

Combustion characteristics and design of hot water boiler

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Abstract. In order to understand the combustion characteristics of biomass, a detailed comparison with coal was made. There are many differences between biomass and coal in combustion characteristics. The burning rate of biomass is much higher than coal. The burning rate of biomass char is also higher than coal char. During biomass combustion, HCl, SO₂ and NO_x emissions mainly concentrate in volatile combustion stage, while CO₂ emission mainly concentrates in char combustion stage. The slagging tendency of biomass ash is severer than coal ash and the adhesive force of biomass ash is higher. However, the wearing tendency of biomass ash is minor. Aiming at the particularity of biomass fuels, this paper briefly introduces the design of biomass hot water boilers. On this basis, a 2.8 MW biomass hot water boiler was developed and tested under the loads of 1.7 MW and 2.8MW. The running results show that the carbon content of bottom slag significantly decreases as the load increases. The boiler efficiency is higher than 85% under both loads.

1. Introduction

As the fossil energy such as coal, oil and natural gas gradually exhausts and the environment problems become serious, development of clean and renewable energy is imminent. Biomass has caused widespread attention because of its near zero emissions of greenhouse gas and acid gases^[1]. At present, biomass accounts for about 9%~14% of the total energy supply in the industrialized countries^[2, 3], while in the developed countries the proportion is about 1/5~1/3^[4], even as high as 90% in some countries. China is rich in biomass resources. The straw and other agricultural waste are up to about 300 million tons of standard coal each year^[5]. And now the area with heating needs in winter accounts for more than 60% of the national area. Accordingly, the population is more than 700 million. Therefore, technology development of biomass hot water boilers is significant in solving winter heating problems and promoting energy conservation and emission reduction. However, the volatile matter content of biomass fuels is usually more than 70%~80%^[6, 7]. The combustion characteristics are different from coal. In addition, biomass also has properties of serious fouling, high moisture and heat value fluctuations^[8-10]. Therefore the design of biomass boilers has its particularity.

Biomass utilization started late in China. The main technology is Danish grate furnace technology. Because of short development time and the lack of theoretical and experimental research accumulation, biomass boilers currently used in China have many problems in fuel preparation, moisture adaptability and boiler efficiency.

In this paper, biomass combustion characteristics and pollutant emissions were studied through experiments. Ash composition and erosion mechanism were analyzed. Aiming at the particularity of



biomass fuels, the design of biomass hot water boilers was briefly introduced. Finally, a successful operation case of a 2.8 MW biomass hot water boiler was provided.

2. Biomass combustion characteristics

2.1. Combustion characteristics

The combustion process of fuels can be divided into volatile precipitation and combustion and residual char combustion. The volatile and char contents of biomass are different from coal, so the combustion characteristics are different. A STA409C thermogravimetric analyzer was used to study the combustion characteristics of wheat straw in this paper. The proximate analysis and ultimate analysis of wheat straw used in tests are given in Table 1. The heating rate was $50^{\circ}\text{C}\cdot\text{min}^{-1}$ and the gas flow rate was $100\text{ml}\cdot\text{min}^{-1}$. Volatile precipitation and fuel combustion characteristics were studied in nitrogen and air respectively. The DTG curves are shown in Figure 1 and Figure 2. The initial precipitation temperature of volatile is about 200°C and the temperature corresponding to the maximum release rate is about 330°C . The index of volatile release characteristics D is 1.1, much higher than that of coal. So the pyrolysis characteristics of biomass are better than coal, with volatile release peak appearing earlier and relatively concentrated, which is beneficial for ignition.

Table 1. The proximate analysis and ultimate analysis of wheat straw.

