# Influence of flue gas cleaning system on characteristics of $PM_{2.5}$ emission from coal-fired power plants

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**Abstract** This study investigated the influence of precipitators and wet flue gas desulfurization equipment on characteristics of $PM_{2.5}$ emission from coal-fired power stations. We measured size distribution and removal efficiencies, including hybrid electrostatic precipitator/bag filters (ESP/BAGs) which have rarely been studied. A bimodal distribution of particle concentrations was observed at the inlet of each precipitator. After the precipitators, particle concentrations were significantly reduced. Although a bimodal distribution was still observed, all peak positions shifted to the smaller end. The removal efficiencies of hybrid ESP/BAGs reached 99 % for $PM_{2.5}$, which is considerably higher than those for other types of precipitators. In particular, the influence of hybrid ESP/BAG operating conditions on the performance of dust removal was explored. The efficiency of hybrid ESP/BAGs decreased by 1.9 % when the first electrostatic field was shut down. The concentrations and distributions of particulate matter were also measured in three coal-fired power plants before and after desulfurization devices. The results showed diverse removal efficiencies for different desulfurization towers. The reason for the difference requires further research. We estimated the influence of removal technology for particulate matter on total emissions in China. Substituting ESPs with hybrid ESP/BAGs could reduce the total emissions to 104.3 thousand tons, with 47.48 thousand tons of $PM_{2.5}$.

**Keywords** coal-fired power station, precipitation, $PM_{2.5}$, emission characteristics, electrostatic precipitator, ESP/BAG

## 1 Introduction

Particulate matter pollution, which results from large consumption of fossil fuels, has become one of the most serious environmental problems in China. The problem of fine particulate matter ($PM_{2.5}$) pollution is particularly prominent (Chan and Yao 2008), and $PM_{2.5}$ is the main cause of reduced visibility and haze formation. $PM_{2.5}$ is more harmful than coarse particles because it contains toxic ingredients and enters the blood circulation system through the alveoli (Linak et al. 2000; Goodarzi 2006). According to Lei et al. (2011), among the $PM_{2.5}$ emissions caused by human activities, the $PM_{2.5}$ emissions resulting from the use of fossil fuel in stationary sources exceeds 60 %. Also, $PM_{2.5}$ emissions from coal-fired power plants account for the highest proportion of stationary sources. Therefore, we must strengthen the study of the formation and control of $PM_{2.5}$ from coal-fired power plants to find more effective and targeted removal approaches.

The particulate matter produced by coal-fired power plants contains an ultrafine mode and a coarse mode (Damle et al. 1982; Xu et al. 2009). Ultrafine mode particles are those less than 1 μm in size and can also be referred to as submicron particles; coarse mode particles are typically larger than 1 μm and are also called residual ashes. These two types of particles have different physical and chemical properties and are formed via different generation mechanisms. Ultrafine mode particles are mainly formed during the gasification-condensation process of inorganic matter from coal. Coarse mode particles originate mainly from major minerals in coal and become solid residues after coke burning.

Coke crushing and surface ash aggregations are the main processes that determine the size distribution of coarse mode particles. Therefore, the boiler type that determines the combustion process, boiler load, coal type, and other factors affects (Yoo et al. 2002; Maguhn et al. 2003; Ninomiya et al. 2004; Zhang and Ninomiya 2006), to a large extent, the initial particle concentration and particle size distribution. By measuring the emissions of power plants, it has also been found that the type of boiler (Liu et al. 2010), boiler load (Yi et al. 2006) and coal type (Giere et al. 2006; Wu et al. 2011; Xue and Wang 2013) influence

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$PM_{2.5}$ concentration and particle size distribution at the entrance of precipitators.

