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Ignition characteristic of blended coal in a drop-tube furnace

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Abstract. The ignition of pulverized coal is an important preliminary step in the coal combustion process, due to its influence on flame stability, the formation and emission of pollutants and flame extinction. In recent years there has been an increasing utilization of coal blends for combustion, but information on the changes of coal flame during ignition process is scarce. In this work the ignition behavior of a series of coal blends, made up from four coals of different rank was studied in a drop-tube furnace. A new method of oscillation frequency based on empirical mode decomposition is introduced. The Ignition feature of oscillation frequency was obtained from the coals studied; the feature proved well in distinguishing ignition mechanisms from homogeneous, hetero-homogeneous to heterogeneous in the ignition section of a drop-tube furnace. The different ignition mechanisms of coal blends were observed depending on the blends mass proportion and inclined to the characteristic of the coal consisted of higher volatile.

1. INTRODUCTION
The coal blending from multiple sources for power generation is a global practice in the commercial utilities. This is due to strategic, environmental reasons or in order to improve the combustion properties of the blended coal. The ignition of coal particles is an important preliminary step in the coal combustion process. The reactivity and ignition behaviors of coal particles are of considerable importance for designing the boiler and controlling the combustion process (Faundez et al., 2005; Su et al., 2001).

It is now generally accepted that coal particle ignition is a multistage process. The ignition of coal particles may take place in homogeneously, heterogeneously or hetero-homogeneously. In the homogeneous ignition, the initial step involves pyrolysis, subsequent ignition of volatiles which react in the gaseous phase surrounding the coal particles and followed by ignition of the char. The heterogeneous coal ignition involves the direct attack of oxygen on the whole coal particles. The hetero-homogeneous ignition is the simultaneous ignition of the volatile matter and the coal particle surface, which is the intersection of homogeneous and heterogeneous ignitions (Essenhigh et al., 1989; Zhang et al., 1994).

TGA techniques have been widely employed to determine the ignition behavior of coal, they can operate at very different conditions to those encountered in a pulverized coal combustor (Arenillas et al., 2004; Essenhigh et al., 1989;). Drop-tube furnaces (DTF) more closely simulate combustion conditions in industrial pulverized-coal combustors than thermogravimetric analyzers.
This paper reports a novel method on judging the ignition behavior of coal blends at the ignition section in a drop-tube furnace. The characteristic parameter based on empirical mode decomposition of the flame signal is determined from a flame monitoring system. The ignition behavior of coal blends can be obtained from the characteristic parameter.

2. Methodology

2.1 Drop-tube furnace and test conditions

A drop-tube furnace (DTF) is designed for laboratory experiments under similar conditions in temperature and residence time as those of industrial boilers and power plants. A schematic diagram of the drop-tube furnace utilized in the present study is depicted in Fig. 1. A heating rate of $10^4$-$10^5 \text{C}^\circ \text{s}^{-1}$ and maximum temperature of 1500°C can be achieved in the DTF. In addition, the particles are in a dynamic, dilute phase, which allows for individual and cloud particle combustion.

The ignition section and burnout section are the main parts of the furnace. The auxiliary equipment consists of an air compressor, air preheater, flow metering device, pulverized fuel feeder, etc. The DTF is heated by silica-carbon rods which are perpendicular to the furnace axis. There are 15 quartz optical windows with a diameter of 7mm along the axial direction of the ignition section which is used to observe the ignition of pulverized coal. The data reported in this paper are obtained from 9 quartz optical windows. The ignition and burnout sections can be heated to maximum temperatures of 1000°C and 1500°C, respectively. The latter is normally used for burnout and slagging experiments. The flow rate of air is measured using a spinner flow meter and the air preheater heats secondary air before it goes into the DTF. Thermocouples are used to measure the wall temperature of the air preheater and the temperatures of ignition section, burnout section and secondary air. The experimental process is monitored and controlled through an on-line computer data acquisition system. A screw feeder is used to feed pulverized coal. By changing the rotation speed of the electromotor, the desired feeding rate can be obtained.

