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# Removal Efficiency of Bimodal $PM_{2.5}$ and $PM_{10}$ by Electret Respirators and Mechanical Engine Intake Filters

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## ABSTRACT

As China is receiving an economic boom, PM (particulate matter) pollutions not only have become a serious regional problem but also frequently impacted its neighboring counties, e.g., Korea and Japan. In addition to its adverse effects on human health, the on- and off-road engines operated in ambient can also be affected. In this study, a simple system for generating simulated ambient bimodal PMs comprising fine ($PM_{2.5}$), coarse ($PM_{2.5-10}$) particles was developed for evaluating the initial efficiency of seven respirator and four engine intake filters. In addition to the size fractional efficiency curves for each filter media determined from the SMPS (scanning mobility particle sizer) and APS (aerodynamic particle sizer), both number and mass based efficiency of these filters for $PM_{2.5}$, $PM_{2.5-10}$ and $PM_{10}$ were also obtained to evaluate their performances against ambient PM pollutions. Data showed that the engine intake filters had a low efficiency for both mass and number based $PM_{2.5}$, which was only about 25–30%. However, there was a large difference between their number and mass based $PM_{10}$ efficiency. The former was much lower than the latter because these filters are with high efficiency only for coarse particles. Besides, the most of particles in number was resided in the fine size range while the mass was in coarse size range. For the respirator filtration tests, results showed that most of them can effectively remove both $PM_{2.5}$ and $PM_{10}$, in which the mass efficiency was always higher than that of number. The $PM_{2.5}$ number efficiency results showed there are three out of seven respirator filters are with N-95 rated level, in which the efficiency of their most penetrating particle size is higher than 95%. The current simple experimental system could be applied to examine different purpose filters which protect human health and outdoor engines against ambient $PM_{2.5}$ and $PM_{10}$.

***Keywords:*** $PM_{2.5}$ in China; $PM_{2.5}$ health effect; $PM_{10}$; Bimodal ambient PM; Electret respirator; Mechanical engine intake filter; Long range transport.

## INTRODUCTION

There are severe particulate matter (PM) pollutions in China and its surrounding countries due to the rapid economic and industrial growth in the past two decades and the highly polluted condition is still ongoing (Pui *et al.*, 2014). There are extremely high $PM_{2.5}$ (particulate matter < 2.5 µm) and $PM_{10}$ (particulate matter < 10 µm) concentrations monitored with above 500 µg $m^{-3}$ a couple of times per year (Kim and Kim 2003; Yang *et al.*, 2011; Guo *et al.*, 2014; Hu and Jiang 2014; Zheng *et al.*, 2015). PM pollution is already known to increase risks for a wide range of health effects, such as respiratory and heart diseases and allergic conjunctivitis (He *et al.*, 2001; Pope and Dockery, 2006; Mills *et al.*, 2009; Brook *et al.*, 2010; Mimura *et al.*, 2014). An analysis showed that outdoor air pollution was responsible for the 1.2 million premature deaths in China in 2010. This made up about 15% of the total deaths in China in the same year (Horton, 2012). In 2013, the International Agency for Research on Cancer (IARC), WHO's specialized cancer agency, has placed outdoor air pollution in Group 1 which is a category used only when a sufficient evidence of carcinogenicity in humans is observed. In addition, particulate matter, a major component of outdoor air pollution, was evaluated separately and also classified as carcinogenic to humans. In Beijing, more than 50% of commuters wear respirators every day. Surgical masks are normal used, which can effectively and easily capture droplets that can be visually seen produced

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through respiratory events such as talking, coughing or sneezing. However, they are not intended and not able to protect the people from micro-meter size droplets or from submicron particles like viruses (Rengasamy *et al.*, 2010), which could be part of $PM_{2.5}$. It raises a question about there is no clear information or criterion for selecting a proper respirator to mitigate $PM_{2.5}$ exposure because the current commercial respirators are not evaluated with realistic atmospheric bimodal particles.