Particulate matters produced by combustion are disposed of by denitration equipment, the precipitator, and the desulfurizing tower before they are eventually discharged into the atmosphere through a chimney. The precipitator is the main piece of equipment that collects particulates in coal-fired power plants. A number of studies addressed the concentration of particulate emissions and particle size distribution from flue gas at precipitator outlets. These were relatively simple studies mainly of electrostatic precipitators (ESPs). Bhanarkar et al (2008) measured the particle concentrations before and after the ESPs in coal-fired power plants in India and China, respectively. However, these researchers were concerned about removal efficiency and elemental composition of $PM_{10}$ only, and did not analyze the removal efficiency of $PM_{2.5}$. Liu et al. (2009) measured four ESPs of small thermal power units (< 200 MW) and found that their removal efficiencies for $PM_{2.5}$ and $PM_{10}$ were 86.1 %–98.8 % and 88.25 %–99.46 %, respectively. Yi et al. (2006) found that the efficiencies of 600 MW unit ESPs when removing $PM_1$, $PM_{2.5}$, and $PM_{10}$ were 95.74 %, 96.75 %, and 98.58 %, respectively. They also measured the efficiency of ESPs when electrodes were stroked in real time. They found that when the electrodes of the ESP were stroked, the overall removal efficiency decreased and $PM_{2.5}$ concentrations increased significantly. Several researchers measured the particle size distribution of the flue gas from the outlet of the ESP to estimate the emission factors of $PM_{2.5}$ and $PM_{10}$ distribution and their impacts on the environment (Yao et al. 2006; Zhao et al. 2008; Pudasainee et al. 2010; Bangert et al. 2013).

According to current measurement results, although the dust removal efficiencies of ESPs can reach 98 % in existing coal-fired power plants, the removal efficiencies of $PM_{2.5}$ are considered low. In terms of the number of particles, $PM_{2.5}$ can account for over 90 % of the total quantity of particles (Zhao et al. 2010). Thus, $PM_{2.5}$ continues to grow as the amount of total suspended particulate (TSP) in the atmosphere declines. Therefore, the key to controlling particulate matter lies in controlling $PM_{2.5}$. For a more stringent $PM_{2.5}$ emission standard, the use of any single conventional removal technology is far from satisfactory. Therefore, developing different control methods using synergistic technologies is an urgent concern. For coal-fired power plants, electrostatically enhanced fiber filter technology for the removal of fine particulate matter combines the characteristics of ESPs and bag filters (Wang 2001; Huang et al. 2006; Yao et al. 2009; Yang et al. 2013). This technology is the most promising approach to efficiently remove fine particulate matter. A hybrid ESP/BAG represents the future development direction of precipitators, and the proportion of total precipitators that use this technology continues to grow. However, few studies have investigated the dust removal performance of the hybrid ESP/BAG during its actual operation in power plants. Thus, measuring and analyzing $PM_{2.5}$ emission characteristic of the hybrid ESP/BAG are necessary.

In terms of flue gas cleaning equipment, flue gas denitration and flue gas desulfurization equipment themselves form new fine particulate matter (Nielsen et al. 2002), thereby changing the emission characteristics of $PM_{2.5}$. In selective catalytic reduction devices, a small part of the ammonia unavoidably slips. The ammonia reacts with $SO_3$ to form sulfate fine particles, which leads to an increase in the concentration of fine particles (Huang et al. 2003). However, according to practical measurements, increases in particle concentrations are negligible. Certain test results on the particulate matter emissions of coal-fired power plants (Meji and Winkel 2004; Wang et al. 2008) have shown that although desulfurization devices that employ the wet limestone-gypsum method can synergistically remove particulate matter from gas, gypsum crystal particles and fine unreacted limestone particles are added to the composition of $PM_{2.5}$. The effects of different towers that remove particulate matter are significantly different. Therefore, the $PM_{2.5}$ removal mechanisms and emission characteristics of the desulfurization towers require further research.

In this study, we examined the influences of precipitators and desulfurization equipment on particle emission characteristics in the flue gas cleaning system. The particle size distributions before and after four different dust removal devices in six coal-fired power plants were measured, including the hybrid ESP/BAGs that have not been measured previously. The influence of different dust removal devices on $PM_{2.5}$ emission characteristics was also analyzed. The measurement data derived from power plants were accumulated to provide the basis for the choice of $PM_{2.5}$ control technology. In particular, the influence of hybrid ESP/BAG operating conditions on dust removal performance was explored. The concentrations and distributions of particulate matter before and after desulfurization devices were also measured in three coal-fired power plants. The results were used to analyze the cleaning effect of wet desulfurization devices on $PM_{2.5}$. The findings of this study can provide a reference for the use of wet flue gas desulfurization (WFGD) technology in removing fine particles in flue gas.

