Feasibility study of a coal-fired coupled to biomass power generation technology on a 300 MW unit boiler

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Abstract. This paper describes the characteristics of a coal-fired coupled to biomass power generation technology on a 300 MW unit boiler, the characteristics of the coal-fired coupled to biomass fuel, and the problems and solutions that may occur in the process of coal-fired coupled biomass power generation, as well as the boiler technology transformation plan on the coal-fired coupled to biomass power generation. In terms of study on the characteristics of coal-burning coupled to biomass fuel, the main characteristics of the coal-burning coupled to biomass fuel, such as the combustion characteristics, the ignition characteristics, the burnout characteristics, the slagging characteristics, and the explosion characteristics of the coal-burning coupled to biomass fuel are described. The paper mainly describes the explosion prone problem of the pulverizing system, the pulverized coal hardening problem of the raw coal bunker and the boiler corrosion, and coking problem of the heating surface of the boiler. The explosion-proof transformation of the pulverizing system is described, and the technology transformation of the pulverizing system is carried out. After adopting the technical transformation scheme of sludge, the problems caused by sludge blending and burning are solved, and the power generation by sludge blending and burning is realized.

1. Introduction
With the rapid development of national economy and urbanization, municipal sewage treatment plants produce a huge amount of sludge to be urgently treated. The traditional sludge disposal methods have some disadvantages, such as harm to human beings and environment, which do not meet the current environmental requirements.

Incineration, this method can carbonize the organic matter, kill pathogens, and reduce the sludge volume [1]. The volume of sludge decreases sharply after incineration [2], and the sludge ash after appropriate physical and chemical treatment can be used as raw materials for cement, soil improvement materials, subgrade materials, etc. [3]. Incineration as the core sludge treatment method is the most thorough method, but also the current international mainstream of sludge treatment direction. Sludge disposal in China has also changed from the traditional agricultural and landfill treatment to incineration treatment.

Pulverized coal mixed with dried sludge has been successfully used in China, but the application of the furnace is mostly limited to circulating fluidized bed boiler. There are few cases in which sludge is mixed into a pulverized coal furnace [4-8].

2. The background of a technical transformation project
The power plant sludge resource treatment project as a local demonstration project, uses dried sludge into the power plant coal-fired boiler to burn, realizes with sewage sludge disposal and utilization, not only increases economic efficiency for the power plant, but also greatly reduces the sludge landfill pollution to the environment, and realizes the city sludge reducing emissions.

The plant is located in Shijiazhuang city, Hebei Province, and currently has two 300 MW coal-fired heating units, and unit 1 and unit 2 started production in January and April 2009 respectively. The power plant sludge resource comes from three sewage treatment plants under the jurisdiction of Shijiazhuang sewage company, with a total sewage treatment capacity of 990,000 t/d. The technical transformation project is scheduled to start construction in August 2019 and put into operation in January 2020.

3. The study on the characteristics of coal-fired coupled to biomass fuel

As biomass fuel, wet sludge usually has a high moisture content and low calorific value, and the low calorific value of wet sludge is about 2.091 MJ/kg, which cannot be directly burned in the boiler. When dried sludge moisture content is generally about 30%, and low calorific value is about 8.364 MJ/kg, it can be used as low quality biomass fuel.

According to a certain mixed proportion, coal and biomass (sludge) can be directly into the boiler as a mixture of fuel to burn, not only can achieve the reduction of sludge disposal, but also can reduce the boiler fuel consumption, at the same time, can reduce the power generation coal consumption.

3.1. Main characteristics of coal-fired coupled to biomass fuels

See table 1 for the study of sludge, local power plant burning coal, different proportion of coal-fired coupled to biomass fuel characteristics.

According to the data in table 1, it can be seen that:
- Volatile matter content of sludge in dry ash-free basis is high, which is 86.17%; the total moisture content is moderate, which is 19.3%.
- Carbon content of sludge in as received basis is low, which is 23.84%, The calorific value of sludge is low, and the calorific value of sludge in as received basis is 10.14 MJ/kg.
- Fe and Hg content of sludge are slightly higher, and Fe and Hg content are 4.40 g/g and 2.89 g/g, respectively.
- The total moisture content of mixed fuel with the 10% proportion sludge is slightly higher than the current coal, it is 1.25 percent higher.
- The low calorific value of the mixed fuel with the 10% proportion sludge is slightly lower than that than the current coal, it is 0.88 MJ/kg lower.