Proximate analysis (%)				Ultimate analysis (%)				
A	M	VM	FC	C	H	O	N	S
4.76	3.24	75.78	16.22	42.54	3.43	45.13	0.83	>0.06

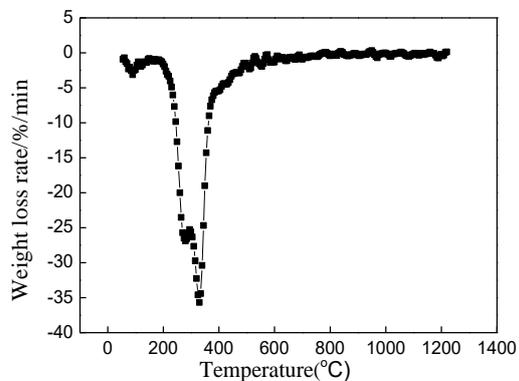


Figure 1. DTG curve in nitrogen

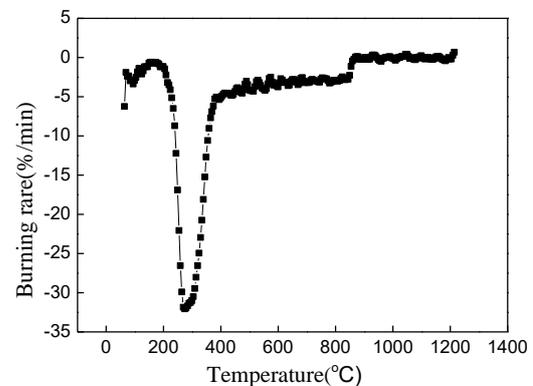


Figure 2. DTG curve in air

In order to further compare the combustion behavior, biomass char and coal char were heated to 900°C in nitrogen and then to 1200°C in air. The DTG curve is shown in Figure 3. It can be seen that the burning rate of biomass char is much higher than coal char.

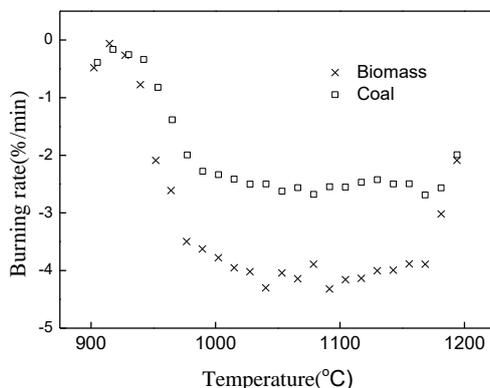


Figure 3. Burning rate of biomass char and coal char

Due to the high content of volatile matter in biomass, accounting for about 80%, as shown in Table 2, its burning rate is higher and burnout time is shorter. A comparison of different biomass and coal is shown in Table 3. The maximum burning rates of different biomass are similar, much higher than bituminous coal and anthracite coal.

Table 2. The proximate analysis and ultimate analysis of biomass

Item	Corm straw	Wheat straw	Korean pine	Sandbreak forest
M _{ad}	4.59	6.30	6.91	1.57
A _{ad}	3.67	3.87	5.57	1.34
V _{ad}	78.84	79.61	79.00	83.93
FC _{ad}	12.90	10.23	8.51	13.17
C _{db}	44.99	45.28	43.74	48.82
H _{db}	5.89	6.12	5.90	6.29
N _{db}	0.82	0.63	0.75	1.16
S _{db}	0.06	0.10	0.06	0.07
O _{db}	48.24	47.87	49.55	43.66
HHV _{ad} (kJ/kg)	17355	16967	17280	19750

Table 3. The maximum burning rate and burn out time of biomass and coal

	Maximum burning rate (s ⁻¹)	Burn out time (s)
Anthracite coal	0.0063	353
Bituminous coal	0.0396	136
Corm straw	0.0530	74
Korean pine	0.0620	73
Wheat straw	0.0600	78
Sandbreak forest	0.0506	69

2.2. Pollutant emissions

Compared with coal, biomass has great advantages in terms of pollutant emissions. In this paper, TGA-FTIR was used to study the pollutant emissions of wheat straw. The samples were heated from 30°C to 900°C in a mixture of N₂ and O₂ with mixing ratio of 4:1. The heating rate was 20°C/min. The flue gas components were recorded. As shown in Figure 4, HCl emission mainly concentrates in volatile combustion stage, with temperature range of 220 ~ 450 °C. The release curve has a single peak with temperature of 310°C. The release curves of SO₂ and NO_x present double peaks as shown in Figure 5 and Figure 6. The first peak is located in the volatile combustion stage with temperature of 320°C. CO₂ emission mainly concentrates in char combustion stage, depending on the carbon content of biomass.