## 2 Experiments

### 2.1 Experimental conditions

The particulate matter emissions of six coal-fired power stations were measured. During each test period, the boiler testing load, fuel, and burning operation mode did not vary. The equipment and operating conditions in the power plants were normal and the conditions of these power plants are described in Table 1.

The mass concentration of the inlet and outlet of WFGD equipment in three power stations were also measured. The parameters of these three WFGD towers are listed in Table 2.

**Table 1** Summary of experimental conditions of stationary sources

| No. | Boiler | Feed coal | Capacity (MW) | Load (%) | Dust collecting equipment |
|---|---|---|---|---|---|
| 1 | PC | Bituminous coal | 12 | 98 | ESP (3 electrostatic fields) |
| 2 | CFB | Low quality bituminous coal | 135 | 98 | ESP (4 electrostatic fields) |
| 3 | PC | Bituminous coal | 200 | 100 | Bag filter |
| 4 | Chain boiler | Mixed bituminous coal | 40 t/h (Heat supply) | 80 | Wet scrubber |
| 5 | PC | Bituminous coal | 1000 | 100 | Hybrid ESP/BAG |
| 6 | PC | Bituminous coal | 600 | 85 | Hybrid ESP/BAG |

**Table 2** Information on tested desulfurization tower

| No. | Scrubber | $SO_2$ removal efficiency (%) | Liquid–to-gas ratio ($L/m^3$) | Flue gas speed (m/s) | Slurry residence time (s) | Boiler | Capacity (MW) |
|---|---|---|---|---|---|---|---|
| 7 | Liquid column | ≥90 | 14.7 | 3.1 | 4.2 | PC | 300 |
| 8 | Spraying | ≥90 | 8.61 | 3.8 | 4.2 | PC | 300 |
| 9 | Spraying | ≥90 | 11.5 | 3.8 | 4.08 | PC | 1000 |

## 2.2 Experimental systems and methods

Testing points were located at both the inlet and outlet of the precipitators and the outlet of the WFGD equipment (Fig.1).

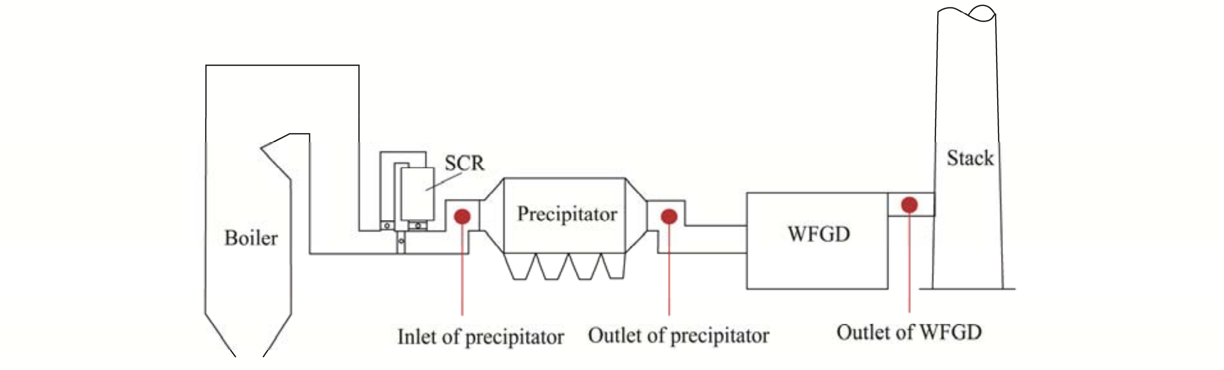

**Fig. 1** Schematic diagram of testing points

Based on the actual condition of the power plants, four different equipment configurations were adopted to measure particle concentrations. The equipment assembly modes are presented in Table 3.

An 8-stage Andersen Stack Impactor (Thermo Andersen Instruments Inc.) was used at the inlet and outlet of power plants 1, 2, 3, and 4. The method is in accordance with EPA Method 17 (Yue et al. 2005). At the inlet of the precipitator of plant 5, a dust sampling instrument was used to collect the total dust, according to GB/T 16157–1996. Then, a Mastersizer 2000 Laser Particle Analyzer (Malvern Instruments Ltd.) was used to measure particle size distribution (Zhang et al. 2005). The Electrical Low Pressure Impactor (ELPI) (Dekati Ltd.) was used to measure the size distribution of the precipitator outlets. In plant 6, an 8-stage Andersen Stack Impactor was used at the inlet of the precipitator, and the ELPI was used at the outlet. In plants 7 and 8, the 8-stage Andersen Stack Impactor was used to measure the size distribution of the inlet and outlet of the WFGD equipment, while the ELPI was used for these measurements in power plant 9.