| Item                  | Unit  | Sludge                          | Local plant burning coal | 95% proportion of coal-fired coupled to biomass fuel | 90% proportion of coal-fired coupled to biomass fuel |
|-----------------------|-------|---------------------------------|--------------------------|---------------------------------------------------|---------------------------------------------------|
| Low Value             | Calorific Value | % 10.14 | 18.96 | 18.52 | 18.08 |
| Total Moisture Content | % 19.30 | 7.80 | 8.38 | 8.95 |
| Volatile Matter in Dry Ash-free Basis | % 86.17 | 19.00 | 22.36 | 25.72 |
| Ash Content in as Received Basis | % 30.20 | 34.20 | 34.00 | 33.80 |
| Carbon Content in as Received Basis | % 23.84 | 49.99 | 48.68 | 47.38 |
Table 1: Characteristics of coal-fired coupled to biomass fuels

| Item                        | Unit | Sludge in Local | power burning | 95% proportion of coal-fired coupled to biomass fuel | 90% proportion of coal-fired coupled to biomass fuel |
|-----------------------------|------|-----------------|---------------|-----------------------------------------------------|-----------------------------------------------------|
| Hydrogen Content in as Received Basis | %    | 4.11            | 2.37          | 2.46                                                | 2.54                                                |
| Oxygen Content in as Received Basis | %    | 17.48           | 3.40          | 4.10                                                | 4.81                                                |
| Nitrogen Content in as Received Basis | %    | 4.21            | 0.96          | 1.12                                                | 1.29                                                |
| Sulfur Content in as Received Basis | %    | 0.86            | 1.28          | 1.26                                                | 1.24                                                |
| Chlorine Content in as Received Basis | %    | 0.059           | -             | -                                                   | -                                                   |
| Hg Content in as Received Basis | μg/g | 4.40            | -             | -                                                   | -                                                   |
| Fe Content in as Received Basis | μg/g | 2.89            | -             | -                                                   | -                                                   |

3.2. Characteristics of coal-fired coupled to biomass fuels

3.2.1. Combustion characteristics of coal-fired coupled to biomass fuels. The thermogravimetric analysis is an important method for the study of solid chemical reaction characteristics, which is widely used in the study of solid reaction characteristics [9]. In combustion process of sludge, the precipitation of volatile plays a major role in the whole combustion process. The higher the volatile matter content of the mixed fuel is, the better the combustion performance is.

See figure 1 for TG and DTG curves of co-firing sludge with different moisture content and coal with different proportions.

Figure 1. TG and DTG curves of co-firing sludge with different moisture content and coal with different proportions.
3.2.2. **Ignition characteristics of coal-fired coupled to biomass fuels.** Ignition characteristics refer to the degree of ignition difficulty of coal-fired coupled to biomass fuel. The lower the ignition temperature is, the more easily coal will catch fire [10].

The ignition temperature curve of different mixed proportions of sludge and coal is shown in figure 2.

![Ignition Temperature Curve](image)

**Figure 2.** The ignition temperature curve of different mixed proportions of sludge and coal.

As can be seen from figure 2, from the ignition temperature, the ignition temperature of sludge significantly lower than single coal. The ignition temperature of S20 sludge is 200.0°C, and the single coal ignition temperature is 388.0°C, relatively difficult. The ignition performance of coal-fired coupled to biomass fuel with the different proportions is between single coal and single sludge. With the increase of mixed proportion of sludge, the ignition temperature of the mixed fuel decreases slightly. The reason is that the large amount of volatiles in sludge precipitates and burns at a lower temperature, and a large amount of heat is released at the same time, so the ignition temperature is lowered. Therefore, the ignition performance of coal mixed with sludge is better than that of single coal.

3.2.3. **Burnout characteristics of coal-fired coupled to biomass fuels.** The burnout time and burnout temperature of coal are the main indexes reflecting the burnout characteristics of coal. In terms of burnout characteristics, the burnout temperature of coal mixed with sludge is lower than that of single coal due to high volatile matter and low fixed carbon in sludge. As the volatile matter content of coal mixed with sludge increases, the precipitation and combustion of volatile matter provide more heat for the ignition of fixed carbon at the initial stage of combustion, so the ignition of fixed carbon is advanced [11] and the burnout time is shorter than that of single coal. The burnout performance of coal mixed with sludge is better than that of single coal.

