Experimental and Numerical Analyses on Ignition and Burnout Characteristic of Low-Rank Lignite and Semi-Char Blends

Ye Yuan, Shuiqing Li, and Qiang Yao

Abstract

The coal utilization and conversion in China are mainly consumed by combustion. In particular, co-firing of coal blends plays an important role in solving the urgent energy problems in China. In this work, the fundamental work on the combustion characteristics (ignition and burnout) of low-rank lignite and semi-char are conducted. TGA (thermal gravimetric analysis), WMR (wire mesh reactor), ODF (one-dimensional furnace), and Hencken flat flame burner are the main research techniques and also the method used in this work to study the two characteristics. The ignition is quite easy when the char fraction is between 15 and 40 %. The heterogeneous ignition becomes much easier when we increase the fraction of semi-char in the blends. The peak burnout value is of 10–30 % semi-char fraction. Results indicate that the blend coal characteristic ignition time is close to char in 1800 K and approaches low-rank coal ignition in 1500 and 1200 K, in accordance with the mechanism effect.

Keywords

Ignition • Burnout • Heterogeneous • Homogeneous

1 Introduction

The coal utilization and conversion in China are mainly consumed by combustion which is contributed to the environmental pollution. However, the huge amount exist of low-rank coal brings more challenges to energy efficiency improvement and environmental pollution control. Meanwhile, the semi-char application in power plant after low-rank coal upgrading is also one of the most promising short-term options for clean coal utilization field. Compared with other kinds of coal, semi-char is difficult to ignite with less volatile remained. In practical system, blend coal combustion or co-firing system is adopted. In this research, the fundamental work on the combustion characteristic, including ignition and burnout of low-rank coal and semi-char, is conducted [1, 2].

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First, a short summary is given for the previous research on the ignition mechanisms of a single particle burning in air. Coal particle may experience a homogeneous gas phase ignition (GI), heterogeneous ignition (HI), or hetero-homogeneous joint ignition. The GI refers to a gas phase ignition of pyrolytic vapors from coal that is similar to oil drop ignition, whereas the HI stands for the direct oxidation of char and in situ volatiles at the particle surface [3, 4]. Artos et al. [5], Qiu et al. [6] and Pan et al. [7] have done some work on blend ignition. Factors influencing the coal or blend combustion behavior include the nature of coal blend, fluid dynamic pattern, mixing, thermal energy release and loss and the structure of burner and boiler furnace. Besides, the difficulty of evaluating the performance of blended coal is due to he interaction, different volatile release behavior, and ignition temperature. It is necessary to understand the combustion behavior of coal blends to predict the ignition and flame stability for designed boiler [8]. The burnout of coal can depend on the amount of volatile matter quickly released from the coal, the resultant structure of char, the size of the char

G. Yue and S. Li (eds.), *Clean Coal Technology and Sustainable Development*,
DOI 10.1007/978-981-10-2023-0_9

particle, the reactant, the partial pressure of the reactant, furnace temperature, and the residence time in the furnace. Laboratory-scale experiments have significant differences compared with practical power plant system. Some experiments show that there is no interaction between burnout of coals in coal blends burned in the thermal gravimetric analysis (TGA) and DTF. The pilot scale studies are more necessary than laboratory-scale to make a conclusion about the additivity of blended coals burnout [9, 10].

TGA, WMR (wire mesh reactor) [11], ODF (one-dimensional furnace) [12], and Hencken flat flame burner [13] are the main research techniques and also the method used in this work to evaluate the ignition and combustion characteristic. Due to their heating rate and reaction type, TGA is normally used for homogeneous ignition and WMR is special for heterogeneous ignition. High-temperature ODF [14] has highest heating rate among these methods, and it is most similar to coal combustion in power plants. Besides, the ignition characteristic measured on high heating rate Hencken burner combined with a novel-dispersed particle feeder can be regarded as a statistical summation of ignitions of all isolated particles, which meanwhile refers to the large particle spacing ratio in industrial pulverized coal combustion [15]. All these above setups used in this paper are to evaluate the combustion characteristic of coal blends. The understanding of coal blends combustion behavior in different heating rate and reaction type will be useful in assessing the combustion characteristics.