At the outlet of the WFGD equipment, the flue gas was saturated, which is beyond the tolerance range of measuring instruments. Therefore, a diffusion dryer was used to dry the flue gas and to ensure the accuracy of the measurement.

**Table 3** Testing instruments

| No. | Inlet of precipitator | Outlet of precipitator | Outlet of desulfurization tower |
|---|---|---|---|
| 1 | Andersen Impactor | Andersen Impactor | |
| 2 | Andersen Impactor | Andersen Impactor | |
| 3 | Andersen Impactor | Andersen Impactor | |
| 4 | Andersen Impactor | Andersen Impactor | |
| 5 | Laser Particle Analyzer | ELPI | |
| 6 | Andersen Impactor | ELPI | |
| 7 | | Andersen Impactor | Andersen Impactor |
| 8 | | Andersen Impactor | Andersen Impactor |
| 9 | | ELPI | ELPI |

## 3 Results and discussion

### 3.1 Particle size distribution of inlet and outlet of precipitators

The particle mass concentration distributions at the inlet and outlet of the precipitators, which are expressed in $D_p$-d$M$/dlog $D_p$, are shown in Figs.2 and 3.

The distribution of particle size at the inlet of power plant precipitators is obviously bimodal. The peaks occur near 1 μm and 10 μm in Fig.2. The two peaks reflect two different mechanisms of particle formation in the process of coal combustion. Fine particles result mainly from the gasification-condensation process of inorganic matter in coal, and coarse particles consist mainly of residual minerals from the coke. The coke crushing and aggregation of surface ash are the main processes that determine the eventual size distribution of coarse particles. Also, for the coal types that contain more external minerals, mineral crushing also has a highly significant influence on the formation of residual ash particles. The size distribution of particles at the entrance of the precipitator in power plant 4, which was a chain boiler, differed slightly from the size distribution of other power plants.

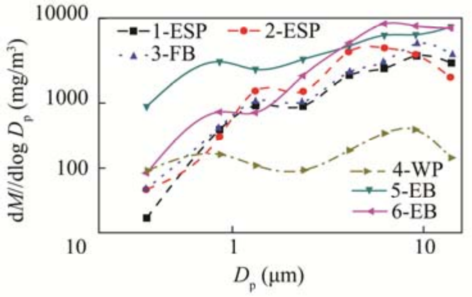

**Fig. 2** Mass concentration distribution at inlet of precipitators.

*Notes: 1-ESP means electrostatics precipitator in plant 1. The other abbreviations and numbers of plants are similar.*

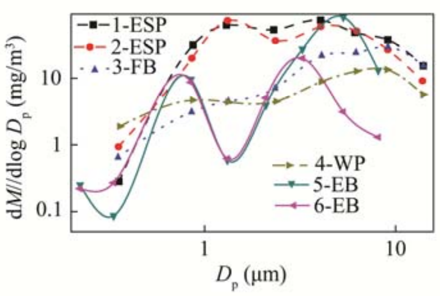

**Fig. 3** Mass concentration distribution at outlet of precipitators.

Fig.3 shows that after the precipitators were installed, the size distribution of particles remained obviously bimodal, but the concentration decreased greatly. The peaks moved to the small particle size range. In outflow gas flowing through different precipitators, the size distributions of particles indicate different forms. The particle concentrations when bag filters and hybrid ESP/BAGs were used decreased more significantly than when just ESPs were used, particularly for $PM_{2.5}$. Thus, the total dust removal effects and fine particle removal effects of the hybrid ESP/BAG and bag filter were superior to those of ESPs. After the hybrid ESP/BAG, the peaks in the hybrid ESP/BAG occurred near 0.7 μm and 2.0 μm, and the bimodal distribution of particles was more distinct. Nonetheless, after other types of precipitators, the peaks remained relatively flat.