For coal-fired boilers, the burnout characteristics of the pulverized coal will directly affect the combustion efficiency and the operation economy of the boilers. The longer the burnout time is, the worse the burnout performance is. The burnout time and the burnout temperature curves of sludge and coal are shown in figure 3.
3.2.4. Slagging characteristics of coal-fired coupled to biomass fuels. When the ash content of coal is particularly high or extremely low, its ash slagging capacity is weaker than that of medium ash coal [12]. The ash melting point of sludge is low, and it is lower than single coal above 300°C, and sludge slagging characteristics belongs to the type of serious slagging. The ash melting point of coal-fired coupled to biomass fuel decreases with the increase of the proportion of sludge, and the decrease of ash melting point will make the degree of slagging become serious after the coal-fired boiler is mixed with sludge.

3.2.5. Explosive characteristics of coal-fired coupled to biomass fuels. The explosive characteristic index of coal synthesizes the influence of flammability and ash content of coal. According to the calculation formula of explosive index, the explosive characteristic index of current coal is 8.81, and the explosive characteristic is medium. The explosive index of sludge is 102.73, and the explosive characteristic is extremely explosive. When the mixed proportion of sludge is 10%, the explosive characteristic index of coal-fired coupled to biomass fuel is 14.07, so the explosive characteristic of coal-fired coupled to biomass fuel with the 10% proportion of sludge is extremely explosive.

4. Main technical problems of coal-fired coupled to biomass power generation
Based on the analysis of the characteristics of coal-fired coupled to biomass fuel, when the boiler burns mixed fuel, it is easy to have problems such as the explosive of the pulverizing system, the pulverized coal hardening of the raw coal bunker, the coking and corrosion of the heating surface of the boiler.

4.1. The problem of pulverizing system explosibility
When the mixed proportion of sludge is 10%, the mixed fuel belongs to the extremely explosive coal, and the fuel is prone to spontaneous combustion, which leads to the explosion accident in the pulverizing system.

The power plant adopts intermediate storage type pulverizing system, which is prone to pulverized coal deposition and spontaneous combustion of gas mixture. Powder accumulation and spontaneous combustion are the main inducement of pulverizing system explosion. The explosion of pulverizing system is usually the secondary explosion or multiple chain explosion, which has the characteristics of randomness and suddenness. When the mixture of coal and sludge meets high volatile matter content, spontaneous combustion and explosive accidents are likely to occur. In order to prevent the explosion...
of the pulverizing system, cold furnace smoke is generally introduced into the sludge pulverizing system as inert medium.

4.2. The pulverized coal hardening of the raw coal bunker
When the mixed proportion of sludge is 10%, because of the mixed fuel moisture content increases, the dew point temperature is about 45.8°C in the pulverizing system, and mixed fuel hardens on the raw coal bunker, which extremely easily cause raw coal bunker blockage, and the coal feeder feeds coal interrupt, the boiler output accident reduction. In order to prevent the raw coal bunker from hardening, it is usually adopted to add dredging device in the raw coal bunker for protection.

4.3. Corrosion and coking of the heating surface of the boiler
Due to the high content of Cl and F elements in sludge, the HCl and HF components content in the flue gas of combustion products are on the high side after burning the fuel mixed with sludge. Meanwhile, due to the high content of alkali metals in sludge, with the increase of the proportion of sludge blending and burning, the melting point of the mixed fuel gradually decreases [13], and its compounds are easy to be sintered [14], which makes the heating surface of the boiler easy to coking and corrosion.

In general, the method of spraying on the heating surface of the boiler and optimizing the soot blowing system is adopted, and the auxiliary means of the soot blowing device is added in the main combustion area to prevent the corrosion and coking of the boiler. In order to reduce the acidity of flue gas and inhibit the synthesis of dioxin, a dry purification process of flue gas through sodium based micro-powder is added at the denitration system inlet.

5. Boiler transformation plan on a coal-fired coupled to biomass power generation technology

5.1. Introduction to technical transformation system on the coal-fired coupled to biomass power generation
According to the actual situation of power plant at present, the dried sludge conveying system needs to add a dried sludge storage bin, a feeder, etc.. As the drying and inert medium, the hot or cold furnace smoke is introduced into the dried sludge conveying system and pulverizing system.

See figure 4 for the schematic diagram of the technical transformation project of coal-fired coupled to biomass power generation.