2 Experimental Methods

The TGA used in this paper is Q500. The TGA measures only ignition at low heating rates of held samples. The low heating rate will result in volatile release at lower temperature. The WMR established by our research group and is similar to that described by Gibbins et al. [16]. A thin layer of coal particles is sandwiched between two layers of wire mesh that are heated directly with an electrical current, which can achieve a high heating rate around 10^4 K/s. The reaction gas mixture (air) passed through the sample laden mesh. The volatiles were swept away by this stream of reaction gas from the parent coal as soon as they were released from the particles. The burnout experiments were performed in a 25 kW one-dimensional, self-sustained, down-fired combustor, with 150 mm ID and 3.4 m height. A detailed description of the setup as well as the procedure of conventional air mode can be found in literature [11]. A multi-element non-premixed flame burner, known as Hencken burner, is also used in this work. The burner can provide a steady high-temperature environment with good optical access. The main part of the burner includes a ceramic honeycomb with hundreds of ID 1.2-mm stainless steel tubes producing hundreds of multi-element non-premixed flamelets offering uniform hot flow of combustion product gases. Meanwhile, a novel particle feeder is developed based on the deagglomeration principle for particle feeding and the LaVision QE ICCD (intensified charge-coupled device) is adopted to get the visible light intensity, including black body emission and chemiluminesce. The height above the burner corresponding to the 10 % peak signal intensity is regarded as the characteristic ignition position for future analysis. The smaller characteristic ignition position, the less time the particle need to be ignited, and the coal are easier to be ignited [15].

Four kinds of coal are used in this work, including a lignite coal from Hulunbel sites, a bituminous, a semi-char from lignite and lantan (name of char). Table 1 shows the proximate analysis and elemental analysis of the three kinds of coal. All the coal particles have been screened to 65–74 μm as the same size of the pulverized coals in industrial

Table 1 Research methods for coal combustion

Content	TGA	WMR	Drop tube	1DEFR
Scale	Micro	Micro	Bench	Polot
Feeding rate	10 mg	A few particles	5–20 g/h	1.5 kg/h
Reaction type	Fixed bed	Particle dispersed	Particle dispersed	Entrained suspended
Controlled regime	Kinetic	Kinetic	Diffusion	Diffusion transport
Heat balance	External heated	External heated	External heated	Self-sustained
Heat rates	10–100 K/min	10^3–10^4 K/s	10^4–10^5 K/s	10^5–10^6 K/s
Usage	Reaction release	Ignition	Reaction PM	Burnout ash fouling

Table 2 Proximate analysis and elemental analysis of three kinds of coals

Content	Semi-char	Lignite	Bituminous	Lantan
Proximate analysis (wt% dry basis)				
Fixed carbon	62.76	49.07	55.52	82.52
Volatile	20.22	38.83	24.11	7.27
Ash	17.02	12.10	20.37	10.21
Heating value (MJ/kg)	23.39	19.83	25.26	27.7
Elemental analysis (wt% air dry)				
C	61.4	62.14	63.88	73.78
H	2.36	3.5	3.4	0.31
O	13.0	17.18	8.73	8
N	1.06	0.84	0.69	0.9
S	0.16	0.26	0.72	0.46

power plant. All the pulverized coals are dried before ignition experiments, so there are only dry basis analysis data in Table 2.

3 Results and Discussion

There is a lot of burning profile curves of a powered sample with time as a function of furnace temperature determined by TGA/DTG. To the extent that heating rate and particle packing is different compared with those in practical power system, the temperature when the volatile is released is more important than other parameter. The initial temperature (IT) in a burning profile is defined as the temperature at which the rate of weight loss is above 1 %/min. The IT is not the ignition temperature; however, it is the temperature at which the coal starts devolatilization. As shown in Fig. 1, the trend of the two IT trends is consistent and the IT decreases first and remains increase as the char ration increases (lantan is also a kind of char). The IT in the char fraction between 15 and 40 % is about 30 centigrade lower that any other blend char ratio. The blend coal devolatilization and homogeneous ignition is easier in the region mentioned above. In this case, more volatile is not better. An appropriate ration of low-volatile char contained in the blends can only enhance the devolatilization and homogeneous ignition characteristics. Similar experiments are also executed on WMR. Based on the heating rate and the way of reaction gas passing, the surface reactivity and heterogeneous ignition ability have more significant effect on the ignition temperature during WMR heating process. The coal sandwiched between the two layers of mesh is heated in the absence of secondary reaction with volatile and we get the heterogeneous ignition temperature. We can find from Fig. 2 that when the proportion of Lantan ratio is less than 50 %, there are some fluctuations in the ignition temperature, but do not differs too much, suggesting that the smaller proportion of Lantan does not affect the ignition temperature of bituminous coals. When the Lantan ratio is higher than 50 %, the ignition temperature drops significantly. We can also find the phenomenon in lignite and semi-char blend WMR experiment. It seems like that the lantan and semi-char separately own better surface reactivity than bituminous and lignite. As their ratio is above 50 %, their higher heterogeneous reaction performance decreases the overall ignition temperature. Because the homogeneous and heterogeneous ignition mechanisms are different, blend coal ignition characteristics show different trends of variation with that in TGA experiments, due to the less impact of volatile in WMR.

