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Application of Sludge Coupling Power Generation Technology in Coal-fired Power Plant

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Abstract. The coal quality characteristics of urban sludge were analyzed, and three types of coal-sludge-coupled power generation technologies were introduced, including direct sludge mixing, flue gas direct drying sludge and steam indirect drying sludge coupling power generation. Three types of sludge coupling power generation technologies in coal-fired power plant were introduced, including direct sludge blending process, sludge blending after drying directly by flue gas and indirectly by steam. The control values of sludge blending ratio and moisture content after sludge drying are analyzed, and it is considered that the direct sludge blending ratio should be controlled within 5%. The moisture content after sludge drying should be controlled at 30-40% and the blending ratio should be controlled within 10%. The influence of sludge blending on the operation of the unit is analyzed. The operation of coal-fired boiler is stable, the quality of fly ash and slag has little change, and the emission of pollutants and heavy metals reaches the standard if the proportion of sludge mixed with combustion is controlled within 10%.

1. Introduction

With the gradual improvement of China's urbanization level and the improvement of the national living standard, the domestic water consumption is increasing year by year, and the urban sewage discharge in China is increasing year by year. In 2017, the domestic sewage discharge in China reached 51.78 billion tons [1], and the sludge produced by the domestic sewage treatment is more than 30 million tons (based on 80% water content). It is estimated that the sludge production in China will exceed 60 million tons in 2020 [2]. Sludge is rich in pollutants in sewage, containing a large number of nutrients such as nitrogen and phosphorus, as well as toxic and harmful substances such as organic matters, viral microorganisms, parasite eggs and heavy metals. Without effective disposal, it will cause serious harm to the environment. Sludge disposal has become an urgent environmental problem in China.

The traditional methods of sludge disposal include landfill, composting, reclamation and incineration. Landfilling not only takes up a lot of land, but also may cause soil and groundwater pollution if the anti-seepage technology is not appropriate; due to the fact that the sludge contains many harmful substances and the composition is complex, the sludge composting has more difficulties in practical application; sludge reclamation will pollute the marine environment and harm marine organisms, which has been banned by international conventions [3].



In contrast, sludge incineration can not only eliminate harmful substances, but also greatly reduce sludge volume, which can realize sludge reduction, stabilization, harmless and resource-based treatment, and is one of the most promising sludge disposal methods.

As a form of sludge incineration, the sludge coupling power generation in coal-fired power plant has the unique advantages of large capacity, strong adaptability and high system efficiency. It can use the original combustion, flue gas purification, power generation and other equipment of the unit to greatly reduce the cost of sludge incineration disposal, which has developed rapidly in recent years.

2. Analysis of coal quality characteristics of sludge

The total moisture of sludge after mechanical dewatering in most urban sewage treatment plants is about 80%. Table 1 compares the main coal quality parameters of typical sludge and typical coal.

Table 1. Comparison of coal quality parameters of typical sludge and typical coal.

Fuel type	Industrial analysis (%)			Elemental analysis (%)					Calorific value (MJ/kg)	ST (°C)
	M _t	A _{ar}	V _{daf}	C _{ar}	H _{ar}	O _{ar}	N _{ar}	S _{ar}	Q _{ar,net,p}	ST
Wet sludge1	85.50	7.13	88.51	4.02	0.65	1.88	0.44	0.37	-0.35	1220
Wet sludge2	84.41	8.13	95.32	3.71	0.49	2.53	0.60	0.14	-0.71	1040
Wet sludge3	79.30	11.75	93.94	4.48	0.70	2.97	0.69	0.12	-0.31	1266
Wet sludge4	78.96	11.86	92.82	5.63	0.91	2.32	0.61	0.67	0.36	1250
Dried sludge1	40.00	32.19	92.00	17.58	2.09	6.33	1.58	0.23	5.06	1240
Dried sludge2	20.00	41.95	87.05	19.63	3.32	11.19	3.21	0.70	7.28	1210
Young lignite	50.00	12.20	62.88	25.28	2.22	9.80	0.24	0.26	8.83	1310
Bituminous coal	3.90	28.94	33.09	55.82	3.31	6.03	0.95	1.05	21.53	1440

It can be seen from Table 1 that the quality of sludge and bituminous coal commonly used in large-scale power plant are quite different. The moisture and volatile content of sludge are high, while the carbon content and the calorific value are low. And the properties of sludge from different sources are different. The ash melting point of sludge is low, which is close to that of young lignite. The total water content of wet sludge is about 80%, the volatile matter of dry ash free sludge is about 90%, and the low calorific value of received basis is very low and basically negative. After sludge drying, water content decreased, ash content increased and calorific value increased. Dried sludge belongs to high water, high ash, high volatile, low calorific value and serious slagging fuel.

