Recent experiences of upgrading electrostatic precipitators for PM10 and PM2.5 emission control from coal-fired power plants

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Abstract This paper reviews our recent experiences for upgrading electrostatic precipitators (ESPs) for both reducing emission and saving energy. Since 2013，we have upgraded 16 electrostatic precipitators (ESPs) for 2×135 MW, 2×145 MW, 4×330 MW, 4×600 MW, 2×660 MW and 2×1050 MW coal-fired boilers. Moreover, we performed their full scale demonstrations of PM2.5 and PM10 (particles with diamaters of less than 2.5 µm and 10 µm) emission control with the support of the Chinese 863 program. Both cold-side and colder-side ESPs are evaluated according to their size, electrode, rapping, high-voltage power source, energy consumption, ash inlet load, coal property, PM2.5 and PM10 emission, respectively. Systematic design of both ESPs and flue gas desulfurizaation (FGD) not only benefits SO_2 but also PM10 and PM2.5 emission control. For coal-fired boliers, PM2.5 and PM10 concentrations at the ESP outlet are usually below 2.5 mg/m^3 and 20 mg/m^3, respectively. Their concentrations at the FGD outlet are usually below below 2.5 mg/m^3 and 5mg/m^3, respectively. For colder-side ESPs with a specific collection area of not less than 100 m^2/m^3/s, the PM10 and PM2.5 concentrations can be controlled to be below 10 mg/m^3 and 1.0 mg/m^3, respectively. In comparison with traditional ESP at 120-140 ºC energized by single-phase transformer reactifers (T/Rs), PM10 and PM2.5 emission are usually reduced by a factor of 10 by using three-phase T/Rs.

Keywords: Electrostatic Precipitator, Gas Cleaning, PM Removal, PM10, PM2.5

1. Technical background

Traditional flue gas cleaning system usually consists of Selective Catalytic Reactor (SCR) for NOx reduction, ESP for ash collection and Flue Gas Desulfurization system (FGD) for SO_2 scrubbing. Over the past years, Chinese National Emission Standards of Air Pollutants for Thermal Power Plants, such as the GB13223-2011, have been upgraded several times. Today, almost all Chinese power plants have to control their particle matter emission below 10mg/m^3 or 5 mg/m^3 at 6% of O_2 concentration.

In terms of the inlet flue gas temperatures, ESPs are usually divided into three groups, 1) high-temperature ESP of around 300-450°C usually installed before the SCR, 2) cold-side ESP of around 120-140°C usually installed after air-heater, and 3) colder-side ESP of around 90-110°C, which is below SO_3 acid dew point.

With regard to our 14 Pulverized Combustion (PC) and 2 Circular Flow Bed (CFB) coal-fired boilers and their ESPs as listed in Table 1, we applied both colder and cold-side ESPs energized by using three-phase transformer rectifiers (T/Rs) high-voltage power sources. All of PC boilers are also equipped with SCR and wet FGD for NOx and SO_2 emission control. ESPs usually have four or five electrical fields with a specific collection area of around 80-126 m^2/m^3/s. Ash inlet load is usually around 20-35 g/m^3. For the two CFB boilers of LinZhou plant, it is based on SNCR+ESP+WFGD system with inlet load of around 70 g/m^3.

Table 1 List of power plants and their ESPs

	Name	MW	Colder	Cold
1	FuKang	2x125		√
2	LinZhou	2x135		√
3	DaGang	4x330	√	
4	WangQu	2x600		√
5	HeQu	2x600	√	
6	YuanYangHu	2x660	√	
7	WanZhou	2x1050		√

In order to control PM from the FGD, we optimized their mist eliminators, gas and slurry flow distribution inside the FGDs to keep the mist concentration below 20 mg/m^3. Systematic design of ESP and FGD could realize cost-effective charged scrubbing to limit PM concentration below 5 mg/m^3.

In this paper, we discuss ESP sizing method, effects of high-voltage power source, effect of flue gas temperature, effects of ESP operation on PM10 and PM2.5 emission control.