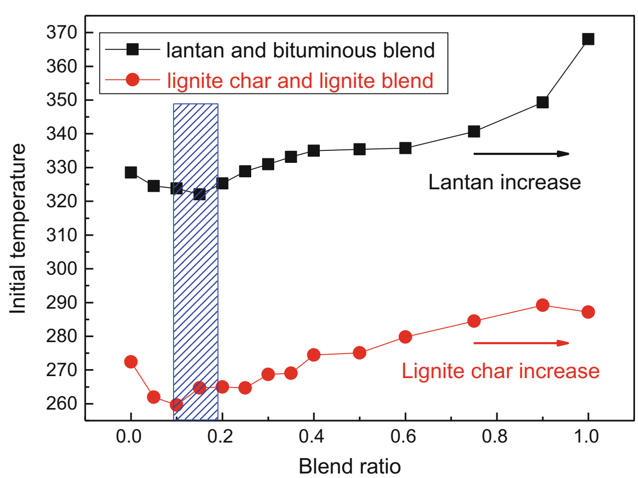

Fig. 1 Change of initial temperature via blend ratio

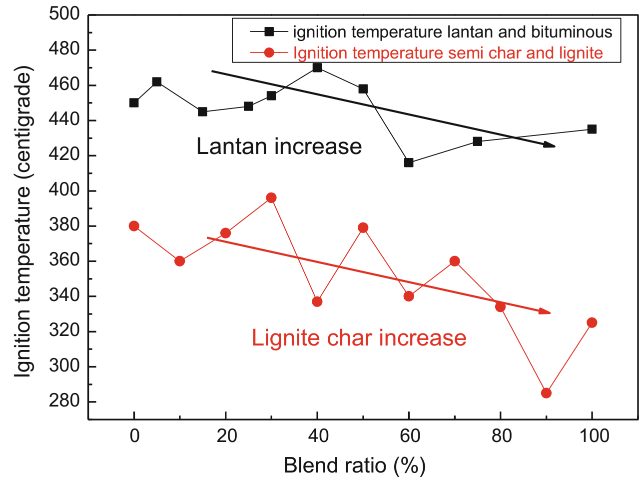

Fig. 2 Change of ignition temperature via blend ratio

Compared with the reaction type in TGA and WMR, the ignition in Hencken burner is much more similar to the practical power system ignition. Here, the blend coal ignition experiments of lignite and semi-char were carried on Hencken to examine the characteristic ignition time compared with their separate ignition. The semi-char blend ratio was 50 %. In our previous work [15], we find that in the temperature range from 1200 to 1800 K, a transition from heterogeneous ignition to heterogeneous–homogeneous ignition occurs due to coal pyrolysis occurring earlier. In heterogeneous or heterogeneous–homogeneous ignition modes, the semi-char coal exhibits a relatively lower ignition time than the lignite coal because of its better carbon reactivity. Further in high temperature, the reason why the difference between the two kinds of coal is narrowed is contributed to the earlier gas phase flame participation. Results in Fig. 3 indicate that the blend coal characteristic ignition time is close to char in 1800 K and approaches low-rank coal ignition in 1500 and 1200 K. In relative low temperature, the ignition is dominated by surface reactivity.

