Analysis on Feasibility of Applying Low-Temperature Emission to Coal-fired Power Plant in Cold Weather

Jian Wang*, Yi Liu, Guangri Li, Dongdong Sun, Yi Qu, Yunfei Lai
Electric Power Research Institute, State Grid Jilin Electric Power Co., Ltd., Changchun 130021, China

Abstract: After the ultra-low emission (ULE) transformation, the emissions of ULE coal-fired power plants in China have been reduced greatly. However, considering the total amount of emissions, coal-fired power plants are still among the largest sources. And there may still have great potential in the removal of colored plume and some unconventional pollutants such as condensable particles matter (CPM) and sulfur trioxide (sulfuric acid mist). Though in cold days, hazes occur frequently. Besides, low-temperature condensation is conducive to the condensation and removal of vapor, CPM and sulfur trioxide in the flue gas. In this paper, a new method of low-temperature flue gas emission is proposed for coal-fired power plants in severe cold areas. The flue gas is cooled by ambient air, and discharged without reheating, and remarkable effects can be achieved in removing the pollutants. The technical feasibility and environmental compliance of applying this method to a power plant in cold weather have been analyzed. The results show that low-temperature emission of flue gas for coal-fired power plants in winter is effective in water-saving, emission reduction of pollutants and elimination of wet plume.

1 Introduction

China’s primary energy resources and its vision of “carbon neutrality” determine that coal power will continue to play a basic role in the form of pondage type power supply in China. [1] After the ultra-low emission (ULE) transformation, the emission concentration of conventional pollutants from coal-fired power plants will reach the lowest level in history, and further emission reduction will be not cost-effective.

Condensable particles and sulfur trioxide (sulfuric acid mist) have become new targets for pollutant emission reduction of coal-fired power plants. The above pollutants mainly exist in gaseous form in the flue gas, and will precipitate due to low-temperature condensation [2] after entering the atmospheric environment.

In northern China’s colder winters, the units will run at high load so as to meet the need for heating and thus the pollutant emission will become intense; meanwhile, temperature inversion is frequently seen in autumn and winter, and poor meteorological conditions make it difficult for pollutants to diffuse, so smog is frequently seen. Enterprises are facing external pressure of “stopping or restricting production”. In addition, in order to achieve flue gas water recovery and white plume control, some power plants in coastal areas are testing emission of the flue gas after condensation and reheating [3-5].

Based on the above factors, this paper proposed a method of low-temperature flue gas emission in autumn and winter (heating period) for coal-fired power plants in severe cold areas, and then demonstrated the technical feasibility of this method.

2 Low-temperature Flue Gas Emission

2.1 Technical Principles

Low-temperature flue gas emission is to lower the temperature of the flue gas, so that water vapor, sulfuric acid mist and condensable particles in the flue gas are separated out by demister and other devices, and removed in the form of flue condensate, and then, the flue gas is directly discharged through the chimney at a slightly higher ambient temperature.

According to the heat exchange mode, flue gas condensation methods can be divided into direct heat exchange condensation and indirect heat exchange condensation; according to the cooling source, it can be divided into water cooling, air cooling and heat pump cooling; according to the circulation mode of the cooling source, it can be divided into open circulation and closed circulation.

2.2 Compliance

At present, flue gas condensation is often combined with reheating to lower the temperature of “clean flue gas” to 40℃ first and then reheat it to 70℃ for discharge, which can achieve flue gas water recovery, and removal of sulfur trioxide (sulfuric acid mist), condensable particles
and other pollutants, and also eliminate “wet plume” without changing the operation parameters of existing equipment in coal-fired power plants. There is no need to recheck the whole boiler flue gas, air and pulverized coal system; low-temperature corrosion, leakage and other problems can be avoided during operation, and at the same time, potential environmental compliance problems can be avoided. The reason is that although the emission concentration and total amount of pollutants are reduced, the reduction of flue gas temperature may lead to the deterioration of pollutant diffusion conditions and changes in compliance results of prediction about impact on the atmospheric environment in the original environmental impact assessment.

There have been no specific numerical requirements for emission parameters of flue gas in the current relevant regulations, standards and design specifications for coal-fired power plants. With the continuous improvement of environmental protection facilities of coal-fired power plants in recent years, the emission parameters of flue gas have also changed greatly. For example, after the installation of wet desulfurization equipment, the flue gas temperature at the inlet of the chimney decreases from 150°C to 80°C [6], and the moisture content increases. After that, the power plants gradually cancelled the installed Gas-Gas Heater (GGH), and strengthened the anti-corrosion transformation of the existing wet chimney [7] for the direct use of saturated wet flue gas emission.