High level of $PM_{10}$ and $PM_{2.5}$ pollutions not only frequently impact China but also transport to its surrounding countries, Japan and Korea as well as North America, during fall and spring when the Westerlies pick up (Kim and Kim, 2003; Mori *et al.*, 2003; Chin *et al.*, 2007; Shimadera *et al.*, 2014; Yamazaki *et al.*, 2014; Vellingiri *et al.*, 2015). For example, during a dust storm event in 2001, there was an extremely high $PM_{10}$ concentration at the upstream Beijing with 1000 µg $m^{-3}$ and that of the downstream Yamaguchi, Japan, was 200 µg $m^{-3}$. To be noted, not only during a dust storm event, some extreme high $PM_{2.5}$ episode generated locally in mega cities of China can also impact the air quality in Japan, Korea as well as Taiwan (Zheng *et al.*, 2015). It was found, during the dust storm in 2001, the mass distribution in Beijing showed a single coarse mode peaking at 5–8 µm while that in Yamazaki was a bimodal distribution peaking at 0.5 µm and 3–5 µm for the fine and coarse mode, respectively. In comparison, the peaking sizes of ambient fine and coarse modes around the world were frequently measured with ~0.2–0.7 and ~3–20 µm, respectively (Whitby *et al.*, 1972; USEPA, 1996; Harrison *et al.*, 2000; Chen *et al.*, 2010a). These ranges should be a criterion for preparing simulated bimodal PM for the respirator and filter testing.

The current protocol for respirator testing, 42 CFR 84, uses only fine particles and does not consider the existing coarse PM in the real environments. They are examined by challenging with 300 nm particles, which usually represents the lowest efficiency of mechanical based respirators. However, electret media are commonly applied in the respirators to reduce the flow resistance to achieve a better comfort of wear. But it has been found there is high penetration occurring in both nano-sized (20–50 nm) and submicron-meter or micro-meter size range in electret filter media (Lathrache *et al.*, 1986; Lathrache and Fissan, 1987; Mostofi *et al.*, 2010; Rengasamy *et al.*, 2010; Chen *et al.*, 2014). Therefore, to evaluate respirators filters with more realistic bimodal PMs is essential.

In addition to human health, environmental PM pollution would adversely affect the mechanical equipment located at outdoor environments, such as on-road and off-road combustion engines which always acquire a large amount of filtered cleaner air. Engine intake filters are taking this task to provide clean air to protect engines. Therefore, they also should be tested using the more realistic ambient bimodal particles. However, in the standard test method, ASHRAE 52.2, the ISO dusts which have a lack of fine particle mode, e.g., A1 and A2 dusts, are usually used to challenge the filters. Poon and Liu (1997) conducted a series of efficiency tests for HVAC and engine intake filters using bimodal particles. Later, Endo *et al.* (1998) studied the loading characteristics and cake formation of those filters experimentally and theoretically for bimodal particles. However, the size distributions of the particles generated to challenge the filters were not close to the ambient PMs or not shown. For example, the fine particle MMAD of the bimodal distribution in Endo *et al.*, (1998) was as large as 1 µm.

Up to date, there is a lack of or only limited research has rated respirator or engine intake filters for $PM_{2.5}$ and $PM_{10}$ removal efficiency. Therefore, this study intends to develop a simple system for generating simulated bimodal particles, in which the concentration and mass median aerodynamic diameter (MMAD) is within the criterion and could be adjusted and controlled. The criterion given by this study is that the MMADs of fine and coarse particles are within 0.2–0.7 and 3–10 µm, respectively, and the ratio of fine to coarse mode concentration is within 0.5–2. The bimodal PMs were then used to challenge respirator filters and engine intake filters for their initial efficiency against both number and mass based $PM_{2.5}$ and $PM_{10}$. Although the initial performance cannot represent filtration characteristics of their whole life cycle and filters are expected to have an increased efficiency with time due to particle loading. But this is only applicable for mechanical filters. Electret filters usually have an efficiency reduction with time, due to the loss of filter charge, before the occurrence of cake filtration. It has been found the period with reduced efficiency could remain 2–3 months for HVAC electret filters (Raynor and Chae, 2004; Shi *et al.*, 2013). Therefore, the initial efficiency could be regarded as the 'best' performance in the first 2–3 months and extra caution should be paid if the initial efficiency is not reasonably high and an improved design to ensure a proper initial performance is required. The final goal is to provide a more practical, realistic and accurate method for evaluating the respirator as well as engine intake filters against $PM_{2.5}$ and $PM_{10}$.