### 3.2 Influence of precipitators on $PM_{2.5}$ emission characteristics

The classification of particle removal efficiencies of precipitators is shown in Fig.4. The removal efficiencies of ESPs on particles decreased as particle size diminished. The lowest removal efficiency point was at 1 μm, where the efficiency was approximately a relatively low 91.9 %. Various forces are exerted on particles in the process of collection. The final particle removal effect is a comprehensive result of different forces. The efficiencies of inertia and gravity on the particles increase as particle size increases, whereas the diffusion mechanism acts on particles in an opposite manner. Thus, the critical point of all forces is generally believed to appear near 1 μm. In this particle size range, the mentioned forces have the weakest comprehensive effects and the lowest removal efficiency point exists (Friedlander 2000). The ESP of case 2 equipped with four electrostatic fields was more effective than the ESP of case 1 equipped with three electrostatic fields, even while the lowest valley value of 93.4 % was higher than the value of 92 % for the ESP of case 1. However, increasing the number of electrostatic fields had a negligible effect on the efficiency of removing submicron particles.

The particle removal efficiency of the bag filter in case 3 was similar to that of the hybrid ESP/BAG of cases 5 and 6. All of these devices have removal efficiencies of 99 % or more on particles with different sizes. These removal efficiencies are significantly higher than those of the ESPs in cases 1 and 2, particularly in terms of the removal effect of $PM_{2.5}$. A Venturi water film dust precipitator is a wet precipitator in which the removal of particles by droplets is accomplished mainly through inertial collision, interception and cohesion between particles and droplets. Thus, the particle removal efficiency of this precipitator is a relatively low 95 % to 97 %, as shown in Fig.4. However, with the existence of droplets, small particles agglomerate in a wet precipitator. Thus, the removal efficiency of the wet dust collector for fine particles less than 1 μm is not low, and is between that of bag filters and the ESP.

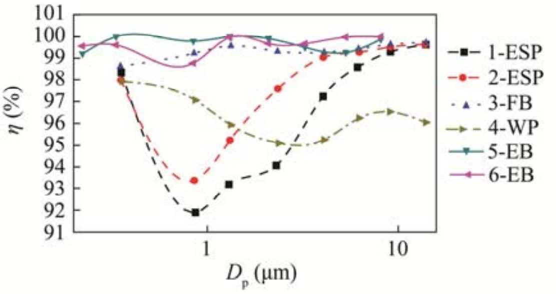

**Fig. 4** Fractional removal efficiencies of precipitators.

A comparison of the removal efficiencies of different precipitators is shown in Fig.5. Removal efficiencies increased as particle size increased, except for the wet precipitator. With increasing particle sizes, the efficiencies of ESPs increased by approximately 5 %, whereas the efficiency of the hybrid ESP/BAG rose only slightly because its efficiency for $PM_1$ exceeded 99 %. The removal efficiency of the bag filter was similar to that of the hybrid ESP/BAG, but its overall efficiency was less than that of the hybrid ESP/BAG. The hybrid ESP/BAGs exhibited the best elimination ability, with an efficiency of over 99 % not only for $PM_{10}$ but also for $PM_{2.5}$ and $PM_1$.

Although most power plants in China are equipped with ESPs, the $PM_{2.5}$ removal efficiencies of ESPs are relatively low at approximately 93 % (Lei et al. 2011). Thus, the amount of $PM_{2.5}$ continues to increase as the total amount of particulate matter emission declines. For more stringent $PM_{2.5}$ emission standards, the use of any single conventional removal technology is far from satisfactory. Therefore, hybrid ESP/BAGs can be applied more widely, which is the reason for the current popularity of hybrid ESP/BAGs. Studies that investigate the increase of particle removal efficiency and test the emission characteristics of hybrid ESP/BAGs should be strengthened.