Emission parameters of flue gas are restricted by two major conditions:

1) the safety of chimney, such as thermal stress, and leakage and corrosion of the shell (related to residual static pressure and corrosive effects of flue gas);
2) the pollutant diffusion meets the air quality standard requirements in the environmental impact prediction results. The effects are as follows: a) Lowering flue gas temperature is not conducive to its diffusion. The maximum rate of the ground concentration of pollutants increases. b) The lower the flue gas temperature, the better effects can be achieved in precipitation and removal of water vapor, sulfur trioxide (sulfuric acid mist) and condensable particles in the flue gas.

At the same time, the emission concentration of conventional pollutants has been greatly reduced compared with the legal limit and design value of ULE units, which lays a good foundation [8].

Therefore, this paper proposed the flue gas condensation and low-temperature direct emission method. Taking 300 MW unit as an example, we have conducted on-site simulation experiments to evaluate the pollutant emission reduction effect, and analyzed the compliance through ambient air quality model to test the feasibility.

3 Experiments (Effects of Temperature on CPM Precipitation in Flue)

3.1 Test Units

The research object is a thermal power plant in Jilin Province, with two 330 MW coal-fired units installed. The ULE transformation was completed in 2017. Its flue gas treatment process is of low nitrogen burner + SCR denitration + electrostatic precipitator (ESP) + wet desulfurization (FGD) + wet electrostatic precipitator (WESP). The only air pollution source of the project is a point source, that is, the chimney of the power plant, with a height of 210 m, an inner diameter of 7 m and an altitude of 188 m. During the test, the unit load should keep stable (with a fluctuation of less than 5%), and the blending ratio of the coal as fired should remain unchanged.

3.2 Sampling and Sample Processing

The sampling points are set in the flue between the WESP outlet and the chimney inlet. Before sampling, the O2 content, moisture content, flue gas temperature and other parameters in the flue gas are measured; a soot sampler (Wuhan Tianhong TH-880W) is used for isokinetic tracking sampling, and a Dekati PM2.5 impactor train is used to determine the concentration of PM10 and PM2.5 in the clean flue gas of the units; a CPM condensing device is connected in series between the electric tracing smoke sampling gun and the sampler to measure the CPM concentration. The whole set of sampling device is as shown in Fig. 1.

The self-made device by Yang et al. [9] has been referred to for the CPM condensation sampling device. In order to control the condensation temperature, a large condensate storage tank is connected with the water bath, and windshield washer for vehicles is used as the coolant; the filter flask is replaced by a dry impact bottle with scale. The flue gas with filterable particulate matter (FPM) filtered enters the secondary spiral condenser, and the coolant of 30°C (USEPA method 202), 20°C, 10°C, 0°C, -10°C and -20°C is injected into the condenser respectively. In order to fully condense and collect the CPM, the residence time [10] of the flue gas in the condensing state is very important. It is estimated that the volume of the condensing device is 1.05 L and the flue gas flow rate at the sampling point is 12.5 m/s. When sampling nozzles of 6, 8, 10 and 12 mm are used respectively, the corresponding residence time is as shown in Table 1. See Table 2 for residence time of the flue gas in a typical pollutant treatment facility of coal-fired units. Considering that the residence time of 6 mm sampling nozzle is equivalent to that of wet desulfurization device, we have selected 6 mm sampling nozzle for the experiments.

The sampling time of each group of samples is 20 min, and the sampling volume is recorded after sampling. After each sampling, the sampling gun, spiral condenser and connecting pipeline shall be rinsed with ultrapure water and n-hexane respectively. Each group of samples
collected on site includes condensate, ultrapure rinsing solution and n-hexane solution. Three groups of samples are collected at each sampling point.