3. Sludge coupling power generation technology in coal-fired power plant

The sludge coupling power generation technology in coal-fired power plant mainly includes direct blending and dry blending combustion of sludge. Dry blending combustion can be divided into direct drying and indirect drying processes according to different drying technologies.

3.1. Direct sludge blending

Direct sludge blending is to directly feed the mechanical dewatered sludge with moisture content of about 80% discharged from sewage treatment plant into the furnace of the boiler through the conveying equipment and burn with coal. Sludge conveying methods include pumping and belt conveying.

Fig.1 shows the flow chart of direct sludge-blending process by pumping for CFB boiler. The wet sludge is transported to the sludge bin of the power plant by the tank car. The sludge falls into the bottom pre-pressure screw conveyor through the unloading carriage at the bottom of the sludge bin. The sludge is sent to the sludge pump through the pre-pressure screw conveyor. After being pressurized by the sludge pump, it is sent to the CFB boiler through the pipeline for combustion or to the discharge port above the coal conveyor belt to make the sludge spread on the original coal layer (pulverized coal boiler).

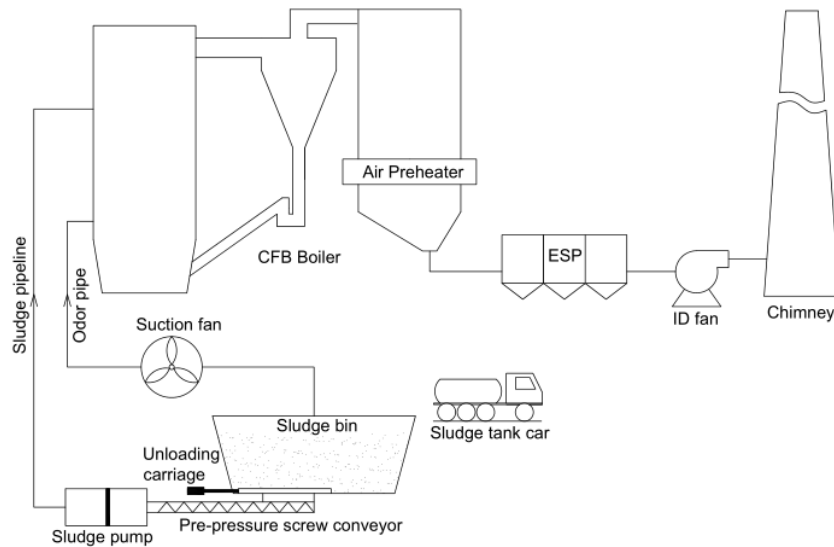


Figure 1. Flow chart of direct sludge-blending process by pumping for CFB boiler.

Fig.2 shows the flow chart of direct sludge-blending process by belt conveying. The wet sludge is self-unloaded into the discharge bin, and then sent to the sludge bin for storage through the screw conveyor and discharge belt at the bottom of the discharge bin. The hydraulic push rod at the bottom of the sludge bin pushes the sludge to the discharge screw, and then it is sent to the A or B sides of the coal conveyor belt of the power plant through the first and second belt conveyors (switchable operation). The sludge is evenly mixed with the coal through the sludge distribution device. In order to prevent odor diffusion, the sludge conveying belts are all installed with a sealing cover.