2. ESP Sizing

Today, more than 200 Chinese companies are invloved in maufacturing ESPs and/or power sources. Traditional ESP sizing is according to the following revised Deutsch equation [1]:

$$\ln(1-\eta) = -(\omega \cdot s)^k \qquad (1)$$

where η, ω, s and k are the mass collection efficiency (%), particle effective migration velocity (m/s), ESP specific collection area ($m^2/m^3/s$), and empirical constant, respectively. The equation has been widely adopted for sizing ESP and predicating PM emission. The velocity ω and the coefficient $k \approx 0.5$, however, are dependent on individual experiences. Our industrial experience shows ESP performance can not be easily predicated by using the revised Deutsch equation when either upgrading the HV power sources, switching coal, reducing flow gas temperature, changing the rapping. ESP collection efficiency mainly depends on both the specific collection area and the applied voltage level during ESP operation, which was called the ESP index ESP_{index} as expressed by the equation (2). It is derived by multiplying the area s with the electric field strength [2]. Both ESP size and power source can be evaluated according to the equation (3), which has been used for more than 70 ESPs optimization [3].

$$ESP_{index} = E_a \cdot E_p \cdot S \tag{2}$$

$$\lg \frac{m}{\beta \cdot M_0} = -\alpha \cdot ESP_{index} \tag{3}$$

where, E_a and E_p are the average and peak electric field strengths (kV/cm), respectively. M_0 and m are ESP inlet and outlet dust concentrations (mg/m^3), respectively. The α and β are empirical correction coefficients, respectively.

According to the size equation (2), one can easily conclude that effects on ESP performaces of many factors, such as gas flow rate, collection area, gaseous temperature, dust load, back corona, rapping and power sources can be evaluated via the Index value [2,3].

3. ESP Eneriziation

Today, most of Chinese ESPs are usually equipped with single-phase T/Rs, high-frequency switch mode power source and three-phase T/Rs. For reducing energy consumption and limiting PM emission, ideal high voltage controller could be designed according to the following two fundemental princiles to maximize the index value and minimize the power consumption as expressed by following equations.

$$\min(P) = \left. \frac{\sum_{k=1}^{n} \int_{0}^{T_0} V_k(t) \cdot i_k(t) \cdot dt}{T_0} \right| \tag{4}$$

$$\max(ESP_{index}) = \left. \frac{\Delta \sum_{k=0}^{n} E_{ak}(t) \cdot E_{pk}(t)}{\Delta t} \right| \tag{5}$$

where $V_k(t)$, $i_k(t)$, $E_{ak}(t)$ and $E_{pk}(t)$ are time-resolved secondary voltage, secondary current, average electric field and peak electric field, respectively. T_0 and Δt are time constants for optimizing the index and the power consumption. n is the number of all electric fields. For 1050 MW boliers, the ESPs are usually equiped with 30 high-voltage power sources, i.e. n = 30.

For each electrical field, the voltage-current characteristics not only denpend on electrode geometry, flue gas temperature and composition, ash concentration and its resistivity, but also high-voltage circuit topology and its automatic voltage controller (AVC). As an example, for our colder-side ESP energized with three-phase T/Rs [4,5], typical voltage-current characteristics can be expressed as the following equation (5) or equation (6). The current density of the collection electrode ranges from 0.1 mA/m^2 to 0.5 mA/m^2. The averaged electric field is between 2.0-4.0 kV/cm.

$$\frac{I_2}{V_2} = k \cdot (V_2 - V_c) \tag{6}$$

or

$$V_2 = \frac{V_c}{2}\left(1 + \sqrt{1 + \frac{4I_2}{k \cdot V_c}}\right) \tag{7}$$

where I_2, V_2, V_c and k are the secondary corona current, the applied secondary voltage, the corona inception voltage and coefficient, respectively.

4. ESP outlet via the Index value and inlet load

Figure 1 summarizes PM emission via the Index value with more than 70 coal-fired boilers [2,3].