### Table 1 Residence time in condensing system with sampling nozzles of different sizes

<table>
<thead>
<tr>
<th>Size of integrated nozzle for soot of low concentration/mm</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°C</td>
<td>4.45</td>
<td>2.51</td>
<td>1.60</td>
<td>1.11</td>
</tr>
<tr>
<td>20°C</td>
<td>4.60</td>
<td>2.59</td>
<td>1.66</td>
<td>1.15</td>
</tr>
<tr>
<td>10°C</td>
<td>4.77</td>
<td>2.68</td>
<td>1.72</td>
<td>1.19</td>
</tr>
<tr>
<td>0°C</td>
<td>4.94</td>
<td>2.78</td>
<td>1.78</td>
<td>1.24</td>
</tr>
<tr>
<td>-10°C</td>
<td>5.13</td>
<td>2.89</td>
<td>1.85</td>
<td>1.28</td>
</tr>
<tr>
<td>-20°C</td>
<td>5.33</td>
<td>3.00</td>
<td>1.92</td>
<td>1.33</td>
</tr>
</tbody>
</table>

### Table 2 Residence time of flue gas in a typical pollutant treatment facility

<table>
<thead>
<tr>
<th>Pollutant-treatment facilities</th>
<th>Denitration</th>
<th>Electrostatic precipitator</th>
<th>Wet desulfurization</th>
<th>Wet electrostatic precipitator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residence time of flue gas/s</td>
<td>1.8</td>
<td>16.1</td>
<td>4.5</td>
<td>9.6</td>
</tr>
</tbody>
</table>

![Fig.1 Schematic of CPM Sampling Train](image)

Weigh the weight gain \(m_1\) of the integrated sampler for soot of low concentration before and after sampling (Mettler MS105DU, Switzerland).

Measure and record the volume of condensate collected \(V_1\).

Combine the condensate and ultrapure rinsing solution; Add 30 mL n-hexane solution, and conduct ultrasonic extraction in the separation funnel for 2 min; the experiment is performed in triplicate. Take the n-hexane solution after extraction, transfer it to a watch glass of constant weight, and put it into the fume hood to volatilize to the constant weight; and then put the watch glass into the dryer for 24 hours to constant weight. Weigh it every 6 hours, and the mass difference shall be not more than 0.5 mg, and the result is accurate to 0.1 mg. The weight gain of the watch glass \(m_2\) is the amount of CPM organic matter.

The volume of the extracted inorganic phase is fixed to 100 mL. Transfer 50 mL to a watch glass of constant weight, which is titrated with 0.1 N NH\(_4\)OH solution to pH = 7, evaporated to no less than 10 mL at 105°C, and cooled at room temperature. Then, transfer the watch glass to a dryer for 24 hours to constant weight. Weigh it every 6 hours, and the mass difference shall be not more than 0.5 mg, and the result should be accurate to 0.1 mg. Weight gain of the watch glass minus weight gain caused by titration \(m_c = 17.03 \times V_{\text{Titrated}} \times N\), and the weight gain obtained \(m_3\) is 1/2 of the mass of CPM inorganic matter.

Combined with the sampling volume and flue gas parameters, the mass concentrations of FPM, CPM Organic, CPM Inorganic and CPM in the flue gas are calculated.

Ultrasound treatment is conducted to the remaining 50 mL for 6 min, and then use 0.45 μm membrane for filtration, after which the concentration of sulfate ion is measured (Dionex DX-600, USA).
3.3 Sampling Results and Analysis

Table 3 Mass concentration values of CPM and sulfate ions at different temperatures

<table>
<thead>
<tr>
<th>Condensate temperature/℃</th>
<th>Captured CPM mass concentration</th>
<th>Captured mass concentration of sulfate ions</th>
<th>Condensate volume/(mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30℃</td>
<td>5.19</td>
<td>1.35</td>
<td>19.3</td>
</tr>
<tr>
<td>20℃</td>
<td>5.31</td>
<td>1.46</td>
<td>25.7</td>
</tr>
<tr>
<td>10℃</td>
<td>5.44</td>
<td>1.56</td>
<td>29.3</td>
</tr>
<tr>
<td>0℃</td>
<td>5.63</td>
<td>1.63</td>
<td>31.3</td>
</tr>
<tr>
<td>-10℃</td>
<td>5.90</td>
<td>1.64</td>
<td>31.6</td>
</tr>
<tr>
<td>-20℃</td>
<td>5.97</td>
<td>1.69</td>
<td>31.7</td>
</tr>
<tr>
<td>FPM</td>
<td>1.72</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

4 Results and Analysis

For units in service, the chimney height and the inner diameter of outlet cannot be changed. There are two major factors that can change the emission parameters of flue gas [11-12]:

1. Make them meet the requirements of environmental protection regulations. For example, it shall be conducive to the diffusion of pollutants to meet the requirements of environmental impact assessment. The outlet flow rate shall not be too small or too large to cause plume downwash or chimney rain; (2) Keep the safe operation of chimney. During operation, excessive residual static pressure from chimney should be avoided to minimize the damage from corrosion caused by flue gas.