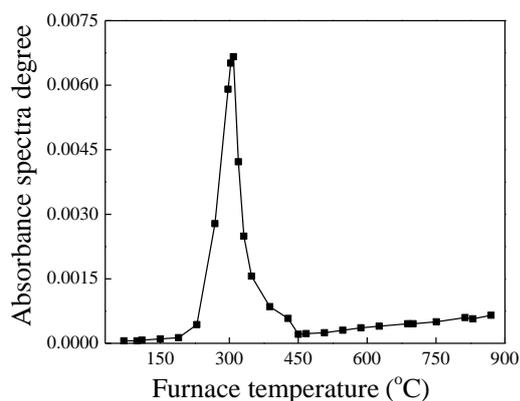


Figure 4. HCl release curve

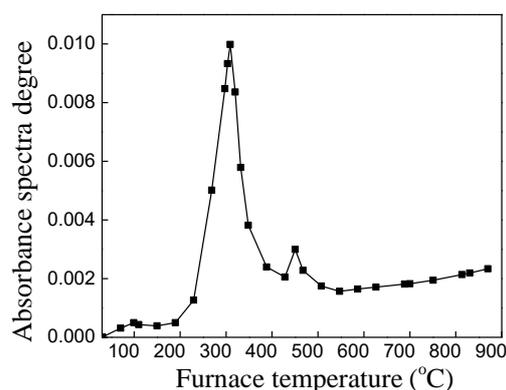


Figure 5. SO₂ release curve

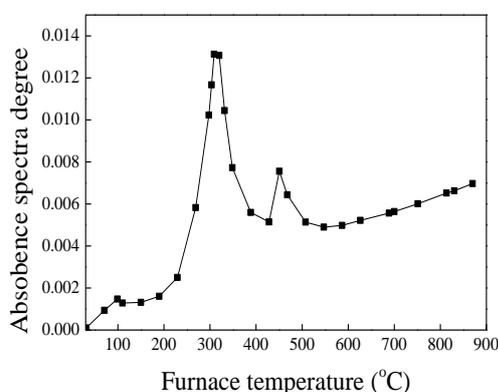


Figure 6. NO_x release curve

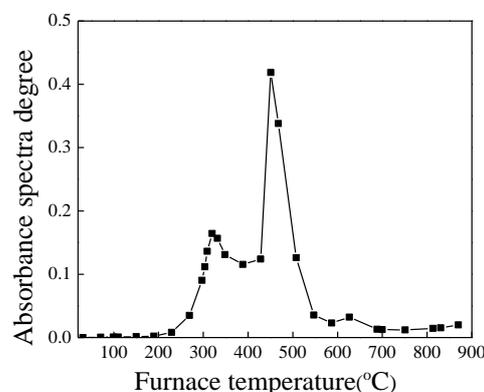
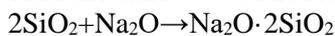


Figure 7. CO₂ release curve

2.3. Ash composition and erosion mechanism

In the process of biomass combustion, sintering may occur. The influencing factors of sintering include temperature and surrounding atmosphere, in which the temperature is the more important one. The size, number and hardness of sintering blocks increase as the temperature increases. The sintering temperatures of different biomass vary, corn straw about 740°C, rice straw and sorghum straw about 680°C. However, the melting points of sand and ash are higher than 1000°C. Generally, this is because that biomass is rich in K and Na. The compounds of these elements react with SiO₂ in sand, generating low melting point eutectic which can bond the sand [11, 12]. The reaction equations are as follows:



Ash slagging characteristics can be estimated by indexes such as Base/Acid ratio B/A, silicon ratio G, silicon aluminum ratio S/A, and iron calcium ratio. The fouling and wearing characteristics can be estimated by indexes H_W and H_M respectively.

$$B/A = (Fe_2O_3 + CaO + MgO + Na_2O + K_2O + P_2O_5) / (SiO_2 + Al_2O_3 + TiO_2).$$

$H_W = B/A \cdot Na_2O$. $H_M = A \cdot (SiO_2 + 0.8Fe_2O_3 + 1.35Al_2O_3)^{[13]}$, in which A is ash content. The discriminant boundaries of these indexes are shown in Table 4^[14-16].