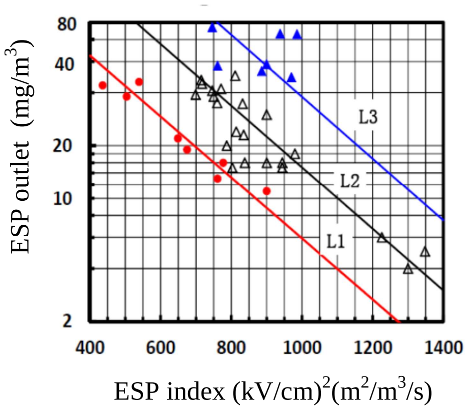

Figure 1. ESP outlets via ESP index

Three typical lines, indicated by L1, L2 and L3 represent three types of coals with ash contents of around 10%, 20% and 40%, respectively. The ESPs are typical 400-410 mm wide space and at 95-145 ˚C. The results can be approximated very well by using the equation (3) but not by the Deutsch equation (1). With regard to our power plants listed in Table 1, the ESP index are usually larger than 900 $(kV/cm)^2(m^2/m^3/s)$ as illustrated by the L2 line. The ESP outlet concentration via their inlet loads are shown in Fig. 2. For achiving near 5 mg/m^3 concentration, the index value is aroud 1300 (kV/cm)^2(m^2/m^3/s).

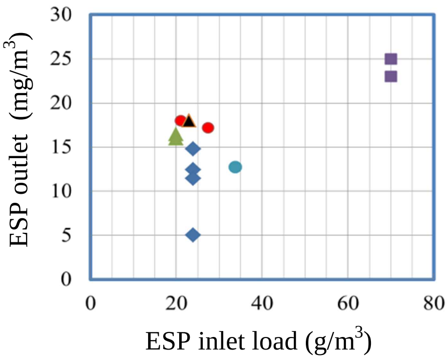

Figure 2. ESP outlets via inlet load

5. Effects of high-voltage power source

5.1. Single-phase via three-phase T/Rs

In comparsion with single- and three-phase T/Rs, as an example, Table 2 lists ESP power consumption and PM, PM10 and PM2.5 emission for a 660 MW coal-fired bolier. The bolier are equiped with two four channel and four fields ESPs with the surface area of 90 m^2/m^3/s and inlet load of 20 g/m^3. Retrofittingincludes replacement of 16 single-phase T/Rs by 16 three-phase T/Rs and installation of an heat exchanger to reduce the gas temperature from 120-140°C to about about 90-100°C [6].

With the single-phase power source, the secondary input power is limited due to the voltage rapple rate [2,3], which is defined as the following equation (8)

$$k = \frac{V_p - V_{\min}}{V_a} \tag{8}$$

where V_p, V_{min}, V_a and k are the secondary peak, minimun and averaged voltages, and the rapple rate, respectively.

When the AVC is under spark-rate mode, the k is around 75%. For current limiting and intermidiate modes, it is around 250%. Thus, it is always the input power is limited due to the peak voltage V_p. For the three-phase T/Rs, however, the rapple rate is usually less than 10%. Thus, it is always the input power is limited due to the output current, which in fact refers to very different AVC methodologies. Moreover, the power factors of single-phase and three-phase T/Rs are usually around 70% and 95%, respectively, these two type sources give very different input power consumption. The primary input power is reduced from 1225 kVA to about 962 kVA. The PM emission is reduced from 71 mg/m^3 down to about 15-16 mg/m^3. At the same time, the PM2.5 is reduced to from 23.9 mg/m^3 to 1.4 mg/m^3.

Table.2 Comparsion with single-phase and three-phase T/Rs with a 660 MW generator

Specifications	Single-phase Cold-side ESP	Three-phase Colder-side ESP
PM（mg/m^3）	71	15~16
PM10（mg/m^3）	63.5	14.4
PM2.5（mg/m^3）	23.9	1.4
Secdary output（kVA）	753	904
Parimary input (kVA）	1225	962
PM drop (%）		78.1
PM10 drop（%）		77.3
PM2.5 drop（%）		94.1