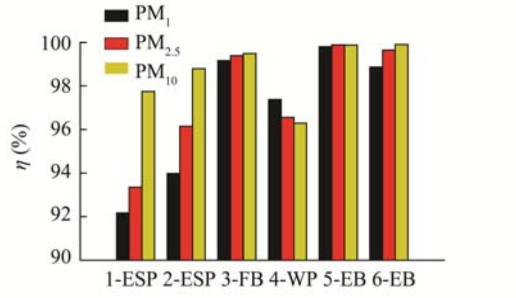

**Fig. 5** Removal efficiency of $PM_1$, $PM_{2.5}$ and $PM_{10}$ of different precipitators.

### 3.3 Influence of operation condition on hybrid ESP/BAG removal efficiency

In hybrid ESP/BAGs, particles are pretreated through electrostatic elimination to eliminate certain particles, particularly large ones. The rest of the charged particles flow along with the gas into the bag filters and are eliminated through interception, inertial collision, and diffusion. Fibers capture fine particles in the bag filter. The advantage of hybrid ESP/BAGs is that the ESP part functions by working with the bag filter part. The ESP part has low energy cost. As most particles are eliminated, the load of the bag filter part is reduced and a smaller pressure difference is expected. Thus, the cost of the hybrid ESP/BAG system is reduced and the elimination efficiency for fine particles is increased. Given that ESPs have limited elimination efficiency for small particles as well as high specific resistivity particles, hybrid ESP/BAGs can increase the elimination efficiency for fine particles.

In this study, we investigated particle removal efficiency under coupled ESP and bag filter conditions with the first electrostatic field shut down. The effect of the ESP part of a hybrid ESP/BAG on removal efficiency was also discussed.

The experiment was conducted on the hybrid ESP/BAG of power plant 5, which had three electric fields, followed by a bag filter. The particle size distribution measured at the exit of the hybrid ESP/BAG is listed in Fig.6, when the first electric field was shut down while all other parameters were kept constant. Under normal operating conditions, $PM_{10}$ and

$PM_{2.5}$ concentrations were 27.214 mg/m$^3$ and 2.758 mg/m$^3$, respectively, after elimination. This changed to 155.767 mg/m$^3$ and 36.924 mg/m$^3$ when the first electrostatic field was shut down. Obviously, particle concentration at the exit significantly increased when the first electric field was shut down. Thus, removal efficiency dropped significantly. With the aforementioned results, the ESP part and bag filter part are suggested to function cooperatively in the hybrid ESP/BAG. When the first electrostatic field in the ESP part is shut down, although two electrostatic fields remain, Dovich's equation indicates that the efficiency of the ESP part drops significantly. Thus, the subsequent bag filter part has a higher load that exceeds the designed maximum entrance particle concentration, and the overall elimination efficiency drops from 99.91 % to 97.92 %. For a hybrid ESP/BAG, designing the loading ratio between the ESP part and bag filter part helps increase the overall elimination efficiency.