Table 4. Criteria of slagging, fouling and wearing characteristics

Index	Extent			
	Slightly	Moderately	Seriously	
Slagging	B/A	<0.206	0.206~0.4	>0.4
	G	>78.8	78.8~66.1	<66.1
	SiO ₂ /Al ₂ O ₃	<1.87	1.87~2.56	>2.56
	Fe ₂ O ₃ /CaO	<0.3or >3	0.3~3	Around1
Fouling	H_W	<0.2	0.2~0.5(Moderately)0.5~1.0(easily)	>1.0
Wearing	H_M	<10	10~20	>20

Components of different ash samples used in tests are shown in Table 5. Contents of alkaline elements in biomass ash such as K, Na, Ca, and Mg are higher than in coal ash, while contents of acid elements in biomass ash such as Al and Ti are lower than in coal ash. Although the content of Fe₂O₃ in biomass ash is lower, the Base/Acid ratio B/A of biomass ash is still much higher than that of coal ash. So the slagging tendency of biomass ash is severer, especially wheat straw, in which the content of K₂O is as high as 24.60%. The contents of Na in two kinds of biomass ash are similar. However, compared with coal ash, the wearing tendency of biomass ash is minor.

Table 5. Ash composition (%)

Samples	K ₂ O	Na ₂ O	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SiO ₂	TiO ₂
Wheat straw	24.60	1.71	2.48	1.53	7.21	2.54	54.82	0.08
Corn straw	4.40	1.29	6.20	2.80	7.59	8.45	48.99	0.22
Fuxin coal	1.07	0.58	22.26	13.03	3.17	0.53	56.41	1.16
Datong coal	0.91	0.35	27.04	8.09	2.66	0.40	57.70	1.25

Table 6. Slagging, fouling and wearing characteristics of ash samples

Samples	B/A	G	S/A	Fe/Ca	H_W	H_M
Wheat straw	0.66	82.83	22.10	0.21	1.13	2.58
Corn straw	0.44	72.22	7.90	0.37	0.57	1.79
Fuxin coal	0.23	77.13	2.53	4.11	0.13	21.31
Datong coal	0.14	83.81	2.13	3.04	0.05	36.36

The adhesive force of ash was measured. The value of corn straw ash is about 46mg/cm², while coal ash is only 3mg/cm². It can be seen that the adhesive force of biomass ash is significantly higher than that of coal ash. Adhesive force has dual influence on dust removal. If the adhesive force is too high, cleaning performance of bag filter will be affected. If the adhesive force is lower, the tendency of

adhesion in the boiler will weaken, but flying up again of settled dust in rapping will reduce the ESP efficiency.

Microstructures of ash samples were observed through SEM. It can be seen that the microstructure of corn straw ash is small stick and floc with serious surface adhesion and coalescence. However, the microstructure of coal ash is irregular lumps mixed with many porous particles, as shown in Figure 8. This explains the reason of biomass's serious slagging and fouling tendency. It means that the fouling of the convective heating surface is more serious and it should be considered during the convective heating surface design.