5.2. High-frequency Source via three-phase T/Rs

Over the past ten years, a number of Chinese utilites have replaced their single-phase T/Rs by using switch-mode high-frequency power source for energy saving and PM reduction. Lots of applications, however, also demonstrated that effectiveness of PM reduction is not obvious due to input power limitation. The limitation is not due the rapple rate but the charging rate when spark-rate rises about 50/min and the heat loss of the power source. Chinese ESPs are usually designed with a stray capacitance of 30-50 pF/m^2 of the colletion electrode. It rises with increasing ash load. For our two 135 MW CFB boilers, the four fields ESPs were firstly upgraded with Chinese-made high-frequency power sources. Each bolier is equiped with a ESP of two channels and four fields, or 8 high-voltage power source. The power rating is 72 kV and 1200 mA, which usually give outputs of no more than 300 mA and/or 500 mA. As a rusult, ESP outlet is usually higher than 100 mg/m^3 due to near 70 g/m^3 inlet load. With three-phase T/Rs. Both PM10 and PM2.5 at the ESP outlet are around 20 mg/m^3 and 1.0 mg/m^3, respectively. The significant PM reduction is due to achieving an high-input power after replacing the power sources by three-phase T/Rs. Almost identical power source upgrading have been also performed with 2×600 MW and 2×1050 MW coal-fired generators for either cold-side or colder-side ESPs.

6. Effects of gas temperature

Reducing flue gas temperature not only reduce the gas flow rate or increase the specific area but also affect the ash resistivity and spark-over voltage. As an example, Fig. 3 shows typical PM10 concentration at ESP outlet when the temperature drops from 160°C to 110°C with a 330 MW boiler. Experiments were performed at the same power generation, the same coal specifications, but changing flue gas temperature via the front heat exchanger. PM10 concentration drops from about 50 mg/m^3 down to less than 10 mg/m^3. Moreever, from 110°C to 90°C, the PM10 concentrations are very similiar.

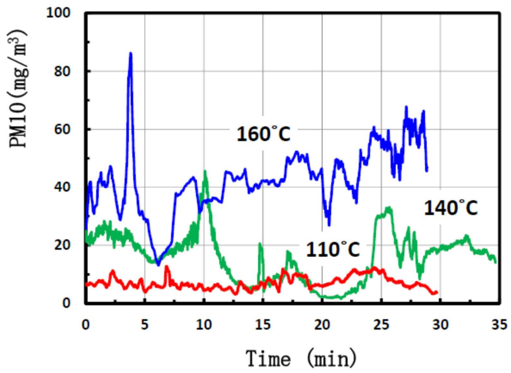

Figure 3. Effects of gas temperature

7. Effects of rapping

Most of Chinese ESPs are based on US design, which is referred as top rapping, and Europen design, which is referred as side rapping. During our ESP retrification, both top and side rapping have been either redesigned or replaced. Details of rapping effect on ESP performance were reported early [7]. Fig. 4 shows the state of the art of what we have observed with one 330 MW bolier. PM10 and PM2.5 concentrations are below 5 mg/m^3 and 1.0 mg/m^3, respectively. During the rapping period the emission rises by a factor 3, which lasts a few tens of seconds.

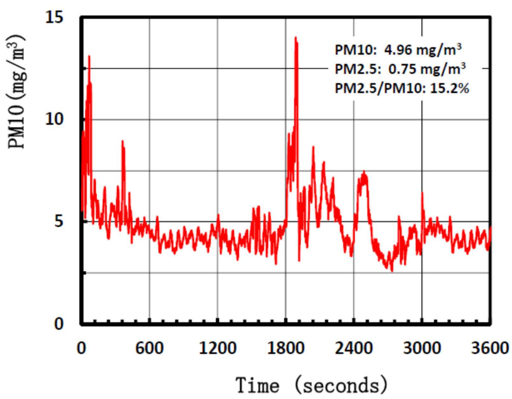

Figure 4. Effects of rapping

Considering the cost effectiveness, hybrid rapping design have been applied for our two 2×600 MW boilers. The first and second fields are based on side-rapping and the last three fields are based on top-rapping. Details of the cold-side ESP performances were early reported [8]. The ESP outlet drops from about 70 mg/m^3 with all top rapping and single-phase T/Rs to about 16mg/m^3 with the hybrid rapping and three-phase T/Rs.