## METHODS AND MATERIALS

### *Bimodal Particle Generation and Filtration Test*

Fig. 1 shows the schematic diagram of the bimodal particle generation and penetration test system for evaluating seven respirator and four engine intake filters. Coarse and part of fine dust particles with ~1–20 µm were generated with the TSI fluidized bed by dispersing Arizona road dust (A2 Grade, ISO 12103-1). In comparison, fine NaCl particles with 0.02–2.5 µm were produced by a homemade Collision-type atomizer with aerosolizing 0.5, 1.0 or 2.0 wt% NaCl solution. Figs. 2(a) and 2(b) shows the SEM images of the dispersed Arizona road dusts and NaCl particles collected on the 1 µm pore diameter Nuclepore filters (WHA-111112, GE Healthcare Biosciences, Pittsburgh, PA, USA). As can be seen the road dusts are well deagglomerated by the fluidized bed and there are no or only very few agglomerates. The NaCl particles are with a shape between cubic and spherical. Therefore, this study assumes the both coarse and fine particles are with sphere-like shape in order for simplifying the conversion between mobility diameter and aerodynamic diameter as shown later.

The SMPS (scanning mobility particle sizer) measured the

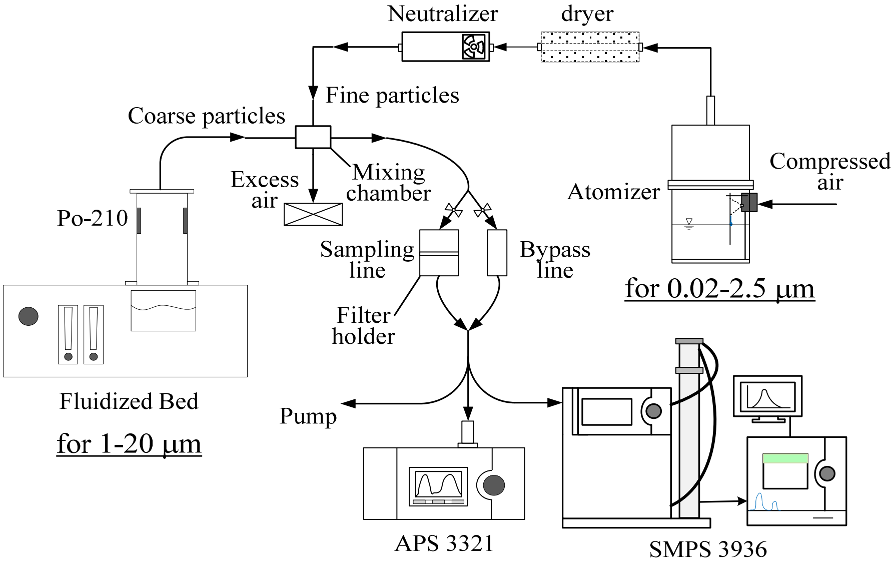


**Fig. 1.** Experimental setup of filter efficiency for bimodal PM.

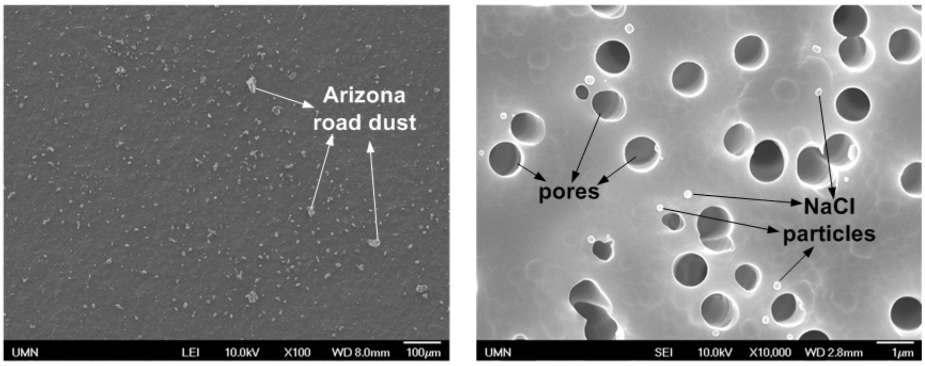


**Fig. 2.** SEM images for the coarse Arizona road dusts (a) and fine NaCl particles (b).

size distribution of the fine particles generated by the atomizer for particles with ~0.02–0.8 µm in mobility diameter. In comparison, the APS (aerodynamic particle sizer) determined the size distribution of particles from ~0.5 to 20 µm in aerodynamic diameter. Since the both generated fine and coarse particles have been assumed to be sphere-like shapes, Eq. (1) was applied to convert the SMPS mobility diameter, $D_m$, to aerodynamic diameter, $D_{pa}$, as (Chen *et al.*, 2010a):

$$D_{pa} = D_m \left( \frac{\rho_p C_c(D_m)}{\rho_0 C_c(D_{pa})} \right)^{1/2}, \quad (1)$$

where $\rho_p$ is the material density of the particle, $\rho_0$ is the reference density (1 g cm$^{-3}$), $C_c(D_m)$ and $Cc(D_{pa})$ are slip correction factor for particle mobility diameter and aerodynamic diameter, respectively.