In this study, the temperatures of the ignition and burnout sections were kept constant at 850°C and 1350°C respectively in all the experiments. The size of coal particles is below 180 micron which is sized through a screen of 80 meshes. The feeding rate of the feeder was 1.2kg/h. In the present research four coals of different rank with a mass ration of 70% to 30%, 60% to 40%, 50% to 50%, 40% to 60% and 30% to 70% were tested. All types of coal were sources from coal fired power stations. Table 1 summarizes the proximate analysis, ultimate analysis and gross calorific value. It is clear that single coals A, B, C and D have the higher volatile content (>25%). The volatile content of coal blends which affect the ignition behavior very much are between 25% and 30%. The property of the coal blends approach to the main coal as its mass proportion increases. It is important to note that two coals with the similar proximate analysis may not have the same ignition and flame stability characteristics, because the ignition and flame stability depend on early heat release, not necessarily early volatile release (Su et al., 2001).
Fig. 1 Experimental apparatus of the drop-tube furnace

Table 1. Properties of pulverized coals tested

| Coal sample | Proximate analysis (wt%, ad) | Ultimate analysis (wt%, ad) | Gross calorific value (MJ/kg) |
|-------------|-----------------------------|----------------------------|------------------------------|
|             | M  | A  | V  | FC | C  | H  | N  | S  | O  |                      |
| A           | 7.24 | 12.13 | 30.57 | 50.06 | 60.61 | 4.45 | 0.98 | 0.47 | 14.12 | 25.72 |
| A:B (70%:30%) | 5.86 | 16.76 | 30.03 | 47.35 | 58.83 | 4.3 | 0.89 | 0.37 | 12.99 | 24.20 |
| A:B (60%:40%) | 5.38 | 18.10 | 29.44 | 47.08 | 57.86 | 4.38 | 0.92 | 0.39 | 12.97 | 24.82 |
| A:B (50%:50%) | 4.88 | 19.60 | 29.28 | 46.24 | 56.94 | 4.29 | 1.16 | 0.36 | 12.77 | 24.36 |
| A:B (40%:60%) | 4.54 | 19.91 | 29.26 | 46.29 | 56.72 | 4.26 | 0.88 | 0.44 | 13.25 | 24.47 |
| A:B (30%:70%) | 4.18 | 21.44 | 29.09 | 45.29 | 55.76 | 4.32 | 0.96 | 0.39 | 12.95 | 23.19 |
| B           | 2.55 | 26.15 | 27.82 | 43.48 | 53.50 | 4.16 | 1.10 | 0.44 | 12.10 | 23.36 |
| C           | 20.26 | 21.67 | 28.40 | 29.67 | 40.40 | 1.56 | 1.09 | 0.33 | 14.69 | 17.11 |
| C:D (70%:30%) | 11.09 | 28.15 | 28.21 | 32.55 | 42.74 | 1.77 | 1.05 | 0.44 | 14.76 | 18.24 |
| C:D (60%:40%) | 11.02 | 29.00 | 27.41 | 32.55 | 42.67 | 2.08 | 1.02 | 0.43 | 13.78 | 18.03 |
| C:D (50%:50%) | 9.68 | 30.28 | 27.51 | 32.53 | 42.32 | 1.78 | 1.01 | 0.46 | 14.47 | 18.13 |
| C:D (40%:60%) | 8.15 | 32.12 | 27.09 | 32.64 | 42.32 | 1.81 | 0.97 | 0.50 | 14.13 | 18.19 |
| C:D (30%:70%) | 6.53 | 34.03 | 28.83 | 30.61 | 42.21 | 1.63 | 0.94 | 0.53 | 14.13 | 18.83 |
| D           | 5.49 | 36.21 | 26.27 | 32.03 | 42.25 | 2.21 | 0.81 | 0.56 | 12.47 | 18.16 |
2.2 Flame monitoring system

The system consists of a flame detecting probe, photodiode drive circuit, signal processing circuit, data acquisition unit and PC-based signal processing software. Fig.2 shows the structure and main components of the system. The flame detector has four photodiodes covering the visible and infrared bands. The detector produces four flame signals containing the dynamic characteristic information of the flame and hence the ignition characteristics of the fuel (Xu et al., 2004). In this study, only one flame signal which band is between 400nm and 1100nm is used to produce the characteristic parameters.

When monitoring, the flame monitoring probe whose diameter is the same as that of the optical window is pressed closely against the observation window of a DTF. The flame signal was sampled with a frequency of 1kHz and a data length of 20 seconds. At the whole experiment the combustion are stable on different observing window at different time due to an on-line furnace monitoring system.

