Application Research on deep recovery and utilization technology of flue gas waste heat of coal water slurry boiler

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Abstract. Coal water slurry boiler has attracted great attention in the field of urban heat system because of its efficient and clean coal combustion. The coal water slurry contains 35% moisture, which makes the waste heat recovery potential of flue gas greater. After the combustion of coal water slurry, the 100℃unsaturated flue gas becomes 50℃ saturated wet flue gas after Wet Desulfurization Process. The Direct Contact Thermal Storage System and Heat Pump technology are used to realize the deep recovery of low-temperature flue gas. The technology has been successfully applied in the 6×70MW coal water slurry boiler of La Shan Heat Source Company. After 120 days of operation, 393000 GJ of flue gas waste heat is recovered, about 23000 tons of coal water slurry is replaced, and 84000 tons of flue gas condensate is recovered. It has good economic and social utility. It is an effective way to recover and utilize waste heat from flue gas of coal-fired boiler, and has a broad application prospect.

1. Introduction

Energy and environmental problems have been plaguing economic development of China. It is feasible to improve energy utilization and use clean energy. Coal water slurry (CWS) is a new type of coal based fuel, which is prepared by physical processing of 64% low sulfur and low ash clean coal, 35% water and 1% chemical additives. Due to its superior combustion stability and low-temperature combustion characteristics, coal water slurry fluidized combustion technology has been applied in the field of urban heat system[1]. For small and medium-sized coal-fired boilers, the boiler thermal efficiency increases by about 1% when the exhaust gas temperature decreases by 15 ℃ ~ 20 ℃. The heat loss of boiler exhaust gas is the largest of all heat losses[2].

In this project, the water vapor volume of coal water slurry boiler flue gas is about 1 / 3 higher than that of conventional coal-fired boiler, and the flue gas with the same temperature contains more heat. Using the "Integrated Technology Of Flue Gas Waste Heat Recovery And Emission Reduction Based On Spray Type Heat Exchange"[5], the heat pump type flue gas waste heat deep recovery technology coupled with spray type heat exchanger and direct fired heat pump is used[3,4]. The flue gas temperature is reduced to below the dew point temperature, so that the thermal efficiency can be increased by more than 10%. Meanwhile, the flue gas condensate can be recovered to save water resource.
2. General Situation of the System

There are 6×70MW coal water slurry circulating fluidized bed hot water boilers in the plant area of La Shan heat source branch. Each boiler is equipped with SCR denitration and bag filter. The flue gas of six boilers is discharged into the atmosphere after entering the chimney through two sets of limestone wet desulfurization system and wet electrostatic precipitator. See Table 1 for boiler parameters.

In the project, a direct contact heat exchanger (spray tower) is equipped at the outlet of two desulfurization towers. The wet flue gas of about 50 ℃ enters the spray heat exchanger from the desulfurization tower, and directly contacts with the low-temperature spray water (intermediate water) produced by absorption heat pump. The exhaust gas temperature is reduced to 25 ℃, and the gas driven absorption heat pump extracts the residual heat in the spray water (intermediate water) and heats the existing heat source plant Water supply of primary pipe network. The water condensed from the flue gas passes the test of the water treatment device and becomes the supplementary water for the heat supply network.

Table 1. Main parameters of boiler

| Name                                    | Specification and model          |
|-----------------------------------------|----------------------------------|
| Boiler model                            | QXF70-1.6/130/70-J               |
| Rated power (load range)                | 70 MW (30%~110%)                 |
| Rated water flow (regulation range)     | 1000 t/h (500t/h~1100t/h)        |
| Boiler efficiency (%)                   | 0.905                            |
| Boiler exhaust gas temperature          | 115 ℃                           |
| Fuel consumption                        | 17319 kg/h                       |
| Rated flue gas volume                   | 140000Nm³                       |
| Supply / return water temperature       | 130℃/70℃                        |
| Supporting environmental protection     | SCR Denitrification              |
| equipment                               | Cloth-bag Dusting                |
|                                        | Desulfurized Smoke with FGD     |
|                                        | Wet electrostatic precipitation  |

3. Theoretical calculation of flue gas residual heat

Coal water slurry contains about 34% moisture, which makes it different from coal combustion. Based on the industrial analysis of coal water slurry designed by La Shan heat source company, the composition of flue gas is calculated. The industrial analysis is shown in Table 2.