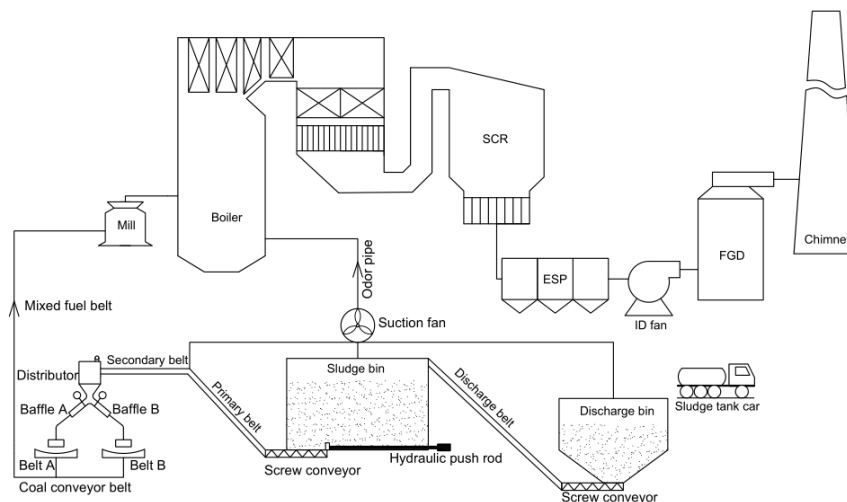


Figure 2. Flow chart of direct sludge-blending process by belt conveying.

During sludge storage period, due to anaerobic fermentation, H_2S , NH_3 and other irritant gases will be produced. In the process of direct sludge blending, both the wet sludge storage workshop and the wet sludge storage bin are constructed in a closed manner. Meanwhile, tail gas collection pipes are installed, collected by fans, sent to the boiler for high temperature decomposition, and then treated by the boiler flue gas purification system to meet the discharge standards. Compared with the belt conveying process, the pumping direct blending process is a completely closed pipeline transportation, and the odor recovery effect is better.

The direct sludge blending technology is simple in technology, small in investment, and requires little operation and maintenance; since the sludge is not dried, the output of malodorous gas is small. Wet sludge has high water content, large volume, low calorific value and difficult combustion organization, so its blending amount is limited. For the pulverized coal boiler, due to the uneven mixing of sludge and other factors, it is easy to cause the blockage of the raw coal bunker and coal feeder, or the insufficient output of the pulverizing system and other problems, so the amount of sludge blending is small.

3.2. Direct drying blending

Sludge drying coupled power generation is to dry wet sludge to 20-40% moisture content, and then send it to the boiler to burning with coal to release heat and generate steam for power generation.

Direct drying refers to the use of hot flue gas, hot air and other drying media to directly contact with sludge for drying. Related drying equipment includes rotary wing dryer, spray dryer, belt dryer, drum dryer, cyclone flash sludge dryer, etc.

Fig.3 is the flow chart of the flue gas direct drying sludge coupling power generation process. The process uses flue gas at the tail of the boiler as a heat source to dry the sludge. The wet sludge of the sewage treatment plant is transported to the wet sludge storage bin in the power plant by a dump truck, and then sent to the inlet of the dryer for drying by the wet sludge screw pump. The dried sludge is transported to the cyclone separator by air flow for gas-solid separation. The dry sludge falls into the dry sludge bin, and then sent to the coal conveyor belt mixing with the raw coal for combustion in the furnace. Part of the dry sludge is directly sent to the coal conveyor belt through the screw conveyor at the bottom of the dryer. The drying medium required by the dryer is composed of high-temperature flue gas (about 380°C) in front of the air preheater and low-temperature flue gas (about 120°C) at the outlet of the electrostatic precipitator. After the drying tail gas is dedusted by the cyclone separator, it is sent to the upper part of the boiler furnace by the negative pressure fan for combustion or tail pollutant treatment system.

