Renewable and Sustainable Energy Reviews 73 (2017) 225–235

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Environmental influence and countermeasures for high humidity flue gas discharging from power plants

Ma Shuangchen*, Chai Jin, Jiao Kunling, Ma Lan, Zhu Sijie, Wu Kai

North China Electric Power University (Baoding), College of Environmental Science and Engineering, No. 619, Yonghua Nor.Str., Baoding 071003, China

ARTICLE INFO

Keywords:
Flue gas moisture
Relative humidity
Environmental impact
Smog

ABSTRACT

The source of moisture in flue gas emissions from coal-fired power plant and the impact of high humidity flue gas on the environment were reviewed. Flue gas moisture from fired power plant mainly comes from the release of hydrogen in coal combustion process and water carried by flue gas from wet flue gas desulfurization system. High humidity flue gas emission increases the overall humidity in the lower atmosphere, which is not conducive to the pollutants diffusion in low atmosphere and even affect the local climate around the plant; high humidity flue gas emission promotes the secondary transformation of air pollutants as well, accelerating the hygroscopic aerosol growth, thus aerosol optical characteristics is changed, and atmospheric visibility reduces. As for the power plant itself, high humidity flue gas emission will cause the increase of water consumption, and take away too much latent heat of vaporization, which is adverse to water conservation and heat reuse. High humidity flue gas and other acidic gases such as SO_3 cause low-temperature corrosion of flue at the end of boiler, shortening the operation span of equipment. High humidity flue gas also produces "gypsum rain" after the wet flue gas desulfurization, which is harmful to the surrounding environment. Through research and analysis for high humidity flue gas emission from domestic and foreign coal fired power plants, the authors believe that a significant increase in the relative humidity and a large number of sub-micron particles discharging due to high humidity flue gas emission throughout the lower atmosphere may contribute to continuous smog, thus the quantitative study about the contribution of high humidity to smog is the next focus for the research of high humidity flue gas emission.

1. Introductions

In recent years, smog has hit many cities in China. $PM_{2.5}$ level has exceeded the measurement range. A wide range of continuous smog occurred frequently; the Chinese social and economic developments, as well as people's health, were influenced greatly. Severe smog pollution was paid more concerns, and more questioning and governance thinking were put forward.

There have been considerable studies in the main source of smog causes and sources of pollutants. Jin et al. [1] analyzed Beijing source emission and found that coal, motor vehicles and industrial production are the major source in the local $PM_{2.5}$ pollution, accounting for 29.2%, 26.2% and 23.3% respectively; coal is the main source of $PM_{2.5}$ in the other areas of Beijing-Tianjin-Hebei in China, the coal in Langfang even accounted for more than 50% of $PM_{2.5}$ source. Obviously, the coal-fired flue gas pollution is one of the main sources of smog, according to statistics, among all pollutants discharged into the atmosphere, 90% of SO_2, 70% of smoke dust, 85% of CO_2 came from coal in China every year, of which more than 50% of the pollution came from coal-fired power plants. As a large consumer of coal, coal-fired power plants have become a key regulatory area of air pollution control in China. In September 2014, ultra-low emissions standard for newly built power plants (The concentration of emission of dust, SO_2, NOx should not exceed 10, 35, 50 mg/m^3 respectively) has been cleared after the "action plan" is issued by three ministries. On December 2, 2015, the State Council decided to fully implement the ultra-low emissions and energy-saving transformation of coal-fired power plants. The strict control has led to significant decline in air pollution emissions. According to the monitoring by environmental protection department, compared with 2014, the concentration of SO_2, NO_2, PM_{10}, and $PM_{2.5}$ has decreased by 38.1%, 11.8%, 12.3%, 6.2%. Although China pollutants have been effectively controlled, the smog is still emerging, why? Smog control cannot simply stay in the level of pollutant control. Although the environmental pollution is the internal cause of smog pollution, the large emission discharge large has made the environmental capacity near saturation, adverse weather condi-

* Corresponding author. Tel./fax: +863127522714.
E-mail address: msc1225@163.com (M. Shuangchen).

http://dx.doi.org/10.1016/j.rser.2017.01.143
Received 15 May 2016; Received in revised form 9 November 2016; Accepted 20 January 2017
1364-0321/

tions is often a decisive factor in the formation of smog days as external cause in the case of relatively stable emission sources [2,3], in which high relative humidity of the atmosphere is the important reason for stable and continuous smog.

Through the annual variations of smog days in Tianjin area exploration into the influence of meteorological factors on smog days annual variation, Mei [4] found the humidity is the main factor that influences smog days in Tianjin，China; The study of Tong [5] showed that the higher relative humidity is benefit to the occurrence of smog, and the visibility and relative humidity were negatively correlated; Yin et al. [6] found the positive correlation between smog and water conditions (precipitation and humidity) has significantly strengthened, the increase of relative humidity will lead to the enhancement of the moisture absorption of aerosol particles, which is a key control factor of smog weather; through the monitoring and analysis in the relationship between different meteorological factors and smog weather in Beijing, Quan et al. [7] found that the decrease in atmospheric visibility caused by the increase in relative humidity and aerosol concentration is the main cause of smog.