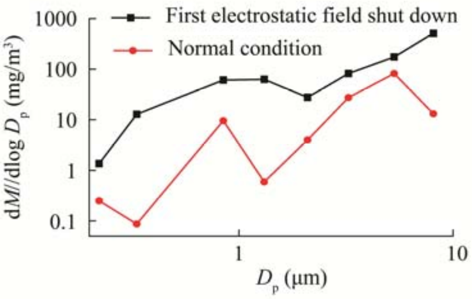

**Fig. 6** Comparison of size distribution of first electrostatic field under shut down and normal conditions.

### 3.4 Influence of WFGD on $PM_{2.5}$ emission characteristics

Existing testing results on the emissions of particulate matter from coal-fired power stations show that wet desulfurization equipment can collaboratively remove particulate matter in gas, but different effects can be observed from different desulfurization towers. Our study measured the particle size distribution of the inlet and outlet of WFGD equipment in three power plants, as indicated in Fig.7. Fig.7(a) and (b) illustrate the reduced concentration of all sizes of particulate matter before and after WFGD devices, where large particles declined the most and $PM_{2.5}$ declined the least. The removal efficiencies of the desulfurization tower of power station 7 were 83.11 % for $PM_{2.5}$ and 89.08 % for $PM_{10}$. For power station 9, the particle size distribution curve of particles greater than 2.5 μm of the outlet gas was lower than that of the inlet gas. However, the outlet particle size distribution curve of $PM_{2.5}$ was higher than that of the inlet. The removal efficiency of $PM_{2.5}$ in power station 9 was −228.15 %, which indicated that coarse particle concentration decreased, whereas $PM_{2.5}$ concentration increased during the wet desulfurization process. In the WFGD tower, the flue gas temperature is about 120 ℃ at the entrance. The temperature is about 50 ℃ and relative humidity reaches above 90 % at the exit. There exists a large temperature and water vapor concentration difference between the flue gas and the desulfurization slurry. Collection mechanisms like inertia impaction, interception, Brownian diffusion, thermophoresis and diffusiophoresis will exert influence on the particles around the desulfurization slurry. Therefore, the WFGD tower can scrub a certain amount of particles in the flue gas. The WFGD parameters will have a significant impact on the capture process including particle and droplet diameter, droplet temperature, flue gas temperature and relative humidity etc. Wang et al. (2008) found that the form and component made up of particles differ between WFGD inlets and outlets. Inlet particles are spherical and outlet particles tend to coagulate into irregular blocks or layered crystals. The S and Ca content of particles increase, and Ba, Fe, Mn, Al and Si decrease correspondingly. Other than fly ash particles in the WFGD outlet, they are also composed of 7.9 % gypsum particles and 47.5 % limestone particles. Presumably, the increase of fine particulate matter concentration at the outlet of WFGD results from the transformation of gypsum particles and limestone particles, which is in turn caused by entrainment and drying. Therefore, the total collection efficiency of the WFGD tower also depends on the amount of particles the tower itself generated.

Our analysis revealed different WFGD removal efficiencies from different power plants. The WFGD equipment in plants 7 and 8 eliminated particles in all diameter ranges, whereas an increased $PM_{2.5}$ concentration was observed in particles after the WFGD equipment of power plant 9. Thus, control and elimination of $PM_{2.5}$ emission should be conducted by considering logical design and setting desulfurization parameters, such as gas/liquid ratio and demister efficiency. Otherwise, an increase in $PM_{2.5}$ concentration may occur. Further theoretical and experimental studies are required to achieve rational parameters in depth.

### 3.5 Influence of removal technology of particulate matter on total emissions in China

A total of 6.032 million tons of dust were emitted by the Chinese industrial sector in 2010, 36.2 % of which were contributed by power plants (State Environmental Protection Administration of China 2010). The size distribution of dust particles emitted by power plants is assumed to obey the particle size distribution at the inlet of the precipitator of plant 1, and all power plants use electrostatic precipitation with the same efficiency as that of power plant 1, i.e., an elimination efficiency of 93.35 % for

$PM_{2.5}$ and 98.87 % for particles with a diameter larger than 2.5 μm. The efficiency of hybrid ESP/BAGs can be calculated from that of plant 6, which corresponds to an elimination efficiency of 99.64 % for $PM_{2.5}$ and 99.95 % for particles with a diameter larger than 2.5 μm. The influence of the WFGD equipment is taken into account because of its extensive application. According to the test results, the elimination efficiency of 62.5 % for $PM_{2.5}$ and 87.0 % for particles with a diameter larger than 2.5 μm are assumed. If all ESPs are replaced with hybrid ESP/BAGs, the resulting particle size distribution at the exit shown in Fig. 8 would be observed. When all power plants adopt ESPs, the total emission is expected to be 2.183 million tons, including 898.5 thousand tons of $PM_{2.5}$. By substituting ESPs with hybrid ESP/BAGs, total emissions would drop to 104.3 thousand tons, of which 47.48 thousand tons is $PM_{2.5}$. Total dust and $PM_{2.5}$ emissions are likely to decrease significantly, and the percentage of $PM_{2.5}$ in total suspended particles may increase to 45.52 %. If the effect of WFGD is considered, the total emission at the base of the chimney is 504.0 and 25.6 thousand tons, respectively, for the combination of two kinds of precipitators and WFGD equipment. The emission of $PM_{2.5}$ is 336.9 and 18.2 thousand tons. Thus, a logical design of WFGD equipment can further control the emission of particles.