During the tests, it was found the coarse particles (> 5 µm) can easily deposit on horizontal and bend transport tubing, therefore for minimizing the coarse particle transport loss, the length of tubing should be shortened and the bend radius should be optimized according to Tsai and Pui (1990). Besides, the APS needs to be located right underneath the sampling-bypass splitter to minimize the transport loss of coarse particles. After mixing the fine and coarse aerosol streams together, the size distribution of the simulated bimodal particles upstream and downstream of the filter were measured by the APS and SMPS for the aerosols in the bypass line and filter line, respectively, for determining the particle penetration. However, this study found that introducing the mixed bimodal aerosol simultaneously into APS could cause a severe coincident effect because of the high fine particle concentration. APS would significantly underestimate the concentration for particles smaller than 2 µm. An alternative way is to use a virtual impactor at the upstream of APS to remove particles smaller than 0.5 µm. However, this small diameter cut impactor could create an essential pressure drop and cause other complexity during the efficiency measurement. Therefore, this study suggests testing the filter efficiency for fine and coarse particles separately by introducing particles from the atomizer and fluidized bed alternatively.

A total of seven respirator and four engine intake filters were challenged with the bimodal PM at 6–11 cm s$^{-1}$ and 5 cm s$^{-1}$ face velocities, respectively, for their initial efficiencies. A total of more than 10 repeats for the efficiency measurement using different filter media for each sample were conducted to obtain the representative results. The penetration of different aerodynamic particle sizes was determined by taking the ratio of the downstream particle number concentration, $N_{conc.}(D_{pa})_{down}$, to that of upstream, $N_{conc.}(D_{pa})_{up}$. The efficiency of the filter for a particle with certain aerodynamic diameter, $\eta(D_{pa})$, is then calculated as:

$$\eta\left(D_{pa}\right) = 1 - \frac{N_{conc.}\left(D_{pa}\right)_{down}}{N_{conc.}\left(D_{pa}\right)_{up}}, \quad (2)$$