8. Fabric filter to ESP conversion

Today, Chinese electricity industies are facing three technical issues, namely coal and water consumption per kWh and near ultra-low emission of multi-pollutants. The SCR induces a few percentage of SO_2 to sulfur trioxide SO_3 oxidation and then increases of sulfuric acid aerosols, which can produce visible near-stack plumes and acid aerosol mists. Ammonia slip is usually designed to be less than 3 ppm. The oxidation rate is less than 2%. Industrial applications, however, shows the formed ammonium sulfate or bisulfate on internal surfaces of the air preheater and FF. As a result, the pressure drop across the fabric filter (FF) could rise significantly up to 1800 Pa, which is usually beyond the fan capacity.

Table 3 lists typical specifications of applied colder-side ESP. And Table 4 lists typical inlet and outlet PM concentrations. Details of SO_3 absorption inside colder-side ESPs have not been evaluated yet, photos in Fig. 5 illustrates very different plume Characteristics. This FF to ESP conversion is the first time in China for both energy and water saving and multi-pollutants (PM, NOx, SO_2 and SO_3) emission control. Following these ESP upgrading experience, we just set a new utility Design and Selection Standards of Electrostatic Precipitator for ultra-low emission of Coal-Fired Power Plants [9], which provides detailed ESP design specificatins and its operation. All our on-going coal-fired power plants will apply the new standard.

Table 3. Typical colder-side ESP

	specifications	value
1	Inlet load (g/m^3)	35
2	Outlet (mg/m^3	< 15
3	Area (m^2/ m^3/sec)	88（90°C）
4	Field	5
5	Field length (m)	14.5
6	Gap (mm)	400

Table 4. ESP performances

Time	ESP	Inlet (g/m^3)	Outlet (mg/m^3)	Notes
2016.3	A	33.62	14.69	Within the 168hours
	B	37.96	9.93	
2016.6	A	35.09	3.93	After optimizing gas inlet flow
	B	24.28	5.02	

Figure 5. Plume characteristics
(left: cold-side ESP, right: colder-side ESP)

9. System integration of ESP and FGD

Wet limstone FGD has become widely used in China for SO_2 scrubbing. The FGD systems were usually designed with 75 mg/m^3 mist outlet concentration. As a result, mist emission containing fly ash, gypsum and other kinds of particles could contribute to a higher-level of PM concentration. Wet ESP can be used to collect these particles for less than 5 mg/m^3. But it is not a cost effective technology [10].

By applying three-phase T/R colder-side ESP and advanced mist eliminator of FGD, PM concentrations at ESP and FGD outlets are designed to be less than 20 mg/m^3 and 5 mg/m^3, respectively. At the same time their PM2.5 concentrations are less than 2.5 mg/m^3. Figure 6 shows typical PM10 concentrations at ESP and FGD outlets with a 600 MW coal-fired power plant, where PM2.5 is usually less than 1.0 mg/m^3. Mist concentration at the FGD outlet is usually below 20 mg/m^3.

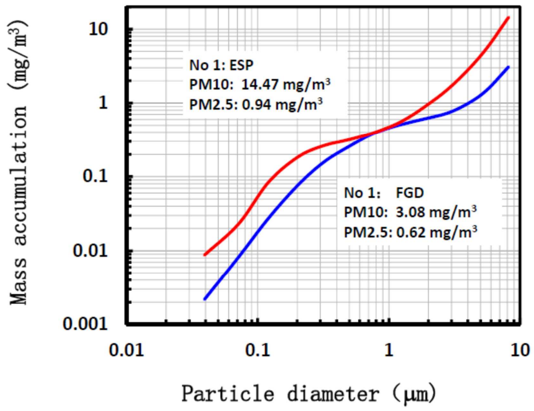

Figure 6. PM10 emission at ESP and FGD outlets

10. Overview of PM2.5 via PM10

According to our evaluation of PM2.5 via PM10, we summarize all data as shown in Fig. 7 [2,3].

