Analysis and Control Technology of blue Smoke in Coal-fired Power Plants

Liqiang Guo\textsuperscript{1,*}, Hanbing Yan\textsuperscript{1}, Yongxiang Li\textsuperscript{1}, Xiufang Chen\textsuperscript{1} and Fengchun Liu\textsuperscript{1}

\textsuperscript{1}Electric Power Research Institute, Shanxi Provincial Electric Power Corp. Taiyuan, Shanxi Province, 030001, China
\textsuperscript{*}Corresponding author’s e-mail: guoliqiang5329@163.com

Abstract: The control of blue Smoke in coal-fired power plants is of great significance to the atmospheric environment. The emission of SO\textsubscript{3} from coal-fired power plants is an important factor of blue Smoke production, which mainly comes from boiler combustion and selective catalytic reduction (SCR) denitration. When the content of SO\textsubscript{3} in the flue gas is too high, it will cause problems such as dust accumulation, low-temperature acid corrosion, increased air preheater resistance, and degraded performance of the electric precipitator, which will affect the economical efficiency and safety of the unit. In this paper, the causes of blue Smoke in coal-fired power plants are analyzed, the conversion rate of SO\textsubscript{3} is calculated and verified, and technical measures to control colored plumes are proposed.

1. Introduction

In order to cope with the serious pollution situation of the atmospheric environment, the state has put forward further requirements for the environmental protection work of coal-fired power plants. In July 2011, the Ministry of Environmental Protection released the latest “Air Pollutant Emission Standard for Thermal Power Plants” GB13223-2011\cite{1}. In September 2014, the National Development and Reform Commission, the Ministry of Environmental Protection and the National Energy Administration jointly formulated and issued the “Energy Saving for Coal-fired Power Generation”. The Action Plan for Emission Reduction and Renovation (2014-2020)\cite{2} is used to curb the current deterioration of air pollution in China by raising relevant emission standards. At present, the flue gas denitrification technology widely used in coal-fired power plants is selective catalytic reduction (SCR) denitrification technology. Part of SO\textsubscript{2} in the flue gas is oxidized to SO\textsubscript{3} through the catalyst of denitrification plant. After wet flue gas desulfurization, SO\textsubscript{3} is discharged from the chimney in the form of H\textsubscript{2}SO\textsubscript{4} aerosol, which may produce colored plume.

The damage of SO\textsubscript{3} to the equipment is obvious, including two aspects: one can cause low-temperature acid corrosion of the flue equipment, and the other is to react with ammonia that escaped from the denitration to form (NH\textsubscript{4})\textsubscript{2}SO\textsubscript{4} or NH\textsubscript{4}HSO\textsubscript{4}, ABS phenomenon will occur, causing the blockage of the air preheater, or causing the performance decline of the electric precipitator\cite{3}. We chose a typical coal-fired power plant with blue smoke as our research object. The plant consists of three 350MW coal-fired generating units. The flue gas is desulfurized by electrostatic dust removal, limestone-gypsum wet process and denitrification by selective catalytic reduction (SCR). Coal-burning sulfur content of the unit is higher, between 1.6-2.1%, the blue smoke is obvious.
2. Production of blue Smoke

2.1. Generation of SO2
The total sulfur in coal includes organic sulfur, pyrite, elemental sulfur and sulfate. The first three parts are combustible sulfur, which forms sulfur dioxide after combustion. Sulfate is non-combustible sulfur and is classified as ash. Normally, the ratio of combustible sulfur to total sulfur is 70% to 90% [4]. Combustible sulfur is oxidized to SO2 during combustion, and its chemical reaction formula is:

\[ S + O_2 = SO_2 \]  

(1)

2.2. Conversion of SO2 to SO3
SO2 is oxidized to SO3 under the conditions of catalyst and high temperature, and its chemical reaction formula is:

\[ 2SO_2 + O_2 = 2SO_3 \]  

(2)

2.2.1. Oxidation in the economizer
The study of Hardman et al. [5] suggested that SO3 was partially generated under the catalytic action of soot and iron oxide in the tube wall in the temperature range of 420 ~ 600℃ in the boiler economizer. The amount of SO3 generated depends on the concentration of SO2, the composition and flow of soot, the surface area of the convection section, the temperature distribution of the flue gas and the surface of the pipe, and the amount of excess air.

2.2.2. Oxidation in the boiler tube wall
Under the catalysis of ash accumulation on the boiler tube wall, SO2 reacts with atomic oxygen (O) and molecular oxygen (O2) to convert to SO3.