This paper analyzes the influence of flue gas emission at a low temperature from the above two aspects.

4.1 Impact on Safe Operation of Chimney

The influence of flue gas temperature on chimney is mainly divided into: 1) temperature effects; 2) change of corrosive effects of flue gas.

4.1.1 Temperature effects

A lower flue gas temperature reduces the temperature difference between the flue gas in the chimney and the ambient temperature, and reduces the axial and circumferential temperature stress of the shell, especially the liner and the horizontal displacement caused by the temperature difference of the shell. [13] Compared with the original flue gas emission mode, it makes the chimney safer.

4.1.2 Corrosive effects of flue gas

At present, wet flue gas emission is most frequently used in coal-fired power plants, that is, the saturated wet flue gas after wet desulfurization or wet desulfurization plus wet electrostatic precipitator is directly discharged into the atmosphere without reheating. Since the flue gas temperature is lower than the dew point of the flue gas, sulfur trioxide is easy to condense on the inner wall of the chimney. Therefore, the anti-corrosion design of the chimney plays an important role in the long-term safe operation of the chimney.

The corrosiveness grade of flue gas is the main basis for chimney type selection and anti-corrosion design, which is related to flue gas composition and content, flue gas temperature and flue gas relative humidity.

Reducing the flue gas temperature is conducive to alleviating the corrosion problem caused by the emission of desulfurized wet flue gas from the chimney. There are three reasons:

1. Sulfur trioxide and salts in flue gas have been condensed and separated, and the total amount of corrosive ions has been reduced.
2. The moisture in flue gas is greatly reduced, which is conducive to eliminating the dry and wet alternative environment that accelerates the corrosion process of metal materials and reinforced concrete.
3. The temperature in the chimney decreases and the chemical reaction rate decreases.

It should be pointed out that additional booster fans may be required since the air density is close to the flue gas density in winter, which results in the fact that self-pulling force of the chimney is not enough to overcome the friction resistance. Because of the additional booster fans, there will be large residual static pressure (positive pressure) in the chimney. Due to low corrosiveness of the flue gas, there will be a lower risk of leakage and corrosion of the chimney shell.

4.2 Pollutant Emission Reduction and Prediction about Impact on Atmospheric Environment

4.2.1 Benefits of pollutant emission and reduction

Under normal conditions, the pollutants at the main flue gas outlet of the unit include SO₂ (12.72 g/s), NOₓ (19.32 g/s), PM₁₀ (0.97 g/s), PM₂.₅ (0.85 g/s), and TSP (1.01 g/s); The outlet temperature of chimney is 45℃, and the outlet velocity of flue gas is 17.78 M/s.

Since CPM is converted into primary PM 2.5 after being discharged into the atmosphere, and the ambient
temperature is low in winter, PM$_{10}$, PM$_{2.5}$, and TSP source intensity at different flue gas temperatures in this table are all included in the CPM concentration (concentration of the CPM discharged into the atmosphere is the difference between the CPM concentration at -20°C and the CPM concentration at the current flue gas temperature).

See Table 4 for flue gas outlet velocity, source intensity and emission reduction ratios relative to initial flue gas temperature (45°C) of coal-fired units at different flue gas temperatures.

Significant emission reduction effects have been seen for PM$_{10}$, PM$_{2.5}$, and TSP. Since the concentration of CPM in flue gas at 45°C is 5.19 mg/m³ (condensation temperature 30°C) ~ 5.97 mg/m³ (condensation temperature -20°C), and the concentration of FPM is 1.72 mg m$^3$, so the concentration of CPM is 3.02 ~ 3.47 times higher than that of the FPM. Consequently, the emission reduction ratios of TSP, PM$_{10}$ and PM$_{2.5}$ are all over 69%.

Low-temperature condensation also has a good emission reduction effect on SO$_3$, which can be up to 25% ~ 42%. The reason may be that the temperature of the clean flue gas is lower than the optimal condensation temperature of SO$_3$ (60°C), and SO$_3$ in the flue gas exists in the form of sulfuric acid mist. With the decrease of the flue gas temperature, the volume of the flue gas shrinks, its flow rate decreases, and a large amount of vapor is condensed, which is conducive to the synergistic removal of sulfuric acid mist.

SO$_2$ and NO$_x$ are gaseous pollutants, and the influence of temperature on them can be ignored.