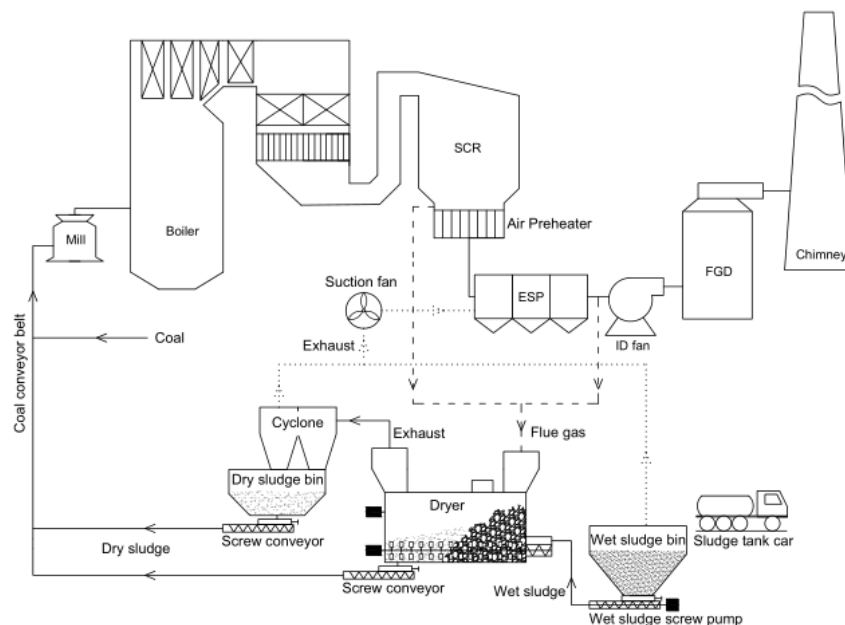


Figure 3. Flow chart of the flue gas direct drying sludge coupling power generation process.

The advantages of direct drying technology are direct contact between sludge and hot medium, high transmission efficiency and evaporation rate, short drying process, compact equipment structure and low initial investment. The disadvantages are that using high-temperature flue gas or hot air as heating

heat source, the available energy loss is large; the flow of drying tail gas is large, the difficulty of tail gas purification and waste heat recovery is high; the requirements of combustion suppression and explosion-proof of drying system are relatively strict. If the proportion of sludge mixed with combustion is too high, the amount of flue gas required is large, which may affect the thermal system of the boiler, resulting in insufficient steam temperature. Therefore, the selection of this process needs to be combined with the thermal calculation of the unit.

3.3. Indirect drying blending

Indirect drying is that steam or heat transfer oil transfers heat to sludge on the other side through the surface of heat transfer element of drying equipment, which makes the water in sludge evaporate, and the drying medium does not contact sludge directly. The water evaporated from the sludge enters the condenser for condensation, and all or part of the thermal medium returns to the original system for recycling. The main equipment includes hollow paddle dryer, thin-layer dryer, disc dryer, etc.

Fig.4 is the flow chart of the steam indirect drying sludge coupling power generation process. The extraction steam of unit turbine is used as heat source in this process. In the sludge drying equipment, the heat is indirectly contacted with the sludge for heat exchange. After the steam heat is released into the condensate, it is returned to the steam water system of the unit. After the sludge is dried, it is cooled into the dry sludge bin and sent to the coal conveyor belt for mixing with the raw coal and then to the pulverizer. The waste gas produced in the sludge drying process is removed most of the solid particles by the cyclone separator, and then enters the condenser for heat exchange with the cooling water. The non condensing waste gas is sent to the boiler for incineration by the negative pressure fan, and the condensing waste water is sent to the waste water treatment system for treatment and then discharged to the standard.