The characteristic of this scheme is to achieve the mixture of dried sludge and coal through feeder and coal belt, then the mixture evenly distribute to each raw coal bunker, and then the mixture enter the furnace for combustion after grinding by the pulverizing system. The advantage of this scheme is that the mixed proportion of dried sludge can be adjusted by controlling the rotating speed of the feeder, so as to ensure the uniform mixing of dried sludge and coal. At the same time, the pulverizing system with burning sludge can be selected according to the needs, so as to ensure the flexibility of the pulverizing system after burning sludge. The disadvantage of this scheme is that the mixing of dried sludge into the pulverizing system may cause adverse effects on the pulverizing system, which requires the explosion-proof transformation of the pulverizing system as well as the transformation of the powder feeding system.
In order to reduce the acidity of flue gas and inhibit the resynthesis of dioxin, the dry purification process of flue gas through sodium based micro-powder is adopted in the inlet flue of denitrification system. The process system consists of several sets of sodium micro-powder grinding equipment, powder conveying equipment, solid-gas separation equipment, precise feeding equipment, etc., and is equipped with an integrated intelligent control system to optimize process parameters. Multiple static gas-solid mixers are used in the flue to operate side by side with the multi-point injection, so as to realize the full mixing and reaction of pollutants and adsorbents in the flue gas and directly connect with the preparation system of sodium micro-powder. On this basis, the feed amount of HCl adsorbent was coordinated to adjust according to the variety and amount of burned sludge in the power plant. While dechlorination of flue gas was carried out, the resynthesis of dioxins was inhibited.

5.2. Technical scheme of pulverizing system transformation

5.2.1. Explosion-proof transformation scheme of pulverizing system. In order to prevent the explosion of the pulverizing system, the original pulverizing system is modified and inert medium is added into the pulverizing system to greatly reduce the oxygen concentration of the pulverizing system and ensure that the end oxygen of the pulverizing system is lower than 16% [15]. The terminal oxygen content of the pulverizing system was controlled below 16%. According to the extracting position of stove smoke point, the medium used for inserting is mainly the hot furnace smoke and cold furnace smoke. Due to the low oxygen content of hot furnace smoke, about 3% ~ 4%, it can effectively improve the safety of the pulverizing system, so it can be extracted from the hot furnace smoke, and can be used as inert medium in the pulverizing system, that is, it is extracted from the steering chamber into the pulverizing system. Since the moisture content of the blended fuel does not increase much, combined with the actual situation on the site, the cold furnace smoke can also be extracted as inert medium in the pulverizing system, that is, it is extracted from the rear of the dust removal system (the outlet of the induced draft fan) to enter the pulverizing system. These two methods can effectively control the oxygen content in the terminal of the pulverizing system below 16%, meeting the relevant requirements in the technical code for explosion design of coal and pulverizing system of fossil fuel power plant. There are two schemes for extraction of the furnace smoke:

- Extract the cold furnace smoke from the induced draft fan outlet
  The system is simple, and is easy to arrange, to operate and maintain. The furnace smoke temperature is low, and requirement for the pipe material is low, the cost is low.
- Extract hot furnace smoke from the steering chamber
  Extraction point is selected in the steering chamber [16], and the pressure difference between the negative pressure at the coal mill inlet and the negative pressure in the steering chamber is used to extract hot furnace smoke. Based on the comprehensive analysis of the advantages and disadvantages of the above two transformation schemes for the pulverizing system, and combined with the previous experience in lignite transformation, it is recommended to adopt the extraction of the cold furnace smoke.
smoke scheme, namely the extraction of the cold furnace smoke from the outlet of the induced draft fan, for the pulverizing system transformation, and adopt the “cold furnace smoke + hot air + recycling agent mixture + cold air” as the drying medium for the pulverizing system.

The boiler is currently hot air powder feeding system, and the hot air temperature is about 370°C, and the hot air temperature for sludge of easy ignition and burning is too high. Blending and burning sludge may make the burner nozzle temperature is exorbitant, and it is necessary to introduce the cold air in front of each burner nozzle to reduce primary air temperature, and ensure the safety of the burner. In addition, for the pulverizing system of the boiler with the burned sludge, too high temperature for the pulverizing system explosion protection is also very unfavorable. Therefore, it is necessary to transform the current hot air powder feeding system into the “hot air + cold air” powder feeding system. Through the above analysis, it can be ascertained that the transformation scheme of the boiler pulverizing system is as follows: the original design of the “hot air + recycling” as drying medium of the pulverizing system instead to the “cold furnace smoke + hot air + recycling agent mixture+ cold air” for the drying medium of the pulverizing system, at the same time the original design of the hot air powder feeding system is replaced by the “hot air + cold air” powder feeding system.

