained by using charge neutralized test particles. Figure 8 compares the penetration of the new and 10 mm nylon cyclones at various charge levels under no mass loading conditions. It can be seen that for the different particle sizes tested, the particle charge has no obvious effect on the penetration of both the cyclones, when the particles carry several hundred elementary units of charge. As the particle charge increases beyond several hundreds, the effect becomes noticeable for the 10 mm nylon cyclone while it still remains negligible for the new cyclone. The most significant influence occurs for the particles near cutoff aerodynamic diameter for the 10 mm nylon cyclone. For

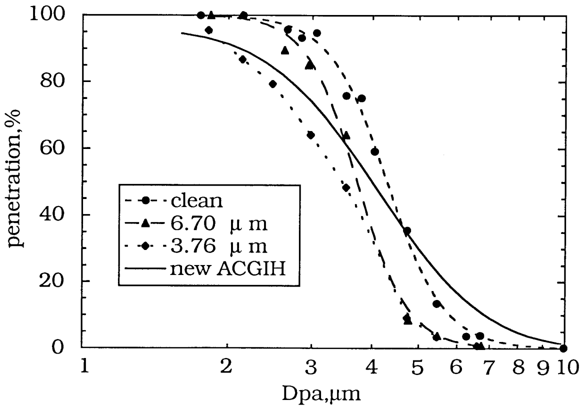

Fig. 7. Particle penetration curve versus particle aerodynamic diameter, when the aerodynamic diameters of the initially loaded particle are different, total loaded mass = 0.06 mg, 10 mm nylon cyclone.

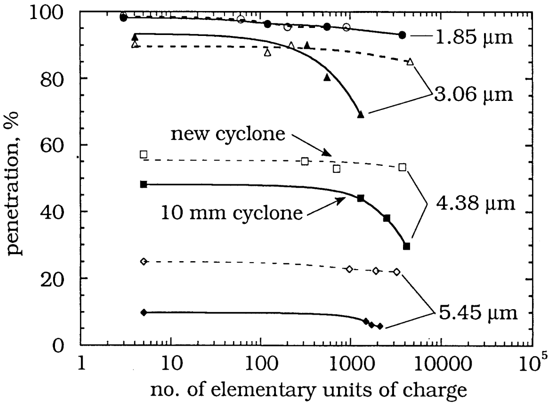

Fig. 8. Particle penetration as a function of the number of elementary units of charge for different particle aerodynamic diameters and under no particle mass loading condition.

example, the penetration decreases from 92.4 to 69.4% when the amount of charge increases from 4 to 1300, for 3.06 $\mu$m particles. For particles much larger or smaller than the cutoff aerodynamic diameter, the effect of particle charge on penetration has been noted to be insignificant for the 10 mm nylon cyclone.

## CONCLUSIONS AND RECOMMENDATIONS

The present study has identified the importance of effect of deposited particle mass on the penetration of small sampling cyclones. The effect appears to be very significant for the commonly used 10 mm nylon cyclone. The operating flow rate of the 10 mm nylon cyclone, to match with the ACGIH sampling criteria, has been different among the previous studies (Tsai and Shih, 1995). The reason for this may lie in the different amounts of deposited particle mass used in the previous experiments. For future determination of the operating flow rates for new sampling cyclones, it is recommended that the effect of deposited particle mass on particle penetration should be considered.

In order to minimize the influence of deposited particle mass on penetration at the commonly experienced loading levels, cyclones that have a larger inner diameter, such as the new cyclone developed in this study, appears to offer a good solution to the problem. This study has demonstrated that the new cyclone, operating at 1.7 L min$^{-1}$, is able to match the new ACGIH criteria much better than the 10 mm nylon cyclone, at all loading levels up to 3.0 mg in the laboratory. The particle electrostatic charge has been shown to have a negligible effect on the penetration of this new cyclone, made of aluminum, while this effect is significant for the 10 mm nylon cyclone when the particles are near the cutoff aerodynamic diameter and charge level is higher than several hundred elementary units of charge. However, for typical workplace aerosols which carry up to several hundreds of elementary charge only, the electrostatic effect can be neglected even for the insulating 10 mm nylon cyclone.

While this paper reports the laboratory test results of small sampling cyclones using monodispersed aerosol particles, it is also important to conduct the field study in the actual workplace. Further work is being carried out to evaluate the best operating flow rate and test the performance of the new cyclone in the actual workplace.

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