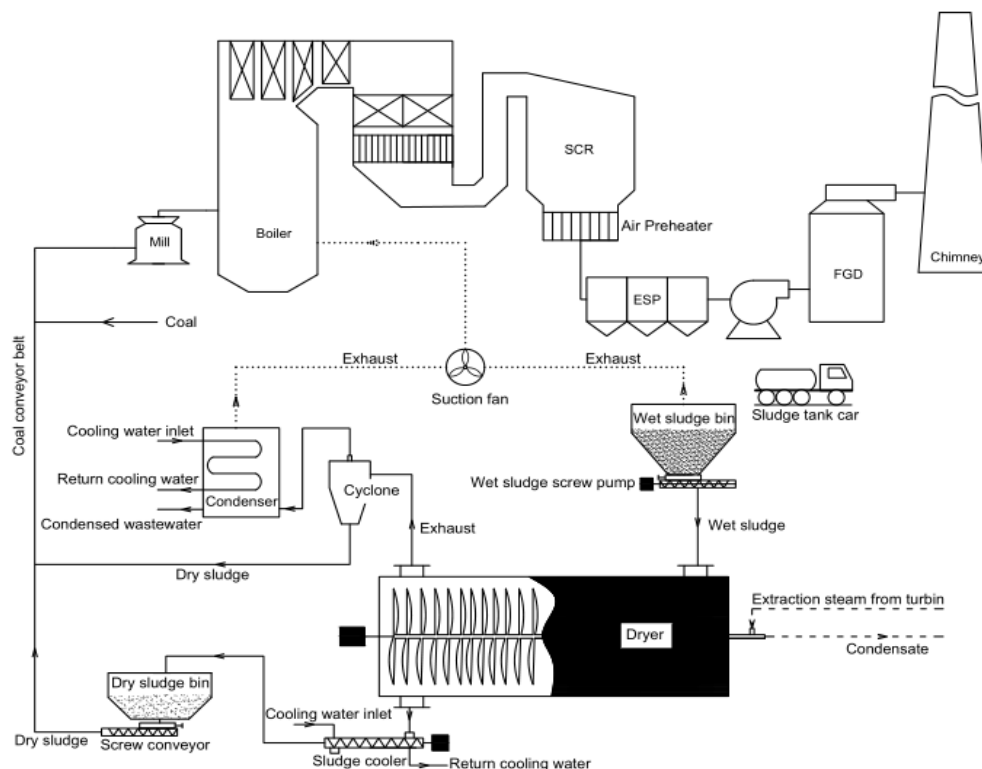


Figure 4. Flow chart of the steam indirect drying sludge coupling power generation process.

Indirect drying technology adopts low-grade heat sources such as low-pressure steam, with small available energy loss and high thermal efficiency of the system. Drying tail gas treatment capacity is

small and drying steam is easy to condense. It can effectively avoid the plastic stage of sludge, with low operating temperature, less loss of combustible components in sludge, good system safety and high degree of automation. Indirect drying sludge coupled power generation process has little influence on boiler operation, especially when the proportion of sludge mixed with combustion is large. However, this process belongs to wall to wall heat exchange, the heat transfer coefficient is lower than that of direct contact heat exchange, the drying rate is low, and the processing amount per unit drying area is small. The equipment has large volume, high initial investment, complex structure and many moving parts, so it has high requirements of corrosion resistance and wear resistance.

4. Important parameters of sludge coupling power generation

4.1. Sludge blending ratio

Sludge blending ratio affects the safety and economy of boiler combustion, which is the most important control parameter of sludge coupled power generation. The “Guidelines for the Treatment and Disposal of Sludge in Urban Sewage Treatment Plants (Trial)” issued by the Ministry of Housing and Urban-Rural Development and the National Development and Reform Commission in March 2011 stated: “The amount of sludge entering the furnace should not exceed 8% of the coal combustion”.

For the unit mixed with dry sludge, the research shows that when the sludge blending ratio is 5%, the combustion and heat release performance of the mixed fuel is the best, which is better than that of bituminous coal combustion alone, and the combustion characteristic parameters are almost the same as that of bituminous coal. When the blending ratio is 10%, the combustion characteristic parameters of the mixed fuel have little difference with that of bituminous coal. When the blending ratio exceeds 20%, the combustion characteristic of the mixed fuel has great difference with that of bituminous coal, and gradually tends to sludge with the increase of the sludge blending ratio [4]. It can be seen that when the power plant coal-fired boiler is mixed with sludge, the theoretical optimal blending ratio is less than 5% from the perspective of combustion characteristics, and the influence on the combustion of boiler is not significant when blending ratio is not more than 10%, and the blending limit ratio should be controlled within 20%. The actual blending test of the unit shows that the blending of dry sludge with 5% blending ratio has no effect on the operation of the boiler. When the blending ratio is increased to 10%, the combustion state of the furnace changes obviously, which shows that the flame temperature drops or the combustion flame extends. Therefore, it is suggested that the blending ratio should not be more than 10%.

There are few researches on sludge direct mixing unit. Table 2 shows the test results of fuel coal quality of a direct sludge blending unit. The ratio of wet sludge blending is 5%. After the wet sludge is blended with bituminous coal, the quality of the mixed fuel has little change, which is within the daily fluctuation range of coal quality. The operation experience of the direct sludge blending unit shows that it has little effect on the combustion of the boiler when the wet sludge blending ratio was controlled within 5%.

Table 2. Test results of fuel coal quality of a sludge direct blending unit.

Fuel type	Industrial analysis (%)			Elemental analysis (%)					Calorific value (MJ/kg)	ST (°C)
	M _t	A _{ar}	V _{daf}	C _{ar}	H _{ar}	O _{ar}	N _{ar}	S _{ar}	Q _{ar,net,p}	ST
Wet sludge	84.41	8.13	95.32	3.71	0.49	2.53	0.60	0.14	-0.71	1040
Bituminous coal	3.90	28.94	33.09	55.82	3.31	6.03	0.95	1.05	21.53	1440
Mixed fuel	7.70	28.8	34.96	52.24	3.16	6.05	1.03	1.02	20.05	1380

Compared with coal-fired boiler, CFB boiler has better adaptability to coal quality, and the ratio of sludge blending can be increased properly. After the sludge is blended, the fuel moisture increases, the calorific value decreases, the comprehensive combustion characteristic index decreases compared with the raw coal, and the combustion condition is worse than that of raw coal. It may even cause boiler

flameout due to poor combustion performance when the boiler is running at low load. Therefore, it is necessary to study the optimal adjustment of sludge blending and combustion process of coal-fired boiler under different operating conditions.