2.3 Empirical mode decomposition

The Empirical mode decomposition (EMD) method which is proposed to analyze the complex signal (Huang et al., 1998) decomposes a time-series into a finite set of oscillatory functions called the intrinsic mode functions (IMF). An IMF function must satisfy two conditions: (1) the number of extreme and the number of zero crossings must either equal or different at most by one; (2) At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero. Obviously, most original signals do not satisfy those requirements and need to be decomposed into some different IMF components. The process is called EMD. The procedure to decompose a signal \( x(t) \) into intrinsic mode functions is as follows:

1. Identify all extreme of \( x(t) \);
2. Interpolate between maxima to obtain an envelope \( e_{\text{max}}(t) \);
3. Interpolate between minima to obtain an envelope \( e_{\text{min}}(t) \);
4. Compute the running mean, i.e. \( m(t) = [e_{\text{max}}(t) + e_{\text{min}}(t)]/2 \);
5. Subtract \( m(t) \) from \( x(t) \) to extract the detail \( h(t) = x(t) - m(t) \);
6. Examine if \( h(t) \) is an IMF;
7. If not iterate on the detail \( h(t) \); this is called the sifting process.

An IMF \( C_j(t) \) is extracted once the detail signal \( h(t) \) is zero-mean and the number of extreme with the number of zero crossings equal or differ at most by one. The first IMF is subtracted from the original signal \( x(t) \); the difference called the first residue \( r_1(t) \). This residue is treated as the new signal and the whole process is repeated. The sifting process ends when the last residue \( r_N(t) \) is a constant or a monotonic function. The signal \( x(t) \) is written as the sum:

\[
x(t) = \sum_{j=1}^{N} C_j(t) + r_N(t) \quad (1)
\]

Fig. 3 is the IMFs of typical flame signal. It can be seen that the coal flame signal can get N IMFs and a residue. C1–C10 are listed from high frequency to low frequency. At the same time IMF with high frequency and low amplitude have great influence on the result of oscillation frequency of a coal flame.
In the calculation of the oscillation frequency, the IMFs with high frequency (>50Hz) are taken as noise from the signal. For example, the coal flame signal in fig. 3, the frequency of C1~C3 are 377Hz, 192Hz and 82Hz which are not belong to the intrinsic fluctuation of coal flame, so they are cut from the original signal. The new signal is made up of the rest IMFs and residue.

\[ f_o = \sum_{i=1}^{n} P_i f_i \]  

Where \( n \) is the number of the IMFs which frequency is below 50Hz, \( f_i \) stands for the \( i \)th IMF which frequency is below 50Hz and \( P_i \) is the weighted factor of the \( i \)th IMF of the flame signal.

Fig.3 the resulting empirical mode decomposition components from the coal flame (a) the original data and the components \( c1~c5 \); (b) the components \( c6~c10 \). Notice the last component res. is not an IMF; it is the trend.

2.4 Feature extraction-
The parameters of a flame can vary, depending upon the type and structure of the furnace and the targeted interests (Lu et al., 2008). It should be noted that the ignition section of a drop-tube furnace is the primary reaction zone of a coal combustion process in term of energy conversion and combustion products formation, the flame signal obtained from flame monitoring system is naturally fluctuating due to the inherent dynamic nature of the flame. According the characteristics of the furnace and the flame, the following parameter is measured:

Oscillation frequency (\( f_o \)) – the mean frequency at which the flame fluctuates, which is defined as the weighted average frequency of the IMFs of coal flame signal.

3. Result and discussion
Fig 4 shows that the oscillation frequency of coals in the process of ignition has three kinds of curve shape along with the flame axis. The one curve of coal A, coal A and B blends with different mixing proportion have two peaks; the first peak is the rapid release and subsequent ignition of volatiles, and the second peak is mainly the char ignition. Its ignition behavior is thought as homogeneously. The other curves of coal B, coal C, coal D and blends of coal C and D with different mixing proportion has one peak. This may be the joint of homogeneous ignition and heterogeneous ignition — heterogeneous ignition behavior. The oscillation frequency curves of coal blends with one coal in higher volatile contents (>25%) in mixing proportion of 70% to 30% and 60% to 40% are similar as well as that of 50% to 50%, 40% to 60% and 30% to 70%. The coal blends are in a higher oscillation frequency because of their higher volatile content. It can also be concluded that the oscillation frequency characteristic of coal blends is the combination of single coals and depends on the coal ranks greatly.

![Oscillation frequency of blended coals](image)

### 4. CONCLUSIONS
A novel method on judging the ignition behavior of coals has been developed in a drop-tube furnace using a flame monitor. A series of tests has been conducted along the axial quartz observing windows of the ignition section during steady combustion. The feature parameter of oscillation frequency based on empirical mode decomposition has been measured from flame signal which is found most sensitive to coal types and therefore can be used as an indicator of the dynamic nature of flame. The results have suggested that ignition behavior can be determined from the feature. It has also been demonstrated that under the experimental conditions the mass ratio between the two coals in coal blends has a major impact on the ignition behavior. The measurement has been proved effective to judging the ignition behavior of coal which provided a new research field to study and understand pulverized coal ignition.

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