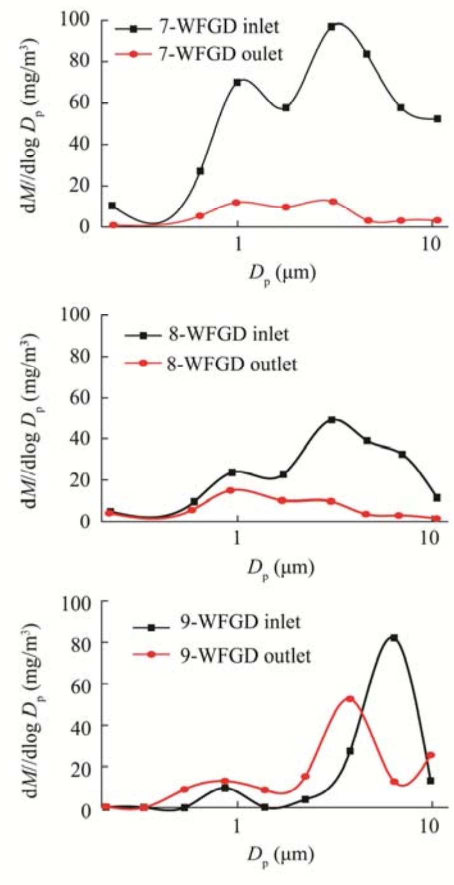

**Fig. 7** Size distribution before and after WFGD.

In summary, total dust emissions and $PM_{2.5}$ emissions can both be reduced significantly through the use of hybrid ESP/BAGs. Higher-level environmental requirements can be fulfilled by applying acoustic and electric agglomeration technology before hybrid ESP/BAGs are used, and by applying wet ESPs after hybrid ESP/BAGs are used (Gellego et al. 1999; Ji et al. 2004; Fan et al. 2009; Matthews et al. 2011).

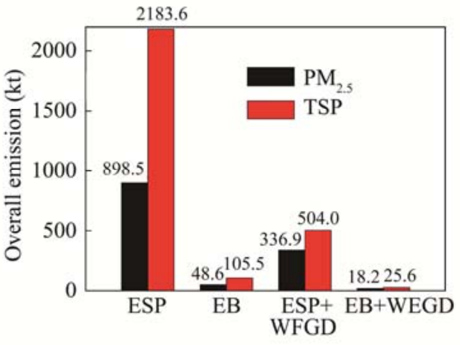

**Fig. 8** Influence of ESP and hybrid ESP/BAG on emission of particulate matters in China.

## 4 Conclusions

(1) By measuring the size distributions of particles before and after four types of precipitators in six power plants, including hybrid ESP/BAGs that have rarely been studied in the past, the mass concentrations of particles at different types of precipitators were obtained. A slight difference in distribution was observed at the entrance of each precipitator because of the difference in boiler types and combustion conditions. After elimination, particle concentrations were significantly reduced. Although a bimodal distribution was still observed, all peak positions shifted to the smaller end.

(2) ESPs are less efficient in eliminating smaller particles, and the lowest efficiency rates are 91.9 % and 93.4 % for particles with diameters of approximately 1 micron. The hybrid ESP/BAGs have the best elimination ability, with an efficiency of over 99 % not only for $PM_{10}$ but also for $PM_{2.5}$ and $PM_1$.

(3) The ESP part works cooperatively with the bag filter part in hybrid ESP/BAGs during the dust elimination process. In this study, the efficiency of hybrid ESP/BAGs decreased by 1.99 % when the first electric field was shut down. For hybrid ESP/BAGs, a higher efficiency can be achieved by carefully designing the load ratio between the ESP part and the bag filter part.

(4) WFGD equipment can assist in eliminating particulate matter in flue gas but efficiency varies for different WFGD towers. Power plants 7 and 8 had $PM_{2.5}$ elimination efficiencies of 83.11 % and 42.85 %, respectively. The WFGD of plant 9 had an efficiency of −228.15 % for $PM_{2.5}$. In WFGD equipment, spraying can eliminate certain particles. However, gypsum and limestone

particles can be further transformed into fine particles through entrainment and drying, thereby increasing $PM_{2.5}$ concentration. Rationally designing the parameters of desulfurization towers can help further eliminate $PM_{2.5}$ after the use of precipitators.

(5) Under current conditions, the use of hybrid ESP/BAGs can significantly reduce total emissions as well as $PM_{2.5}$ emissions. Our calculation based on data from 2010 demonstrates that if hybrid ESP/BAGs are used by all power plants, total emissions can be reduced from 2.1836 million tons to 104.3 thousand tons, with a decrease of $PM_{2.5}$ from 898.5 thousand tons to 47.48 thousand tons.

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