4.2. Moisture content of dried sludge

Sludge moisture content is a key factor restricting sludge disposal and utilization. According to relevant research, the relationship between sludge moisture content and calorific value is shown in Fig.5. The effect of excessive moisture content of sludge is the same as that of coal powder, which may cause blockage of coal pulverizing system and even cause tripping event. The lower the moisture content of sludge, the higher the calorific value and the more favorable for combustion. However, the energy consumption of the sludge drying system will increase in order to reduce the water content of the sludge. Therefore, the optimal moisture content of the dried sludge is a problem that is not easy to control and deserves careful consideration.

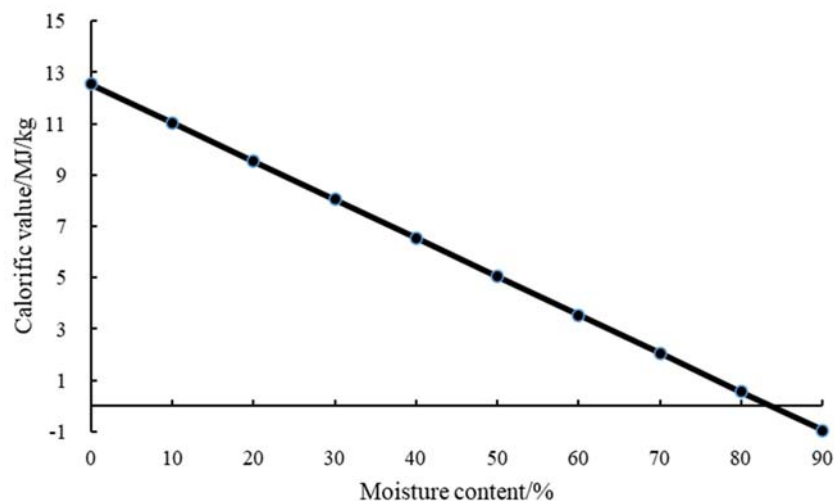


Figure 5. Relationship between sludge moisture content and calorific value.

Sludge drying process includes accelerated drying stage, constant drying stage and reduced drying stage. Sludge drying curve is a typical exponential curve, and sludge drying is mainly in the reduced drying stage. The sludge drying rate decreases as the moisture content of the sludge decreases under the condition of constant drying temperature. The sludge has high cohesiveness when it is dried to a moisture content of 40%-60%, which is not conducive to sludge transportation and needs further drying. When the sludge moisture content is reduced to 30%-40%, the drying rate is already very low, and the energy consumption for further drying will increase exponentially. When the sludge is dried to a moisture content below 30%, the dust content of the dried sludge discharge is large, which leads to serious dust phenomenon during the transportation of dry sludge, explosion risk and dust pollution to the drying workshop and coal conveying trestle[5]. It is suggested that the moisture content of sludge after drying is 30%-40% considering the energy consumption, safety, environmental protection and other factors.

5. Effect of sludge coupling on the power plant

5.1. Boiler performance

Sludge has high moisture content, high volatile matter, low calorific value and high ash content of dried sludge. When the boiler is mixed with sludge, the moisture content and ash content of the mixed fuel increase, and the calorific value of the fuel decreases. As a result, the radiant heat absorption in the furnace decreases, the flue gas temperature at the outlet of the furnace increases, and the flue gas flow

increases, which leads to the increase of the heat loss of the exhaust gas. The blending test shows that the carbon content of the boiler ash decreases after blending the dried sludge, which may be caused by the higher volatile content of the sludge compared with the pulverized coal, and the ignition point of the volatile is lower than that of the fixed carbon. Therefore, in the early stage of combustion, the volatile content of the sludge can release more heat, thus promoting the ignition of the fixed carbon, which can not only advance the ignition of the pulverized coal, but also extend the combustion time of pulverized coal in the furnace, thus improving the burnout rate of pulverized coal. According to the relevant experimental results, when the blending ratio of drying sludge is 7%, there is no significant change of the boiler thermal efficiency.