<table>
<thead>
<tr>
<th>Flue gas temperature (°C)</th>
<th>PM$_{10}$</th>
<th>PM$_{2.5}$</th>
<th>TSP</th>
<th>SO$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>1.57</td>
<td>5.06</td>
<td>5.26</td>
<td>4.27</td>
</tr>
<tr>
<td>30</td>
<td>1.54</td>
<td>7.01</td>
<td>7.14</td>
<td>6.90</td>
</tr>
<tr>
<td>20</td>
<td>1.41</td>
<td>7.27</td>
<td>7.31</td>
<td>7.14</td>
</tr>
<tr>
<td>10</td>
<td>1.28</td>
<td>7.52</td>
<td>7.64</td>
<td>7.35</td>
</tr>
<tr>
<td>0</td>
<td>1.13</td>
<td>7.81</td>
<td>7.94</td>
<td>7.50</td>
</tr>
<tr>
<td>-10</td>
<td>0.93</td>
<td>8.02</td>
<td>8.34</td>
<td>7.80</td>
</tr>
<tr>
<td>-20</td>
<td>0.86</td>
<td>8.37</td>
<td>8.74</td>
<td>8.13</td>
</tr>
</tbody>
</table>

Note: Since CPM is converted into primary PM$_{2.5}$ after being discharged into the atmosphere, and the ambient temperature is low in winter, PM$_{10}$, PM$_{2.5}$, and TSP in this table are all included in the CPM concentration (-20°C).

4.2.2 Eliminate Colored Plume

According to the technical principle of wet plume treatment [14] proposed by Liu et al., direct emission of flue gas after substantial cooling can eliminate white plume due to condensation of a large amount of vapor.

It can be seen from the data in Table 3 that 45 mL of condensate can be collected per cubic meter of flue gas. The amount of flue gas generated by two 330 MW coal-fired units running at full load is about 2.3 million m$^3$/h (standard condition), and the recoverable condensate is about 103 to 170 t/h.

4.2.3 Prediction about Impact on Atmospheric Environment

In this paper, the AERMOD modeling system is used to study the maximum ground concentration of pollutants at different flue gas temperatures in the power plant during winter heating period (from October 20 to April 6 of the next year). The terrain of the assessed area is relatively flat, which is defined as simple terrain according to the guidelines. The terrain data used are from SRTM DEM data set in China, and the ground and upper air meteorological data are from local meteorological departments. See Table 4 for flue gas parameters of pollution sources.
increase is still small. The hourly, daily and monthly ratio increments of SO$_2$ are 6.54%, 4.73% and 4.07% respectively. The hourly, daily and monthly ratio increments of other pollutants are even less than 0.12%.

According to the formula for plume rising height in *Emission Standard of Air Pollutants for Thermal Power Plants* (GB 13223-2003), the effective heights of chimney at different temperatures are calculated, as shown in Table 5.

The common radiation inversion in winter occurs after sunset, with a height of about 200 m to 800 m, and the strongest radiation inversion is before dawn. It disappears from bottom to top after sunrise. It can be seen that most of the time in winter, when the difference between the flue gas temperature at the chimney outlet and the ambient temperature is 10°C, the effective height of the chimney can reach 476m, which is higher than the inversion layer height most of the time.

### 5 Conclusions

To sum up, this paper has proposed a method of low-temperature flue gas emission for coal-fired power plants in severe cold areas in autumn and winter (heating period), and has preliminarily demonstrated that low-temperature flue gas emission can meet the requirements for safe operation of chimneys, and the prediction results of impact on atmospheric environment meet the requirements of relevant environmental protection regulations.

At the same time, the low-temperature emission of flue gas has good effects on synergistic removal and emission reduction of CPM and SO$_3$, and provides a new option in elimination of colored plume and recovery of water resources in flue gas. It can provide a reference for the environmental protection improvement and transformation of coal-fired power units in extremely cold areas.
cold areas. In addition, it should be noted that the flue gas and air system of coal-fired power plants is an integrated whole, and the change of emission parameters of flue gas at the end will inevitably affect the working conditions of front-end boilers, precipitators and other facilities, which should be further studied.

Acknowledgments
This work was supported by the Electric Power Research Institute, State Grid Jilin Electric Power Co., Ltd (KY-GS-18-01-01). The dataset is provided by National Cryosphere Desert Data Center. (http://www.ncdc.ac.cn).

References