In China, 90% of the power plants use limestone - gypsum wet flue gas desulfurization system (WFGD) to remove SO_2, average humidity of the atmosphere is only 9 g/Nm^3, the humidity of flue gas after desulfurization is generally 100–200 g/Nm^3[8], which is over 10 times higher than the average humidity of the atmosphere. It is estimated that flue gas wet desulfurization brings about 1 t of water per ton of coal. Given this data, wet flue gas desulfurization of coal fired boiler discharge about 40 t of water vapor into the atmosphere annually in China [9]. Such a huge amount of water vapor into atmosphere will lead to the increase in relative humidity. But the environmental impact of high humidity flue gas is rarely studied at home and abroad. In addition, after being discharged, a large number of sub-micron particles carried in the high humidity flue gas become nucleus of water vapor condensation, which is exacerbating the formation of smog.

This article summarizes the sources of water in the flue gas in coal-fired power plants and reviews the research progress of high humidity flue gas. The author expounds the influence of high humidity flue gas emission on the environment and put forward the countermeasures and suggestions.

2. Source of water in the flue gas

Early studies have shown that static wind, inversion layer, pollution sources constitutes necessary conditions of the existence of smog [10]. With further research, however, high humidity environment is gradually being concerned [4–7]. The emission of high humidity flue gas from coal-fired power plants is a very important factor to increase the humidity of the atmosphere, thus it has become the focus of attention.

The content of water vapor in the flue gas of coal-fired power plant is 12–16% [11]; the main source of moisture in flue gas mainly comes from coal combustion and wet desulfurization system. In addition, flue gas denitrification systems and wet dust collector can also increase humidity of flue gas, but the amount of water is much lesser than that produced by coal and wet FGD system.

2.1. Combustion of coal

Water vapor is a major product of coal combustion. For different types of coal, quality of coal and unit capacity, the water vapor content in the coal combustion products differs. The volume fraction of water vapor in the flue gas generated by coal combustion is 10–12% in the lignite fueled power plant; while water vapor content is 7–10% when the fuel is coal. The volume of flue gas generated by the combustion of 1 kg coal theoretically is called theoretical flue gas volume, including CO_2, SO_2, NO_x and water vapor, etc. In the theoretical flue gas volume, a part of the water vapor is the product of the reaction of hydrogen and oxygen in coal, and another part is from the evaporation of moisture in raw coal, and a small fraction is brought from the oxidation air [12].

Hydrogen is the second most important constituent in coal elements, which exists in the form of organic and inorganic hydrogen. The hydrogen content decreased with the increase of carbon content in coal. When the carbon content is between 80% and 86%, the hydrogen content is the highest [13]. The occurrence state of moisture in coal is divided into two kinds [14]: one is combined with mineral water, called combined water or crystal water. For example, the crystal water in gypsum ($CaSO_4·2H_2O$) and kaolin ($Al_2O_3·2SiO_2·2H_2O$) combines with mineral in the form of chemical compound. This part of the water can hardly be decomposed or precipitated at less than 200 °C. For example, the two molecules of crystal water in $CaSO_4·2H_2O$ can be completely removed when it reaches more than 500 °C. Water in industrial analysis does not include the crystal water. Another type of water is related to the organic matter of coal in physical form, that is, moisture is present in coal in the form of adhesion and adsorption etc., which is referred to as free moisture. These free moisture can be completely removed after a certain time of evaporation at 105 °C–110 °C. The boiler temperature can reach 1000 °C, at which temperature the free moisture and the crystal water can be completely removed. In addition, to ensure full combustion of the fuel, oxidation air is blown to the boiler in the form of primary air and secondary air, which will also bring a small amount of moisture. Sheng [12] revised the formula for calculating the volume of water vapor produced by coal combustion, shown as Formula(1), coal quality parameters of different coals are listed in Table 1 [15].

$$VH2O = \frac{0.1111Har + 0.0124War + 0.0161(a - 1)Vo}{3.6} \quad (1)$$

where, H_{ar} represents coal hydrogen as received basis; W_{ar} represents coal moisture as received basis; a represents excess air coefficient at dust collector outlet; V_o represents theoretical oxidation air of 1 kg coal combustion m^3/kg.

2.2. Moisture brought by Wet desulfurization system

Wet flue gas desulfurization (WFGD) is the most mature and widely used flue gas desulfurization technology at home and abroad. Fig. 1 is the water balance model of wet FGD system [16,17]. In the desulfurization process, due to the high temperature flue gas in desulfurization tower, part of the water in the slurry will vaporize to form saturated water vapor at the time when gas contact liquid. In addition, the flue gas also carries a large number of small water drops. Then flue gas goes through the mist eliminator in the top of the absorption tower for the removal of the slurry and water mist from flue gas, and then finally discharged to the atmosphere through the chimney. Under normal conditions, the droplet concentration in the flue gas at the outlet of the mist eliminator is lower than 75 mg/Nm^3. However, in the actual operation process, the efficiency of mist eliminator will be decreased [18] by the boiler ash, flue gas flow rate and other effects. In addition,

Table 1
Coal quality parameters of common coal.

Coal	H content%	Full water%	Air dry base moisture%	The actual coal consumption t/h	Excess air coefficient	Theoretical wind volume m^3/kg
lignite	3.28	29.6	14.2	380	1.19	4.15
Bituminous coal	2.84	3.78	1.89	284	1.19	4.99