5.2.2. Calculation of the different mixed proportion of sludge in the pulverizing system and results of the explosion protection transformation design and the calculation of the pulverizing system. The municipal sewage treatment plant treats about 800 t of the wet sludge every day, and the moisture content after the sludge dewatering and drying is about 21.25%, and the sludge weight is about 203 t. The original design of the boiler is 4 tubular ball mills. The coal mills A and B correspond to pulverized coal bunker A, and the coal mills C and D correspond to pulverized coal bunker B. Moreover, the pulverized coal bunkers A and B can be transported to each other. According to the characteristics of the intermediate storage type pulverizing system, the combined operation mode of the coal mills is flexible, and the blending and burning dried sludge amount of two units is 203 t every day. See table 2 for the corresponding relations of the quantity of coal mill, the proportion of dried sludge and the consumption time in 300 MW load.

Table 2. Corresponding relations of the quantity of coal mill, proportion of the dried sludge and consumption time in 300 MW load.

| Serial Number | Item                                                                 | Unit | Numerical Value |
|---------------|----------------------------------------------------------------------|------|-----------------|
| 1             | Proportion of The Dried Sludge                                       | %    | 5.0 7.5 10.0    |
| 2             | Quantity of Coal Mill                                               | set  | 2 3 4 2 3 4 2 3 4 |
| 3             | Maximum Output of A Single Coal Mill after Blending and Burning Dried Sludge | t     | 40.3 40.3 40.3 40.3 40.3 40.3 40.9 40.9 40.9 |
| 4             | Daily Coal Consumption                                              | t     | 3235 3226 3226 3226 3226 3226 3226 3226 3226 |
| 5             | Consumption Time of Blending and Burning Dried 203 t Sludge of Two Units | h     | 29.0 19.3 14.5 19.1 12.7 9.5 14.1 9.4 7.1 |

According to the data in table 2, it can be seen that:
- when the proportion of the dried sludge is 5.0%, and the quantity of coal mill is respectively 2, 3 and 4, the consumption time is respectively 29.0 h, 19.3 h and 14.5 h. At the proportion of 5.0%, when the quantity of coal mill is 2, the consumption time exceeds 24.0 h, which does not meet the requirement of blending and burning. When the quantity of coal mill is 3 and 4, the consumption time is lower than 24.0 h, which meets the requirement of blending and
burning.

- when the proportion of the dried sludge is 7.5 %, the quantity of coal mill is 2, 3 and 4, and the consumption time is respectively 19.1 h, 12.7 h and 9.5 h, which are lower than 24.0 h, and can meet the requirements of blending and burning. The coal mill operation cycle is short, which is relatively high flexibility.

- when the proportion of the dried sludge is 10.0 %, the quantity of coal mill is 2, 3 and 4, and the consumption time is respectively 14.1 h, 9.4 h and 7.1 h, which are lower than 24 h, and can meet the requirements of blending and burning. The coal mill operation cycle is short, relatively high flexibility.

According to the technical code for design and calculations of coal pulverizing system of fossil-fired power plant, the proportion of dried sludge mixed with coal mill is calculated after using inert gas from the cold furnace smoke in 300 MW and 150 MW loads. In 300 MW and 150 MW load, the output of the pulverizing system meets the design requirements, and the maximum terminal oxygen content is 15.8%, which meets the explosion protection design requirements of pulverizing system with terminal oxygen content not higher than 16.0%. Terminal desiccant dew point temperature is about 44.2°C, which meets the design requirements of pulverizing system whose dew point temperature of terminal desiccant is lower than that of terminal desiccant above 5.0°C. The cold furnace smoke volume flow to be extracted is 68045.1~121384.7 m$^3$/h. When the diameter of the flue gas pipeline is 1.0 m, the flue gas flow velocity in the pipeline is 12.03~21.47 m/s.

6. Conclusion

6.1. The expected results of project construction

After adopting the technical transformation scheme of sludge entering into the boiler combustion through the pulverizing system, on the one hand, the problems caused by sludge blending and burning are solved, on the other hand, the system of sludge blending and burning is safe and stable, which can realize the power generation by sludge blending and burning.

6.2. Benefits of the project

6.2.1. Economic benefits. After the completion of the coal-fired coupled to biomass project, an average annual economic benefit of about 6.4 million yuan is brought to the power plant, with a payback period of about 6.5 years.

6.2.2. Social benefits. The environmental pollution caused by sludge landfill is greatly reduced, and the reduced discharge of municipal sludge is realized.

   Sludge incineration saves about 70 mu of land for the country every year.

   Using sludge biomass to generate electricity saves 203,000 tons of standard coal every year.

6.2.3. Demonstration benefits. After the implementation of this project, the environmental pollution caused by the local sludge will be solved, which play a demonstration role in other cities. In short, the project will bring huge benefits after putting into operation, and its social benefits are far greater than economic benefits.

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