In addition to obtaining the efficiency curve for each filter media, both particle number and mass efficiency of the filters for $PM_{2.5}$, $PM_{2.5–10}$ and $PM_{10}$ were measured and determined. Eqs. (3) and (4) show the calculation of the $PM_{2.5}$ number, $\eta(PM_{2.5N})$, and mass, $\eta(PM_{2.5M})$, efficiency, respectively, as:

$$\eta(PM_{2.5N}) = 1 - \frac{\sum_{D_{pa}=0.02}^{2.5} N_{conc.}\left(D_{pa}\right)_{down}}{\sum_{D_{pa}=0.02}^{2.5} N_{conc.}\left(D_{pa}\right)_{up}}, \quad (3)$$

and

$$\eta(PM_{2.5M}) = 1 - \frac{\sum_{D_{pa}=0.02}^{2.5} M_{conc.}\left(D_{pa}\right)_{down}}{\sum_{D_{pa}=0.02}^{2.5} M_{conc.}\left(D_{pa}\right)_{up}}, \quad (4)$$

where $M_{conc.}$ is mass concentration of particles with certain $D_{pa}$, which is determined by SMPS and APS. Similarly, the number and mass efficiency of the filters for $PM_{2.5–10}$ and $PM_{10}$ can be calculated from Eqs. (3) and (4) by substituting the size range with $D_{pa}$ = 2.5 to 10 µm and $D_{pa}$= 0.02 to 10 µm, respectively, for the summarization of particle concentration.

### *Filter Media*

Seven different flat respirator media obtained from Shigematsu (Tokyo, Japan) as labeled with #A-#G and four engine intake filters from a filter manufacturing company as labeled with #1–#4 were tested for their efficiencies against simulated ambient bimodal PMs. The specifications of the respirator media are shown in Table 1. In general, all respirator filters were multilayer with comprising a layer of electret media and some fine or coarse fiber layers. In comparison, all engine intake filters were mechanical filter but the detailed specification of them were not available. The electrete media were electrostatically-charged melt-blown type and have a significant microscopic bipolar charge on the fibers. The charging density was not available and their effects will not be discussed in details since a more detailed discussion can be found elsewhere (Chen *et al.*, 2014). Table 1 also shows their efficiency determined by the TSI 8130 provided by the manufacturer. As can be seen the efficiency is higher than 94% for most of media except that of #F.

## RESULTS AND DISCUSSION

### *Bimodal PM Size Distribution*

Fig. 3 shows three examples of bimodal distributions generated by this study, in which the dash-dotted curve has an essential higher fine mode concentration than that of coarse mode; dashed curve shows the similar fine and coarse peak mass concentration and the solid curve represents the distribution with larger coarse MMAD. As can be seen the cutoff, in terms of the saddle point, of the three bimodal distributions are all located at around 2–3 µm. The MMADs of fine and coarse particle ranged 0.2–0.6 and 6–10 µm, respectively. From the above, it is concluded that the bimodal PMs produced in this study are close to the real world PM size distributions (Hinds *et al.*, 1999) and should be applicable for challenging respirator and engine intake filters to represent their performances against $PM_{2.5}$ and $PM_{10}$. The major distributions that used to challenge filters are the dashed and solid ones in this study. It is to be noted, the MMAD and its concentrations for fine particles can be further adjusted by using a different solution concentration or by dilution or other method such as evaporation and condensation. Similarly, MMAD and the concentrations of coarse dust particles can also be achieved by changing the feeding speed and bed flow of the fluidized bed and the different grade of the dusts. Besides, in the future tests the geometric standard deviation of the coarse mode should be enlarged to better mimic the ambient particles.

Fig. 4 shows the number based size fractional efficiency

**Table 1.** Specifications of electret filter media.

| Media | Thickness (total, major) (mm) | Effective fiber diameter[1] (µm) | Face velocity (cm $s^{-1}$) and pressure drop (in-$H_2O$) | Average efficiency[2] (%) |
|---|---|---|---|---|
| #A | (0.38, 0.19) | 2.3 | (8.6, 0.39) | 99.95 |
| #B | (0.30, 0.12) | 2.7 | (8.6, 0.25) | 99.04 |
| #C | (0.32, 0.11) | 2.6 | (11.4, 0.40) | 99.85 |
| #D | (3.43, 2.88) | 16.8 | (11.4, 0.18) | 99.96 |
| #E | (3.07, 1.18) | 2.2 | (11.4, 0.47) | 99.76 |
| #F | --[3] | -- | (6.3, 0.11) | 66.78 |
| #G | (0.97, 0.18) | 3.3 | (7.3, 0.12) | 93.99 |

[1] Effective diameter of the major (governing the filter efficiency) fiber media; [2] by TSI 8130; [3] not available.