Table 2. Industrial analysis of coal water slurry

| Serial number | Name/Unit | design value |
|---------------|-----------|--------------|
| 1             | Car %     | 49.44        |
| 2             | Har %     | 3.27         |
| 3             | Oar %     | 7.13         |
| 4             | Nar %     | 0.93         |
| 5             | Sar %     | 0.65         |
| 6             | Aar %     | 7.68         |
| 7             | Mt %      | 32.9         |
| 8             | Qnet,ar MJ/kg | 17.97     |

3.1 Volume calculation of flue gas components

The boiler is arranged indoors. The average temperature in winter is 10 ℃, the air humidity is 10g / kg, the steam density is 0.804kg/nm³, and β is the boiler excess coefficient, which is 1.4. The components of flue gas after combustion are calculated, as shown in the table below.
Table 3. Volume composition of flue gas

| Name                        | Calculation formula                                      | Data result |
|-----------------------------|----------------------------------------------------------|-------------|
| Theoretical air volume \( V^o \) | \( 0.0889 (\text{Car}+0.375\text{Sar}) +0.265\text{Har}-0.033\text{Oar} \) | 5.14 Nm³/kg |
| Volume of triatomic gas \( V_{RO2} \) | 0.01866 \text{Car}+0.007 \text{Sar} | 0.93 Nm³/kg |
| Actual water vapor volume \( V_{H2O} \) | 0.0124\text{Mar}+0.111 \text{Har}+0.0161\beta V^o | 0.89 Nm³/kg |
| Volume of nitrogen in flue gas \( V_{N2} \) | 0.008\text{Nar}+0.79\beta V^o | 5.69 Nm³/kg |
| Oxygen volume in flue gas \( V_{O2} \) | 0.21 (\beta-1) \( V^o \) | 0.43 Nm³/kg |
| Actual total volume of flue gas \( V_y \) | \( V_{RO2}+V_{N2}+V_{O2}+V_{H2O} \) | 7.94 Nm³/kg |

3.2 Calculation of flue gas waste heat

The design exhaust gas temperature of the boiler is 115 °C, and the actual operation is about 125 °C. Considering that the exhaust gas temperature is reduced to 25 °C (the temperature at the chimney sampling point), the temperature difference is 100 °C. There is no bottom slag in the combustion process of coal water slurry, and quartz sand is added less than fly ash, which means that the ash content of coal water slurry is all in the fly ash. The sensible heat and latent heat of flue gas components are 1095.1kj/kg and 1717.3kj/kg, respectively. The maximum theoretical recovery heat of boiler at full load is 13.2mw.

4. Overview of waste heat system process

The flue gas waste heat deep recovery system is mainly composed of absorption heat pump, spray heat exchanger, circulating pump and intermediate water treatment device.

4.1 Intermediate water circulation system

After the heat exchange between spray circulating water and flue gas is completed, the temperature rises from 20 °C to 40 °C. After the temperature is reduced from 40 °C to 20 °C, it is sent back to the spray tower to exchange heat with flue gas again to form a cycle.

4.2 Absorption heat pump system

The 40 °C spray circulating water enters the absorption heat pump evaporator as a low-temperature heat source, after extracting the waste heat, it is cooled to 20 °C and returned to the spray tower; the driving heat source of the absorption heat pump in this system is natural gas, and the flue gas formed after the heat pump utilization enters the heat pump spray tower and is discharged into the chimney after the waste heat recovery; the return water of the pipe network at 45 °C is led out to the absorption heat pump after being pressurized by the circulating pump Heat to 90 °C and then to the main water supply pipe of the pipe network.

Table 4. Main equipment parameters of heat pump

| Name                        | Unit   | Parameters |
|-----------------------------|--------|------------|
| quantity of heat            | kW     | 30255      |
| Number of heat pumps        | Number | 4          |
| Heat supply network water   | °C     | 45/90      |
| (single set)                | t/h    | 578.1      |
| Heat source water           | °C     | 40/20      |
| (single set)                | t/h    | 537.4      |
| Gas consumption per unit    | Nm³/h  | 2100       |
4.3 Flue gas system
In this system, the direct contact heat exchanger (spray tower) is used to cool the wet flue gas at 50 ℃ behind the desulfurization tower to 25 ℃. A spray tower is arranged behind the desulfurization tower. The wet flue gas after desulfurization enters the spray tower for deep cooling and condensation, and then enters the inlet of the original wet electrostatic precipitator. A boiler reheater (reserved position) is arranged behind the wet electrostatic precipitator, and finally enters the original chimney for exhaust after online monitoring.

![Fig.1 System diagram](image)

4.4 Water treatment system
The overflow tank of the spray tower is equipped with water treatment and automatic dosing device. According to the pH value of the spray water pipeline system, the acid spray circulating water is automatically neutralized by adding alkali solution. The pH automatic control range is 6.8 ~ 7.2. The neutralization water passes through iron removal filter and mechanical filter to remove iron ions, most suspended solids and organic matters to reduce turbidity; then it enters softening treatment through ion exchange resin system, and after passing the test, it is directly injected into the softened water tank through the feed pump.