The conversion of the above two parts of SO2 to SO3 mainly occurs in the radiant heating section and the convection section, which can be called the pre-conversion rate, which accounts for about 1% of the total SO2 [6].

2.2.3. Catalytic oxidation of SCR denitration reactor
Most coal-fired power plants use SCR (Selective Catalytic Reduction Denitration) technology to control NOx emissions. V2O5-WO3 or V2O5-MoO3 are used as active component catalysts in SCR, in which V2O5 catalyzes the conversion of SO2 to SO3. Generally, the conversion rate of SO2 per layer of catalyst is about 0.25% to 0.5%. In the denitration reaction section, the higher the flue gas temperature, the higher the SO2/SO3 conversion rate. For low-sulfur anthracite, the conversion of SO2/SO3 per layer of catalyst is about 0.75% to 1.25% [7]. This part of the conversion rate can be called late conversion.

2.2.4. Conversion rate measurement and test verification of SO3
Studies have shown that some SO3 will fall down with the dust, and the removal rate of SO3 by air preheater and electrostatic precipitator is 10% to 15%. In the wet desulfurization tower, part of the SO3 will become the H2SO4 aerosol into the desulfurization slurry, which will account for 30% to 40%. The common removal rate of SO3 by air preheater, electrostatic precipitator and wet desulfurization is about 45% [6].

The SCR of the power plant is equipped with three layers of vanadium-tungsten catalyst, and the SO2 concentration of the desulfurization inlet of the 2# unit and the SO3 concentration of the desulfurization outlet are monitored. The monitoring results are shown in Table 1.
The low sulfur content of coal was studied through experiments, and it was found that the intensity of the scattered light is inversely proportional to the fourth power of wavelength, and the blue light energy is the highest in the short wave. The plume of the chimney that emits smoke on the reflective side of the sunlight is blue, while the other side of the plume appears yellow.

In most cases, when the concentration of H$_2$SO$_4$ aerosol in the flue gas exceeds 10 ppm (corresponding to a concentration of SO$_3$ of 35.7 mg/m$^3$), visible blue Smokes appear, and the higher the concentration of sulfuric acid aerosol, the thicker the plume color and the longer the plume length, and even fall to the ground in serious cases[7]. According to the research of Liu Xingchuan and Guo Liqiang [8], the amount of coal and sulfur can be determined whether the colored coal plume with SCR denitrification and wet desulfurization produces blue Smoke. When the sulfur content of coal is higher than 1%, it is likely that blue Smoke will appear. The higher the sulfur content, the thicker the blue Smoke and the longer the plume.

The unit # of the power plant has a coal-burning sulfur content of 1.6%-2.1%, and the blue Smoke is obvious; the unit2# has a coal-burning sulfur content of 1.0%-1.3%, and the blue Smoke is slightly; the unit3# has a coal-burning sulfur content of 0.8% to 1.1%, there are few blue Smokes.

### 2.3. Generation of blue Smoke

SO$_3$ has three phases. It is liquid at normal temperature, solid under standard conditions, and gas after heating. In the limestone/gypsum wet desulfurization system, the flue gas temperature is generally above 45°C, SO$_3$ is a colorless gas, SO$_3$ combines with moisture to form sulfuric acid (H$_2$SO$_4$) after wet desulfurization, submicron dust particles in the flue gas, as The condensation center of H$_2$SO$_4$ strengthens the condensation process and forms an aerosol. The chemical equation is:

$$SO_3 + H_2O = H_2SO_4$$

(3)

H$_2$SO$_4$ aerosol scatters light, which is consistent with Rayleigh scattering. The characteristic of Rayleigh scattering is that the intensity of the scattered light is inversely proportional to the fourth power of the wavelength, so the blue-violet light with a shorter wavelength in the solar spectrum is more scatter than the red light with a longer wavelength, and the blue light energy is the highest in the short wave. The plume of the chimney that emits smoke on the reflective side of the sunlight is blue, while the other side of the plume appears yellow.

### 3.3. Control technology of SO$_3$ in the furnace

The control technology of SO$_3$ in the furnace is mainly from the aspects of fuel, combustion process and addition of inhibitor in the furnace.

1. **Control technology of SO$_3$ in the furnace**

The control technology of SO$_3$ in the furnace is mainly from the aspects of fuel, combustion process and addition of inhibitor in the furnace.

2. **Control of blue Smoke**

   - **SO$_3$ removal technology** mainly includes reducing coal-burning sulfur, performing boiler combustion adjustment, spraying alkaline substances in the furnace, spraying alkaline substances after the furnace, adjusting the ratio of denitrification catalyst, spraying ammonia before the dust collector, and installing the low-temperature economizer. Using low-temperature electrostatic precipitator technology, etc. Several methods commonly used are briefly introduced.