When the boiler is mixed with sludge, the desuperheating water volume increases. The main reason is that when the sludge is mixed, the moisture content of the fuel entering the furnace increases, the calorific value decreases, the flue gas volume increases, the radiant heat absorption in the furnace decreases, the flue gas temperature at the furnace outlet increases, the heat absorption of the platen superheater and convection superheater increases, and the steam temperature at the outlet tends to rise. Therefore, the steam temperature at the outlet of the convection superheater must be guaranteed by increasing the desuperheating water volume.

The ash melting point of the sludge is much lower than that of raw coal. The ash melting point temperature of mixed fuel gradually decreases with the increase of sludge blending ratio. The boiler will be more easily coking if the blending ratio is too large. Therefore, the melting point of the mixed coal ash after sludge blending should be tested regularly, and the boiler soot blowing method and frequency should be adjusted according to the actual situation.

5.2. Pollutant discharge

After mixing with sludge, the total mass concentration of NO_x emission of the boiler decreases significantly. On the one hand, the reduction effect of intermediate products such as HCN (generated by the decomposition and release of the volatiles of the sludge) on NO_x results in the reduction of fuel type NO_x ; on the other hand, the temperature level of the main combustion zone in the furnace decreases after mixing sludge, resulting in the reduction of thermal type NO_x [6].

The SO_2 emission concentration is mainly determined by the sulfur content in the fuel after sludge blending. The SO_2 generated by combustion may react with the oxides in the ash to form sulfates, reducing the concentration of SO_2 emissions. Generally, the sulfur content in coal is higher than that of urban sludge, so sludge blending has little effect on the final SO_2 emission concentration.

There are a lot of chlorine-based substances in the sludge. When the incineration temperature is between 550°C - 700°C , a large amount of dioxins will be produced rapidly (0.1s-0.2s). The results of large-scale sludge incineration show that 25-90% of dioxins are generated in the high-temperature flue gas of incineration at 487 - 643°C . When the incineration flue gas reaches above 850°C and the residence time exceeds 2s, the reaction speed of polymer is far less than the decomposition speed of dioxins, and the decomposition rate can reach over 98%. Sludge is sent into the furnace as fuel in the area of 20-40m, and the combustion temperature is much higher than 850°C . Calculated by the maximum flow rate of flue gas of 12m/s, sludge stays in the area above 850°C for more than 2s, which can basically prevent the formation of dioxins.

5.3. Heavy metal migration

Urban sludge contains toxic and harmful heavy metals such as Hg, As, Cu, Zn, Cd, Ni, Cr, Pb and Mn. During combustion, the non volatile parts of these heavy metals will be discharged from the slag, and the volatile parts will be absorbed in the fly ash and collected or discharged with the flue gas. The results show that the combustion temperature and HCl will promote the migration of heavy metals into fly ash, and the residual rate of most heavy metal elements decreases with increasing temperature. Hg and As in heavy metals usually exist in the flue gas in gaseous form, Pb and Cd usually appear in gas-solid two-phase form, and Cu, Cr and Zn are basically enriched in bottom slag. The mixed sludge will cause the heavy metal content in the ash to increase to a certain extent, but in general, the sludge blending ratio is

usually within 10%, and the main pollutants and heavy metal concentrations in the flue gas can meet the current national emission standards. Ash can also be used comprehensively without treatment. Taking into account the uncertainty of the source of the dried sludge, it is recommended to regularly measure the heavy metal content of the incoming sludge and the fly ash after blending to check whether the heavy metal content exceeds the standard.

6. Conclusion

Sludge coupling power generation in coal-fired power plant is an effective way to reduce, stabilize, harmless and resource-based treatment and utilization of urban sludge.

The processes of direct sludge mixing, flue gas direct drying of sludge and steam indirect drying of sludge coupled power generation have their own characteristics, and all have their technical feasibility and scope of application, which should be comprehensively analyzed and determined in combination with the local sludge treatment capacity and the actual operation of the unit.

The direct sludge blending ratio should be controlled within 5%; the moisture content of the sludge after drying should be controlled within 30-40%, and the blending ratio should be controlled within 10%. When the sludge blending ratio is controlled within 10%, the coal-fired boiler operates stably, the quality of fly ash and slag does not change much, and the discharge of pollutants and heavy metals meets the standard.

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