5. Operation effect analysis

5.1 Single machine performance debugging and whole system debugging

5.1.1 Single machine full load test

![Fig. 2 Flow chart of flue gas system](image)
In this project, the supply and return water temperature of intermediate spray water is 40 / 20 °C. Due to the installation of three boilers and one tower, the test cannot reach the full load condition of three boilers at the same time, and the actual flue gas volume and flue gas temperature do not reach the design temperature. It is necessary to reduce the amount of intermediate water circulation to ensure that the inlet water temperature of the heat pump is increased, and reducing the intermediate water flow will affect the effect of spray heat transfer. Table 5 shows the full load test of No.4 absorption heat pump on March 5, 2020.

During the test period: the average load of No.4 heat pump unit is 29.28mw, the average waste heat recovery load is 12.51mw, and the average natural gas consumption is 1919nm3/h. Analysis of the test data of No.4 heat pump unit shows that the heating load does not reach 30.3mw, which is due to the low boiler load. The temperature of intermediate water into the heat pump is only 35 °C, while the outlet temperature reaches 19 °C and is lower than 20 °C. If the unit is operating at 90% load, the heating capacity can be increased by 10% if the load reaches 100%. Through calculation, the energy efficiency ratio reaches or exceeds 1.70 of the design.

5.1.2 Debugging of the whole system
From January 13 to January 20, 2020, the absorption heat pump unit, spray tower, intermediate water system, heat supply network water system and condensate treatment device were debugged. During the period, the overall operation of the flue gas waste heat recovery system was stable, with an average flue gas waste heat recovery load of 27.56mw, an average heating load of 69.31mw, a total heating capacity of 41923gj, a waste heat recovery capacity of 16671gj, and an hourly condensate volume of 35t / h. See Table 6.

5.2 Economic analysis of operation
The project will be started in July 2019 and put into operation at the end of November that year. After 120 days of operation, 393000 GJ of flue gas waste heat was recovered, about 23000 tons of coal water slurry was replaced, and 84000 tons of flue gas condensate was recovered. It has good economic and social benefits. The total investment of the project is about 69 million yuan (excluding the reheat system), the annual net income after waste heat recovery is about 13.904 million yuan, and the static investment payback period of the system is about 5 years (social benefits brought by pollutant emission reduction and flue gas bleaching are not considered).

Table 5. No.4 heat pump test data

| Time  | Heat pump heating capacity (MW) | Waste heat recovery (MW) | Gas consumption (Nm³/h) | COP |
|-------|-------------------------------|-------------------------|------------------------|-----|
| 10:00 | 29.46                         | 12.59                   | 1929                   | 1.71|
| 12:00 | 29.33                         | 12.49                   | 1925.1                 | 1.71|
| 14:00 | 29.19                         | 12.54                   | 1904.3                 | 1.72|
| 16:00 | 29.33                         | 12.54                   | 1919.6                 | 1.71|
| 18:00 | 29.19                         | 12.4                    | 1920.1                 | 1.71|
| Average | 29.28                       | 12.51                   | 1919.6                 | 1.71|

Table 6. Summary of operation data

| Serial number | Name                                    | Unit  | Data result |
|---------------|-----------------------------------------|-------|-------------|
| 1             | Boiler heating capacity                 | GJ    | 133771      |
| 2             | Heat supply capacity of waste heat pump | GJ    | 41923       |
| 3             | Waste heat recovery                     | GJ    | 16671       |
| 4             | Gas consumption                         | NM3   | 782121      |
| 5             | Average boiler load                     | MW    | 221.19      |
| 6             | Average load of waste heat recovery     | MW    | 27.56       |
| 7             | Average heating load of heat pump       | MW    | 69.31       |
| 8             | Average gas consumption                 | NM³/h | 4566.48     |
| 9             | Flue gas waste heat recovery system COP |       | 1.701       |
6. conclusion
In order to recover the heat in flue gas after wet desulfurization, a new deep waste heat recovery system is proposed in this paper. Through the combination of direct contact heat exchanger and heat pump, the exhaust gas temperature can be significantly reduced and the latent heat in flue gas can be recovered for heating. At the same time, the condensation water in the flue gas is recovered to eliminate the visual white smoke phenomenon, which has good economic and environmental benefits. The total investment of the system is 69 million yuan (excluding reheat system), and other costs are less than that of absorption heat pump drive energy, natural gas and water pump power consumption. A total of 84000 tons of condensate was recovered in one heating season. After alkali addition and softening treatment, it could meet the water supply requirements of heat supply network. According to the analysis, the net income of a heating season is about 13.904 million yuan, and the static payback period is 5 years. This technology responds to the national policy of environmental protection and energy conservation, and has a broad application prospect.

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