   - **Control technology** of SO$_3$ in the furnace

The control technology of SO$_3$ in the furnace is mainly from the aspects of fuel, combustion process and addition of inhibitor in the furnace.

In the fuel mixing technology, low sulfur coal is added into the fuel to reduce the sulfur content of each kind, so as to reduce the generation of SO$_2$ and SO$_3$ in the flue gas. Through experiments, Lou qinggang [10] proved that the generation rate of SO$_3$ in the boiler increased with the increase of sulfur content in the coal. The advantage of the fuel mixing technology is that it can reduce the SO$_3$ concentration in the upstream air preheater of the flue gas, thereby reducing the temperature of the air.
preheater and improving the energy utilization rate, but also needs to consider the problem of slagging in the furnace and equipment wear.

Spray alkaline substances in the furnace. Injecting alkaline substances into the furnace has been proved to be an effective measure to reduce $SO_3$ [10]. By reacting with $SO_3$, the conversion of $SO_3$ in the furnace is reduced by 40%-80%, effectively reducing the concentration of $SO_3$ at the boiler outlet. [11]. Commonly used alkaline substances are mainly calcium hydroxide, calcium carbonate, magnesium hydroxide and other additives [12].

Burning adjustment. In the actual combustion process, the generated $SO_3$ can also be controlled by controlling factors such as excess air ratio and combustion temperature. This method can not only greatly reduce the content of $SO_3$, but also reduce the content of $SO_2$[6]. In the combustion process, the larger the air excess coefficient, the higher the combustion temperature, and the higher the generation of $SO_3$. Under the premise of ensuring combustion, reducing the air excess coefficient is beneficial to suppress the formation of $SO_3$.

### 3.2. Spraying alkaline substances after the furnace
Spraying alkaline substances behind the furnace can reduce the corrosion of $SO_3$ to the air preheater and effectively reduce $SO_3$ emissions [13-15]. In general, to control the discharge of $SO_3$, the injection position of the alkaline substance should be set behind the air preheater. However, for units with low temperature corrosion of air preheaters, the injection point of the absorbent should be selected upstream of the air preheater, and the necessary air preheater cleaning device should be installed. If an alkaline absorbent is sprayed before the precipitator, the influence on the precipitator must be considered, such as the increase in the dust concentration at the inlet of the precipitator and the change in the specific resistance of the soot. With typical CFB and NID processes, the $SO_3$ removal rate can reach 80% ~ 90%[8].

### 3.3. Install low temperature economizer or heat medium gas and gas heat exchange device
Add a low temperature economizer or a heat medium gas heat exchange device (MGGH) in front of the electrostatic precipitator so that the flue gas inlet temperature of the precipitator is lower than the acid dew point temperature (the minimum temperature should meet the requirements of wet desulfurization temperature ), thereby making the flue gas The middle $SO_3$ condenses into a sulfuric acid mist and adheres to the surface of the dust, and reduces the dust specific resistance to improve the dust removal efficiency and achieve $SO_3$ removal[16-18]. The efficiency of $SO_3$ removal has been reported to reach 95% [19].

### 3.4. Wet electrostatic precipitator
Wet electrostatic precipitator: It uses liquid to flush the dust-collecting surface for cleaning. According to the difference of anode type, it can be divided into metal plate wet electrostatic precipitator, conductive glass steel wet electrostatic precipitator and flexible anode wet electrostatic precipitator [20]. Compared with the traditional electrostatic precipitator, the wet electrostatic precipitator has less influence on the dust specific resistance and coal ash properties, and there is no secondary dust caused by vibrating cleaning. It is suitable for treating high temperature and high humidity flue gas, and can effectively collect $SO_3$ mist [21 ].

### 4. Conclusion
4.1. The blue Smoke phenomenon of coal-fired power plants is mainly caused by $H_2SO_4$ aerosol. The content of $SO_3$ in flue gas with the popularization of domestic installed capacity and flue gas denitrification technology, the content of $SO_3$ in flue gas has been significantly increased, which seriously threatens the operation safety of the unit and endangers human health.
4.2. The blue Smoke of coal-fired power plants can be removed by various methods. In actual treatment, the treatment process can be reasonably selected according to the actual situation of production.

4.3. At present, the developed countries such as the United States, Japan and Germany have clearly defined the SO$_3$ emission limits in coal-fired power plants. There is no legal regulation in China for the control of SO$_3$ in coal-fired power plants. It is recommended to combine the current ecological environment. On the basis of the full-scale technical and economic research, the relevant laws have introduced relevant laws to limit the emission of SO$_3$ in coal-fired power plants.