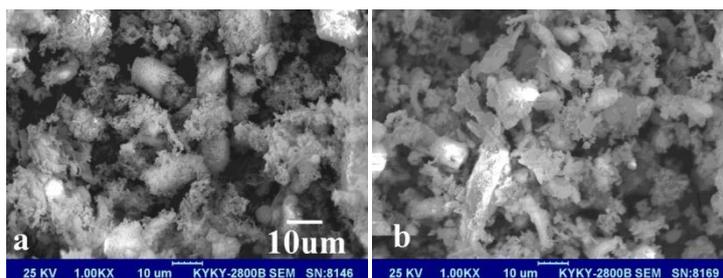


Figure 8. SEM pictures of ash samples
 a: Corn straw ash b: Coal ash

3. Design of biomass hot water boilers

As a fuel, biomass has features such as morphological heterogeneity, high moisture and volatile, low heating value and fixed carbon. It also has corrosive components and properties of heating value fluctuations. Therefore the design of biomass boilers has its particularity. Stable and complete burning should be ensured.

The main parameters of biomass grate-fired boilers are grate heat release rate q_R , furnace volume heat release rate q_V and grate ventilation ratio r . According to the laboratory and industrial research, the recommended value of q_R is 360~435 kW·m⁻², and q_V 160~195 kW·m⁻³. The grate ventilation of biomass boiler is usually small and r can be chosen between 2%~5%. The recommended values of other parameters are shown in Table 7.

Table 7. Characteristic parameters of biomass grate-fired boilers

Item	Symbol	Unit	Value
Excess air coefficient of furnace outlet	a_r	—	1.3~1.5
Heat loss due to unburned gas	q_3	%	0.2
Carbon loss	q_4	%	1~5
Fly ash content	a_{fa}	%	60~90
Supply air temperature	t_k	°C	20~200
Pressure under grate	P	Pa	200~1000

Since biomass burns in semi-suspended state, the secondary air is very important. It not only increases the disturbance in furnace, but also supplies air required for combustion. The secondary air ratio should be 30%~50% and the wind velocity should be 20~30m/s. Based on the experience of tangential pulverized coal boilers, the secondary air of biomass grate-fired boilers can also be arranged tangentially. The nozzle direction can be down dip. The angle is about 10°~25° when the nozzles are arranged on the front and rear wall, and 40°~45° when the nozzles are arranged in the corners. The position of nozzles is related to the down dip angle and airflow range. In order to ensure that the flue gas has sufficient burning time without disrupting normal burning of the bed surface, generally the distance of nozzles to the fuel layer surface should be 0.6~ 2m.

Due to the differences of fuel characteristics and boiler structures, the heat transfer calculation of biomass grate-fired boilers should not simply follow the method of coal grate-fired boilers. In this paper, the heat transfer model suggested by Tsinghua University was adopted to design the furnace^[17]. As the moisture contents of biomass and coal are different, the heat transfer of flue gas also differs. Therefore, the convective heating surface was carefully arranged. The contribution of moisture is considered by introducing a correction factor C_r , which is more than 1^[18]:

$$Re = 150 \sim 400, \text{ for in-line tube bundles subjected to cross flow,} \\ Nu = 0.2C_r C_z C_s Re^{0.65} Pr^{0.33}. \tag{1}$$

$$C_r = 1.18011 + 0.82808(r_{H_2O} - 0.25) - 2.06252(r_{H_2O} - 0.25)^2 \tag{2}$$

$$Re = 150 \sim 400, \text{ for staggered tube bundles subjected to cross flow,} \\ Nu = 0.358C_r C_z C_s Re^{0.6} Pr^{0.33}. \tag{3}$$

$$C_r = 1.01025 + 0.56505(r_{H_2O} - 0.25) - 1.92401(r_{H_2O} - 0.25)^2. \tag{4}$$

$$Re = 5000 \sim 13000, \text{ for tube bundles subjected to longitudinal flow,} \\ Nu = 0.023Re^{0.8} Pr^{0.4} C_t C_1 C_r. \tag{5}$$

$$C_r = 1.13598 + 0.42449(r_{H_2O} - 0.25) - 1.02091(r_{H_2O} - 0.25)^2 \tag{6}$$

4. Operation performance

Based on the above results, a 2.8 MW biomass hot water boiler was developed and tested under the loads of 1.7 MW and 2.8MW. The boiler structure diagram is shown in Figure 9. The fuel is local corn straw bales. On the premise of ensuring the fuel fluidity and boiler stable operation, the fuel cost is reduced^[19]. The proximate analysis and ultimate analysis of corn straw are shown in Table 8.