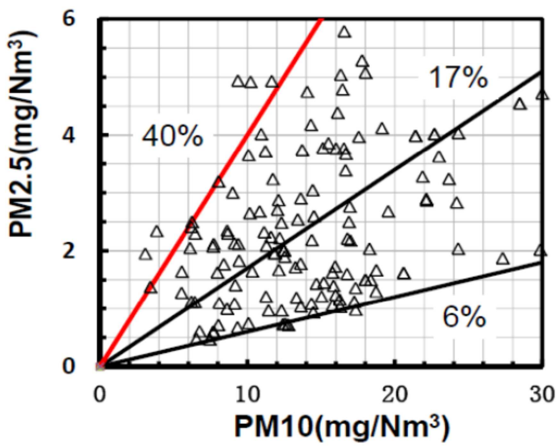

Figure 7. PM2.5 via PM10 at ESP outlet

For four and/or five fields ESPs, by optimizing flue gas temperature, using three-phase transformer rectifier high-voltage power sources and optimizing electrode construction, PM10 and PM2.5 concentrations at the ESP outlets can be limited to below 15 mg/Nm^3 and 1.0 mg/Nm^3, respectively. PM2.5 to PM10 ratio is around 6%-17%. For very high ash load or ESP under energy saving mode operation, the ratio can rise up to 40%. In comparison with previous emission, the PM10 and PM2.5 concentrations drop by 80-95 %.

11. Conclusion

The advanced flue gas cleaning system of SCR+colder-side ESP+FGD can be used not only for reducing PM emission below 5 mg/m^3, but also PM2.5 to be less than 2.5 mg/m^3. The system is not only cost-effective but also suitable for multi-coal switching. According to three years performances, we could give the following conclusions:

1) For four and/or five fields ESPs, by optimizing flue gas temperature, using three-phase transformer rectifier high-voltage power sources and optimizing electrode construction, PM10 and PM2.5 concentrations at the ESP outlets can be limited to below 15 mg/Nm^3 and 1.0 mg/Nm^3, respectively. And PM2.5 to PM10 ratio is around 6%-17%.
2) In comparison with coal-side ESPs equipped with traditional single-phase T/R, three phase colder-side ESPs show much better performance in terms of both power consumption and PM emission reduction. Generally speaking, at the same power consumption, the PM10 and PM2.5 concentrations drop by a factor of 3-5. When burning Shenhua coal and with five-fields colder-side ESP, the outlet PM concentration can be reduced to as low as about 5 mg/m^3.
3) With selective catalysis reduction (SCR) techniques to control NOx < 50 mg/m^3, NH_3 slip has become a common problem, which could lead to a big pressure drop across the following FF. Because of the issue, two FFs used for 2×600 MW generators have been replaced by colder-side ESPs to achieve the so-called ultra-low emission control. Typical colder-side ESPs have a specific collection area of around 100 m^2/m^3/s and emission of 15 mg/m^3.

References

[1] Oglesby S., Electrostatic precipitation, New York, Marcel dekker INC Press, 1978, ISBN 0-8247-6649-0.

[2] Huang Y., Li S., Zheng Q., Shen X., Wang S., Han P., Liu Z., Yan K., International Journal of Plasma Environmental Science & Technology, Vol.9, No.2, 2015, 69-95.

[3] Wang S., Chen Y., Han P., Zhang G., Zheng Q., Shen X., Li S., Yan K., Science and Technology Review, vol 32 No33 (2014) 23-33 (In Chinese).

[4] Wang S., Science and Technology Review (in Chinese), 2014, 32(33):34-38.

[5] Zhu J., Zhao Q., Yao Y., et al., Journal of

Electrostatics, 2012, 70(3):285-291.

[6] Ma Y., Qin S., Chen L., et al., Science and Technology Review (in Chinese), 2015, 32(6):69-72.

[7] Wang S., Chen Y., Han P., et al., Science and Technology Review(in Chinese), 2014, 32(33):39-42.

[8] Liang Z.， Li S.， Chen J., et al., Science and Technology Review (in Chinese), 2016, 34(05). 84-88.

[9] Shenhua Guoneng Energy Group Corporation Limited, "Design and Selection Standards of Electrostatic Precipitator for ultra-low emission of Coal-Fired Power Plants", Q/SH3400 00042016, Beijing, 2016 (in Chinese).

[10] Xiao C.Y., Science and Technology Review, 2014, 32(33):12 (in Chinese).