References:
[1] Ministry of Environmental Protection of the People's Republic of China. (2015) Air Pollutant Emission Standards for Thermal Power Plants (GB13223-2011) [S]. Beijing: China Environmental Science Press.,
[2] National Development and Reform Commission of the People's Republic of China. (2014) Coal-fired energy conservation and emission reduction upgrade and transformation action plan (2014-2020) [EB/OL].
[3] Wang Sheng. (2018) Coal-fired power plant non-traditional atmospheric emission control prospects [J]. Beijing, China Electric Power, 51(8): 173-179
[4] State Environmental Protection Administration. (2004) Practical Manual for Pollution Discharge Reporting and Registration [M]. Beijing, China Environmental Science Press.
[5] Hardman, R., Stacy, R., and Dismukes, E. (1998) Estimating sulfuric acid aerosol emissions from coal-fired power plants[C]. DOE-FETC Conference on Formation, Distribution, Impact, and Fate of Sulfur Trioxide in Utility Flue Gas Streams, Pittsburgh.
[6] Wei Hongge, Cheng Xueshan et al. (2012) Discussion on the generation and transformation of SO$_3$ in coal-fired flue gas and its countermeasures[J]. Power generation and Air conditioning, 33(2): 1-4.
[7] Chen Wei, Xu Yueyang et al. (2011) Causes, effects and countermeasures of SO$_3$ in coal-fired flue gas[J]. nanjing, Electric Power Technology and Environmental Protection, 27(3): 35-36.
[8] Liu Xingchuan, Guo Liqiang, (2018) Analysis on the causes,countermeasure and relative judgment mathematical model of blue smoke in the power plant [J]. Shanxi Electric Power, 211(4): 62-65
[9] Lou Qinggang. (2008) Experimental Study on SO3 Formation in Coal Combustion Process [J]. Energy Engineering, 137(6): 46-49
[10] Liu Xiuru, Zhao Yong et al. (2018) Research progress in control and extraction technology of SO$_3$ in coal-fired power plants[J]. Electric Power Science and Engineering, 34(2): 56-62.
[11] Guo Yanpeng, Di Huajuan et al. (2016) Formation of SO$_3$ in coal-fired flue gas and its control measures [J]. China Electric Power, 49(8): 154-156
[12] Han Binjie. (2012) Experimental study on the removal of sulfur-nitrogen mercury flue gas pollutants by composite calcium-based absorbent[D]. Hangzhou, Zhejiang University
[13] Wang Zhi, Jia Yingguang et al. (2005) Formation and hazard of SO3 in coal-fired power station boilers and SCR denitrification [J]. Northeast Electric Power Technology, 9(1-3
[14] Yang Shijiang. (2005) Introduce a flue gas desulfurization technology suitable for China's national conditions - Charged Dry Absorbent Jet Desulfurization System (SDSI) [C], celebrating the 60th anniversary of the establishment of China Institute of Ceramics, National Glass Kiln Technology Seminar Set assembly, beijing
[15] Chen Peng. (2011) Study on removal of SO3 from coal-fired flue gas by calcium-based absorbent[D] Jinan, Shandong University
[16] Zhang Xuhui. (2015) Study on the synergistic removal of fine particles and sulfur trioxide by low-temperature electrostatic precipitator[D]. Beijing: Tsinghua University

[17] Long Hui, Wang Dun, etc. (2012) Characteristics of low-temperature and high-efficiency flue gas treatment technology and its application prospects in China [D]. Journal of Power Engineering, 32(2): 152-158.

[18] Hu Bin, Liu Yong, et al. (2016) Experimental study on the synergistic removal of fine particles and SO3 by low-temperature and low-temperature electrostatic precipitator[J]. China Electrical Engineering Journal, 2016, 16

[19] Guo Jingjuan. (2017) Study on the emission of colored plume in chimney of coal-fired power station[J]. Huadian Technology, 39(1): 74.

[20] Zhong Denan, Zhuang Zehang, Huang Zhijie. Zhong Denan, Zhuang Zehang, Huang Zhijie.[21] (2015) Research and application of the structure of wet electrostatic precipitator[J]. Energy Saving and Environmental Protection, 12:72-74.

[21] Xiong Guilong, Li Shuiqing, et al. (2015) Development of a new type of electrostatic precipitator technology that enhances the removal of PM2.5[J]. Chinese Journal of Electrical Engineering, 9:2217-2223.