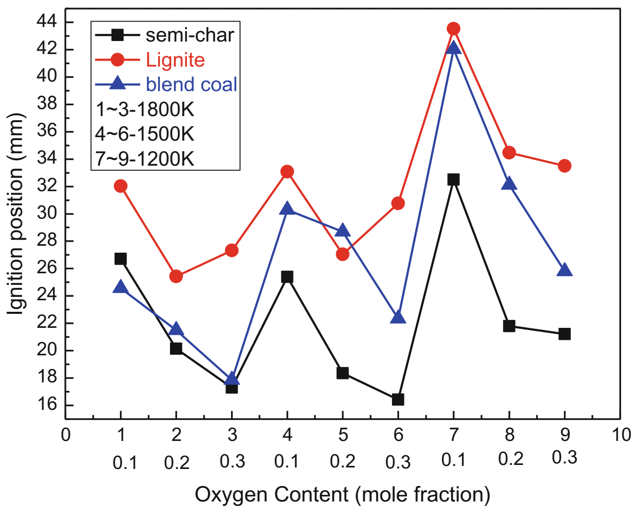

Fig. 3 Change of ignition position via oxygen content

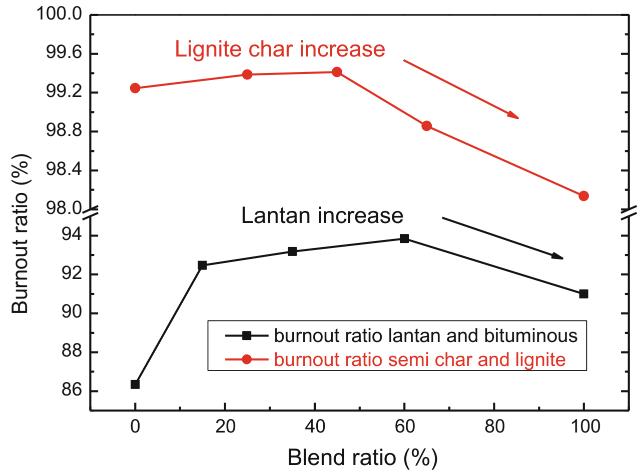

Fig. 4 Change of burnout ratio via blend ratio

The blend ignition characteristic position is close to the one which owns worse heterogeneous ignition characteristic. However, in high temperature such as 1800 K, more volatile releases during particle heating process, and the gas phase flame improves the heterogeneous combustion. So, the ignition characteristic in 1800 K is enhanced a lot and approaches semi-char.

The 1D down-fired furnace is widely used and it possesses advantages in measuring flame stability and burnout characteristic more than measuring ignition characteristic. The burnout test in high-temperature zone is reliable by this setup. The experimental process needs to pay attention to the operational condition control, including the temperature distribution, the residence time of the coal particles, the air flux, and the preheating temperature. In the course of this project, the above factors have been more carefully considered. It is presented in Fig. 3 that burning both Lantan and bituminous alone has lower burnout. Particularly, as for bituminous alone, the burnout value is even blow 90 %, indicating that bituminous is very difficult to burn out. When we blend Lantan with HBC, the burnout rate improves significantly. Particularly, at a point of adding 15 % lantan into bituminous, the burnout value increases by 6 % in contrast to bituminous case. It is included that the mix of Lantan greatly improves the bituminous burnout characteristics. When the ratio of Lantan in bituminous increases from 15, 35 to 60 %, the burnout value increases slightly. It is noted that as for a case of burning Lantan alone, the burnout value is much lower than that in the blending case, which means that a part of bituminous can also improve the combustion of Lantan. The two kinds of coal can enhance each other during the combustion process. For further analysis, we can deduce as below. First, in blend experiments, the initial bituminous devolatilization is helpful to ignition of Lantan. Secondly, in post-flame char combustion, the Lantan char has a much better combustion rate in contrast to the pyrolytic char from bituminous, which is consistent with the results from the wire mesh experiment aforementioned. That is, after the removal of volatile content, the Lantan owns better char reactivity. Similar changing behavior can also be found in semi-char and lignite blend, due to the same reason of the interaction between volatile and surface reactivity. Nevertheless, the burnout ratio of lignite and semi-char changes from 99 to 98 % without interaction improvement. Overall, the suggested blend ratio in blend coal combustion is around 40 % (Fig. 4).

Separate ignition model of homogeneous ignition and heterogeneous ignition is introduced here to analyze the ignition behavior of different blends [17, 18]. As before, blend coal particles experience different ignition mechanisms in different reaction furnaces. Here, we calculate the ignition delay separately. In a gas phase homogeneous one-step reaction, according to adiabatic thermal explosion theory, the ignition delay time is given by:

$$t_{\mathrm{i}} = \frac{C_{\mathrm{v}}(T_0^2/T_{\mathrm{a}})}{q_{\mathrm{c}} Y_{\mathrm{F},0} A \exp(-T_{\mathrm{a}}/T_0)}$$

where C_{v} is the constant volume-specific heat of the background gas, and T_{a} is the activation temperature defined based on activation energy. T_0 is the IT of the local fuel/oxidizer mixture. Q_{c} is the combustion heat release per mass of the fuel, $Y_{\mathrm{F},0}$ is the initial mass fraction of fuel. The ignition delay time of a solid carbon particle in a drop tube furnace can be calculated by the following expression of Bandyopadhyay and Bhaduri, based on energy equation:

$$t_i = \frac{d_p}{B}\int_{T_{p0}}^{T_{pi}} \times \frac{dT}{\frac{273}{T_g}A\left[\frac{0.01O_2}{\frac{1}{k_0 e^{-E/RT}}+\frac{d_p}{2D_0(T_g/273)^2}}\right]+\frac{2k_f}{d_p}(T_g-T)+\sigma(T_w^4-T^4)}$$

where ρ is the density, β is the ratio of the weight of coal to the weight of oxygen, and φ is the calorific value of coal. C_d is the specific heat of coal. D_p is the particle diameter. T_g is the gas temperature, O_2 is the oxygen concentration in the reacting gas, D_0 is the diffusion coefficient at a reference temperature, k_f is the thermal conductivity coefficient of the gas, and T_w is the wall temperature of the furnace. E and k_0 are activation energy and pre-exponential factors in the Arrhenius form of the reactivity of each coal, respectively. The Nusselt number of the flow for small particles of this work is 2.

Under the quiescent gas condition, the blend coal particles ignited homogeneously in TGA reactor. Ignition delay times are plotted in Fig. 5 with hollow symbol against blend ratio. It can be seen that ignition delay times are analogous to the IT for both kinds of blend. The particle which has the lower IT will be ignited more easily in less ignition delay time. However, in higher blend ratio, the homogeneous ignition delay does not show much reduction because of higher energy release. We can infer from the equation that the QC combustion heat release is one of the dominator terms and it will dominate the ignition delay time in higher blend ratio. Actually, the heat release in TGA is rather small compared with the external heat. The equation above illustrates that ignition delay is the area under the curve in the T-$f(T)$ surface. Therefore, the parameter that increases the function $f(T)$ also increases the heterogeneous ignition delay times. Enhancement of oxygen mole fraction, gas conductivity and binary gas diffusivity, reactivity, density, specific heat and calorific value of coal consequently decrease ignition delay time. The heterogeneous delay times are located as lines in Fig. 5. In general, the ignition delay time decreases with increase reactivity kind coal in the blends, which is almost consistent with the changing behavior of ignition temperature measured on WMR.

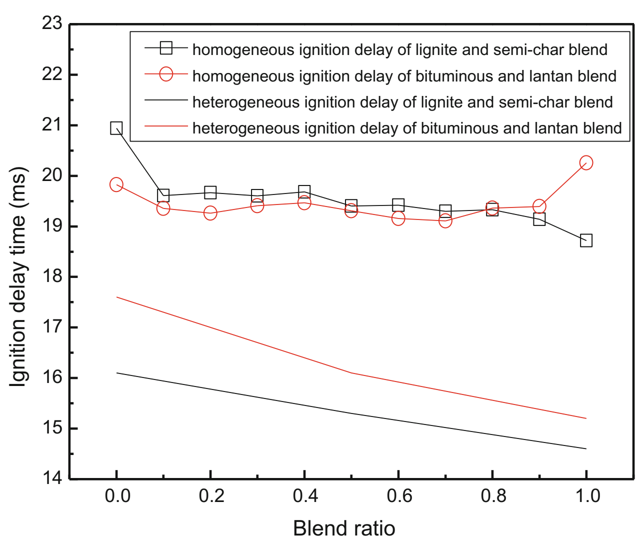

Fig. 5 Change of ignition delay time via blend ratio

4 Conclusion

In this work, the fundamental work on the combustion characteristics (ignition and burnout) of low-rank lignite and semi-char is conducted, which aims to provide the basic data for the current low-rank lignite and semi-char utilization in power plants. TGA, WMR, ODF, and Hencken flat flame burner are the main research techniques and also the method used in this work to study the two characteristics. Based on the experimental and numerical analyses, we can find that the homogeneous ignition is quite easy when the char fraction is between 15 and 40 %. The heterogeneous ignition becomes much easier when we increase the fraction of semi-char in the blends, especially in the ratio above 50 %. In Hencken burner, coal particles experience heterogeneous ignition in high ambient temperature and heterogeneous–homogeneous joint ignition in relative lower ambient temperature. Results indicate that the blend coal characteristic ignition time is close to char in 1800 K and approaches low-rank coal ignition in 1500 and 1200 K, in accordance with the mechanism effect. The peak burnout value of blend coal property appears in the region of 10–60 % semi-char fraction. Overall, the suggested blend ratio in blend coal combustion is about 30–40 %.

Acknowledgments This work was supported by the Key Project of Natural Science Foundation of China (No.) and National Institute of Clean-and-Low-Carbon Energy financial support.

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