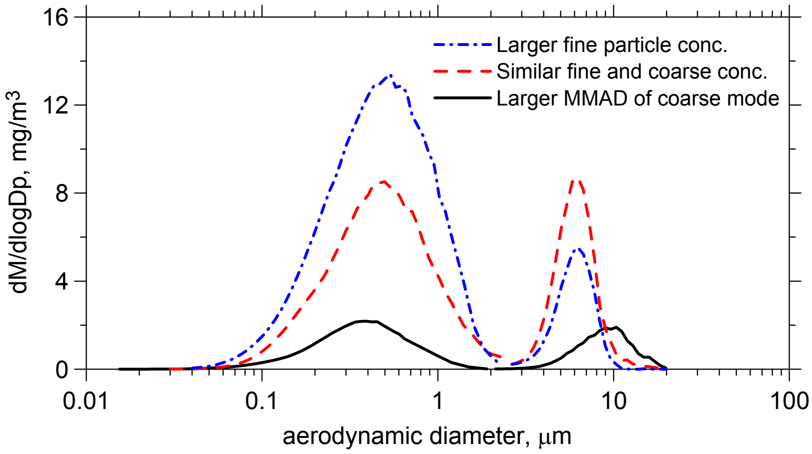


**Fig. 3.** Different bimodal PM distribution could be generated in this study.

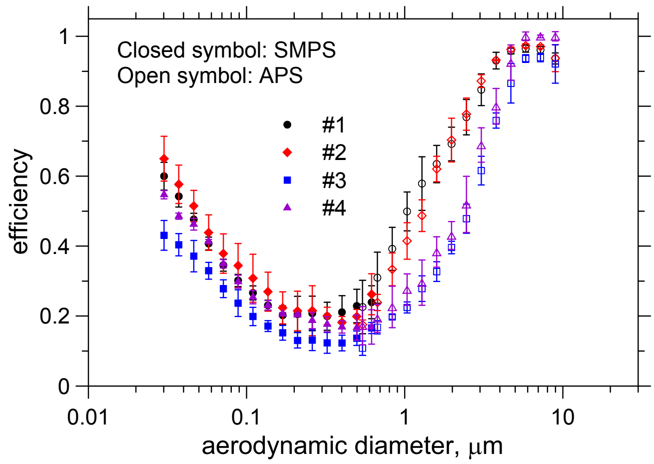


**Fig. 4.** Size fractional efficiency curves for Engine intake filters.

curves of the engine intake filters investigated in this study for the size range of 0.03–10 µm. The results for particles larger than 10 µm won't be shown due to the large deviation of the efficiencies by the low particle concentration in both upstream and downstream of filter. A good continuity of efficiency curves in the overlapped size range of SMPS and APS (~0.6–0.8 µm) indicates the two instruments are comparable and a reliable measurement result is deliverable. It is seen the MPPS for all four filters fall at ~0.3 µm, which is a typical characteristic for mechanical filters. In general, media #1 and #2 have higher efficiency than that of #3 and #4. Their minimum efficiencies at MPPS are as low as ~10–20%, however, the efficiency increased to nearly 100% for 10 µm particles.

Fig. 5 shows the number based size fractional efficiency curves of the seven respirator media for particle sizes with 0.03–10 µm. Obviously, most of media had a MPPS at ~0.05–0.06 µm except media #F which was ~0.3 µm. This could be due to that the media #F contains much less electret media or the electret media had a lower charge than the others. This resulted in that the mechanical mechanism dominated the particle deposition and the MPPS occurred at about 0.3 µm. Besides, it is observed that only media #G has the second penetration mode occurring at ~0.3 µm, which could be due to its lower charging density.

The media #A, #C and #E show a minimum number efficiency with higher than 95%, therefore, they could be regarded as N-95 respirator media (Mostofi *et al.*, 2010). The curves presented in Fig. 5 could be used to calculate the performance of the media again particles with different size distributions.