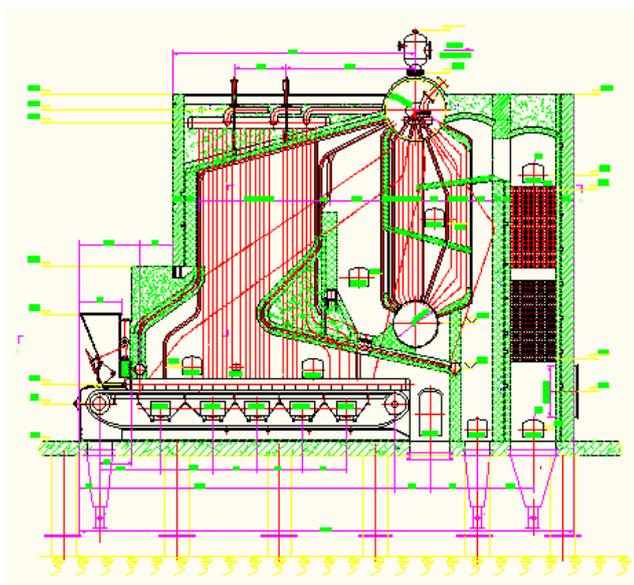


Figure 9. Boiler structure diagram

Table 8. The proximate analysis and ultimate analysis of corn straw (%)

War	Wad	Aad	Vad	Cf	Cad	Had	Nad	Sad	Oad	Qnet(MJ/kg)
39.6	8.8	5.3	65.9	20.0	31.9	3.8	1.7	0.2	62.5	16.3

As the load increases from 1.7MW to 2.8MW, the carbon content of bottom slag significantly decreases, as shown in Table 9. It is because that the total air volume and secondary air flow increase

as the load increases. The secondary air jet flow has an important influence on the flow field of the lower region. With the primary air, it forms a larger vortex area, not only supplying oxygen better, but also increasing the fuel residence time in high temperature zone. Therefore, the overall furnace temperature increases, favourable to fuel burning out and efficiency improvement. The boiler efficiency is higher than 85% under both loads.

Table 9. The carbon content of fly ash and bottom slag

Load (MW)	Bottom slag (%)	Fly ash (%)
1.7	4.33	2.09
2.8	2.60	1.94

Table 10. Operation performance of 2.8MW biomass hot water boiler

Item	Results	
	1.7MW	2.8MW
Circulating water flow (kg/s)	19.89	19.89
Supply water pressure (MPa)	0.5	0.5
Supply water temperature (°C)	42	59
Backwater temperature (°C)	32	35
Feeding water pressure (MPa)	0.550	0.550
Air temperature of fan outlet (°C)	20	20
Blowdown rate (%)	0	0
Exhaust gas temperature (°C)	98	99
Oxygen content in flue gas (%)	9~11	9~11
Boiler efficiency (%)	86.19	88.21

5. Conclusions

Biomass has particularities on combustion characteristics and pollutant emissions. Compared with coal, the volatile matter content of biomass is much higher. The burning rates of biomass and biomass char are also similar. During biomass combustion, HCl emission mainly concentrates in volatile combustion stage, presenting a single peak as temperature increasing. The release curves of SO₂ and NO_x present double peaks. The first peak is located in the volatile combustion stage. CO₂ emission mainly concentrates in char combustion stage, depending on the carbon content of biomass. The slagging tendency of biomass ash is severer than coal ash and the adhesive force of biomass ash is higher. However, compared with coal ash, the wearing tendency of biomass ash is minor. Aiming at the particularity of biomass fuels, this paper briefly introduces the design of biomass hot water boilers. On this basis, a 2.8 MW biomass hot water boiler was developed and tested under the loads of 1.7 MW and 2.8MW. The running results show that the carbon content of bottom slag significantly decreases as the load increases. The boiler efficiency is higher than 85% under both loads.

Acknowledgements

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