Because high $PM_{2.5}$ and $PM_{10}$ pollutions frequently impact China and transport to its surrounding counties, the efficiency of these filters against PMs are of high interests. Both number and mass based efficiency of the four engine intake filters and seven respirator filters for $PM_{2.5}$, $PM_{2.5-10}$ and $PM_{10}$ are summarized in Figs. 6(a) and 6(b), respectively. Besides, the data from manufacturer for the respirator are also included in Fig. 6(b), which were determined by the mass based TSI 8130 filter auto tester as shown in Table 1.

In Fig. 6(a), it is seen the both number and mass based $PM_{2.5}$ efficiencies are much lower than that of $PM_{2.5-10}$ for the engine intake filters. The efficiencies were only ~30%. This was because the rate of the filters was low and also their MPPSs fell in the fine particle range (~0.3 µm). Interestingly, the mass based $PM_{10}$ efficiencies were increased to ~50% but the number based $PM_{10}$ were still kept low as ~30%. Similarly, this was because the particles in number were

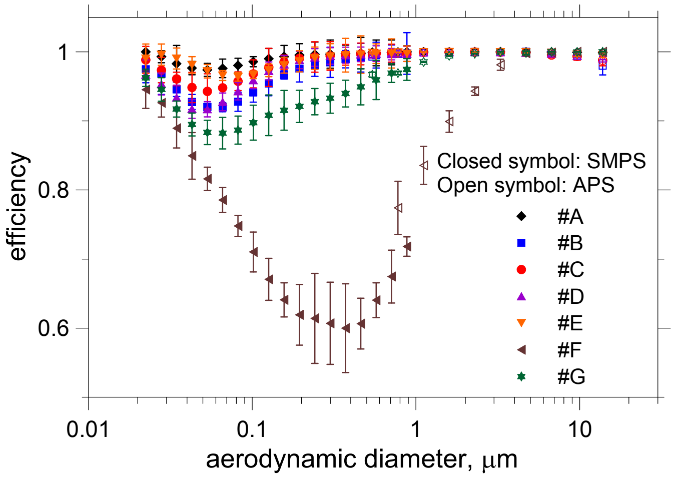


**Fig. 5.** Size fractional efficiency curves for the seven respirator media.

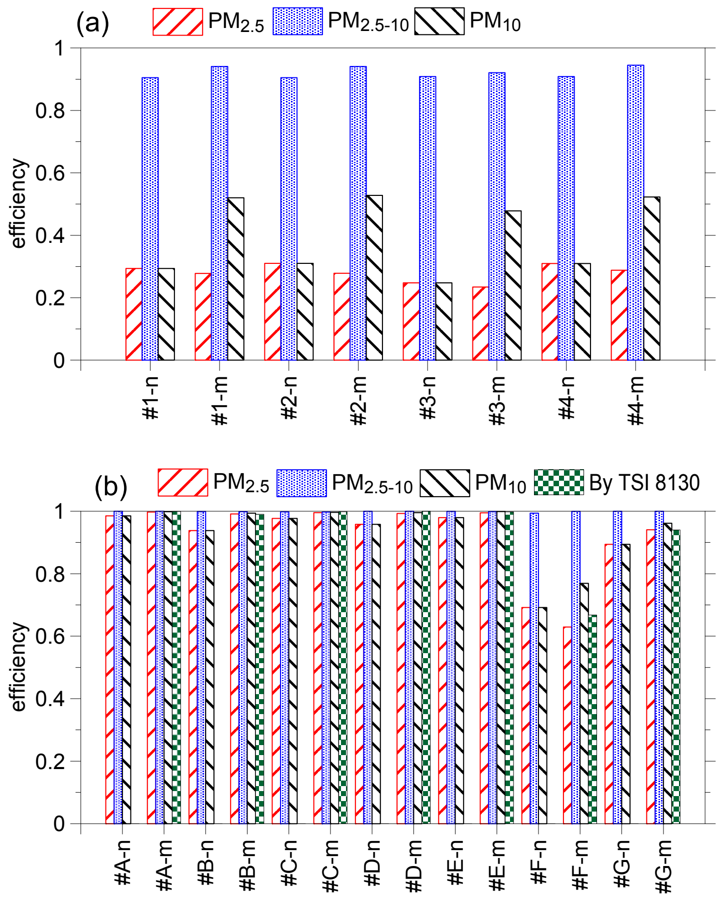


**Fig. 6.** (a) Engine intake filter efficiency against number (-n) and mass (-m) based $PM_{2.5}$, $PM_{2.5\text{-}10}$ and $PM_{10}$; (b) respirator filter efficiency against number and mass based $PM_{2.5}$, $PM_{2.5\text{-}10}$ and $PM_{10}$. The efficiency by TSI 8130 is also shown for respirator filters.

mostly fallen in $PM_{2.5}$ range. The major contribution to the increased $PM_{10}$ mass efficiency was from the high efficiency (~90%) of $PM_{2.5–10}$ coarse particles. In conclusion, engine intake filters had reasonable $PM_{10}$ mass removal efficiency but they are not efficient for both number and mass $PM_{2.5}$. An extra caution may be paid for the low efficiency of the filters against ambient $PM_{2.5}$ because these fine particles usually contain a significant high ratio of acidic and basic inorganic salts (Chen *et al.*, 2010a). These salts could easily cause erosion and pitting on blade's leading edge and other important components of engine if there is an absent of the secondary filter to provide a further protection. It is also to be mentioned, the current bimodal PMs used to challenge the engine intake and respirator filters have a $PM_{2.5}$ to $PM_{10}$ mass concentration ratio of about 0.6. The $PM_{10}$ mass efficiencies will be reduced if the $PM_{2.5}$ to $PM_{10}$ mass concentration ratio is further increased. On the contrary, the $PM_{10}$ mass efficiencies can be increased if the ratio decreases.

In Fig. 6(b), it is found the mass based $PM_{10}$ efficiency obtained by this study was very close to that by the TSI 8130. This finding was reasonable because there were significant high efficiencies in coarse fraction, which largely enhanced the total $PM_{10}$ mass efficiency as discussed earlier. However, a lower efficiency for the both number based $PM_{2.5}$ and $PM_{10}$ than that of mass based ones is found. Again, this was because their MPPSs fell in nanoparticle size range as observed in Fig. 5. The SMPS can accurately measure smaller particles (~10 nm) than the photometer (> 100 nm) and able to catch a more accurate penetration of particles smaller than 100 nm. Therefore, for determining the filter efficiency of sub-100 nm nanoparticles for electret media, SMPS is recommended to be used.

As media #A, #C and #E are rated as N-95 based on their number based MPPS, it is found both #B and #D have high mass based $PM_{2.5}$ and $PM_{10}$ efficiencies. They should be applicable for protecting PM pollutions. As mentioned in the last section, the change of the bimodal distribution can affect the filter efficiency against different PMs and the corresponding changes are able to be determined by the efficiency curves shown in Figs. 4 and 5.

## CONCLUSION

A simple bimodal PM generation and filter efficiency test system was developed to examine the performance of four engine intake and seven respirator filters against ambient $PM_{2.5}$ and $PM_{10}$. In the particle generation, a homemade atomizer was used to produce fine PMs and the TSI fluidized bed was for coarse PM generation. The size distribution of the bimodal PM is close to the real ambient ones and the distribution could be further adjusted.

The experimental results showed that the engine intake filters can efficiently remove coarse $PM_{2.5–10}$. However, their significant low efficiency for $PM_{2.5}$ should be considered since they can damage the metal components of engine. The respirator media tested all have good $PM_{2.5}$ and $PM_{10}$ removal efficiencies except the media #F. Based on the SMPS and APS measurements, media #A, #C and #E are rated as N-95 according to their MPPS in number base. The current experimental system could be applied to examine different purpose filters which protect human health and outdoor engines against ambient bimodal particles.

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