OPTIMAL DESIGN OF HOMOGENEOUS IGNITION OF BIOMASS BY PULSE IGNITION TECHNIQUE

by

Xiaomin LI^{*}, Kunfeng SUN, Kan CAO, and Zhaofeng MENG

School of Energy and Environment, Zhongyuan University of Technology, Zhengzhou China

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The volatile matters in biomass have an essential effect on their ignition stabilization. In the present work, the homogeneous ignition of seven kinds of biomass and eight kinds of coals is studied by the pulse ignition technique. At ignition, the flame brightness of biomass appears more faintly than that of coal. The flame color appears in bluish violet for biomass and yellowish red for coal. The homogeneous ignition temperature ranges from 270 °C to 310 °C for biomass and 390-500 °C for coal, respectively, and it decreases with the decrease of the particle size. A theoretical model is established to predict the homogeneous ignition temperature by the thermal balance method and the thermal explosion theory. Based on the theoretical prediction, a quasi-linear model and a non-linear model are developed through the least square algorithm.

Key words: biomass, coal, pulse ignition technique, regression analysis

Introduction

Ignition can be investigated *via* the pulse ignition technique, the thermogravimetric method, and laser-induced ignition, *etc.* [1-4]. The ignition temperature is a key parameter for ignition and burn-out of biomass [5-8]. As we know, it is not a characteristic parameter but it depends on the fuel tank, the measuring technique and the surrounding conditions [9]. Biomass is rich in volatile matters [10-12] and homogeneous ignition behaviors have an important influence on the design of boiler firing/cofiring biomass. At present, the ignition indicators adopted in the boiler design include the homogeneous ignition temperature, the stable ignition index and the flammability index. In China's JB/T 10440-2004 standard, the flammability index is adopted and its ignition model takes the volatiles content as action variable only. Therefore, for the boiler firing biomass with high moisture, the ignition model is often insufficient to state the effect of moist matter correctly.

This work aims to study the homogeneous ignition of several kinds of biomass and coals by the pulse ignition technique. Several factors impacting the homogeneous ignition are involved, including the volatiles content, the moist content and the particles size. An expression on the homogenous ignition temperature is derived based on the thermal balance analysis and the thermal explosion theory. Starting from the expression, a quasi-linear model and a non-linear model are developed by the least squares algorithm. A comparison of the two models is made according to several statistic indices and their physical meaning.

^{*} Corresponding author, e-mail: lxm13838087417@163.com

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Experimental method

Homogeneous ignition of several kinds of biomass and coals was investigated and shown in tabs. 1 and 2. The proximate analysis of all samples was carried out following China's GB/T 212-2008 standard. Moreover, all samples were screened into four groups by a standard sieve to know the effect of particle size on ignition. Particle sizes of the four-group samples were in the range of $180 \sim 380 \,\mu\text{m}$, $150 \sim 180 \,\mu\text{m}$, $120 \sim 150 \,\mu\text{m}$, and less than $120 \,\mu\text{m}$, respectively.

Table 1. Proximate analysis (air-dried basis) of the biomass samples

Biomass	Moist [wt.%]	Volatile [wt.%]	Ash [*] [wt.%]	Fixed carbon [wt.%]
Wheat straw	6.20	72.01 5.09		16.70
Corn stalk	12.74	75.58 6.29		5.38
Rice straw	7.46	61.20	11.93	19.42
Peanut stalk	8.78	68.10	7.68	15.43
Soybean stalk	8.54	74.56	11.61	5.29
Leaves of phoenix	6.87	68.83	10.55	13.75
Sawdust	5.21	76.28	6.65	11.86

* The ashing temperature was set at 600 °C during the proximate analysis.

Coal samples	Moist [wt.%]	Ash [wt.%]	Volatiles [wt.%]	Fixed carbon [wt.%]
C-1	3.11	16.10	34.42	46.37
C-2	1.58	21.85	24.52	52.04
C-3	2.59	29.24	26.52	41.66
C-4	1.08	25.23	18.15	55.54
C-5	3.58	24.31	23.86	48.25
C-6	0.34	31.23	18.00	50.43
C-7	6.42	13.16	41.75	38.67
C-8	5.97	21.06	38.53	34.44

Table 2. Proximate analysis (air-dried basis) of coal samples



Figure 1. Schematic diagram of the experimental rig

The experimental rig is comprised of the electrical furnace -1, the temperature controller -2, the pulse igniter -3, the camera -4, the K-type thermocouple -5, the exhaust hood -6, and the drive circuit -7, as shown in fig. 1. The experimental procedures are described:

- The sample is loaded into the container. The sample mass is 1 g for coal and 0.5 g for biomass.
- When the furnace is heated to a set value, $T^F = T_i$, the container is plugged into the furnace.
- The volatiles are ignited by the igniter. If the flame continues for longer than 5 seconds, the furnace temperature is reduced to a lower value, $T^F = T_{i+1}$, then first and second steps are repeated until there is no flame or flame continues shorter than 5 seconds.

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- If no flame appears or the flame continues shorter than 5 seconds, T^F is regulated to be middle of T_i and T_{i+1} and the process is repeated.
- The test is over when $|T_i T_{i+1}| < 5^{\circ}$ C.

Results and discussion

Ignition phenomena

Ignition was recorded by the camera and shown in fig. 2. Firstly, the flame of biomass appears more faintly than that of coals. This is because that biomass is rich in oxygen and its volatiles contain more amount of inert components. Secondly, the flame color of biomass appears in faint bluish violet but it is in yellowish-red for coals. The bluish-violet flame lies in the fact that biomass contains more holocellulose, about 60-90 wt.%, and produces a higher amount of the volatiles [13]. As a result, the flow velocity of the released volatiles is high enough to entrain a sufficient amount of the surrounding air to burn completely. Thirdly, the yellowish red flame of coals reveals that the volatiles contains lower inert components and the ignition occurs at a higher reaction rate. The yellowish part for the flame of coals indicates that there exists incomplete combustion. This is because the amount of released volatiles is low and unable to entrain enough surrounding air to burn completely.



Figure 2. The flame of biomass and coal with different particle size; (a) particles size 180~380 μm, (b) particles size 150~380 μm, (c) particles size 120~150 μm, and (d) particles size < 120 μm

Effects of particle size

The factors influencing the homogeneous ignition include fuel properties, particle size, heating rate, and surrounding conditions. Figures 3 and 4 illustrate the ignition temperature of samples with different particle sizes. The ignition temperature is in the range of 270~310 °C for biomass and 390~500 °C for coals. This is due to the different structures between biomass and coals. Biomass is chiefly comprised of hemicellulose, cellulose and lignin. Pyrolysis happens in the range of 220~315 °C for hemicellulose and 315~400 °C for cellulose and 210~900 °C for lignin [14]. During pyrolysis, hemicellulose is easy to degrade to the volatiles, such as CO₂ and CO. Different from biomass, coal is rich in alkyl side chain and bridged bond, such as COOH, C = O, CH₂, O-CH₃. Among them, the removal of COOH is at about 200 °C and it produces CO₂ and H₂O. Therefore, the ignition of coal is due to CO, CH₄, and H₂.



Figure 3 The homogeneous ignition temperature of biomass with different particle sizes

Figure 4. The homogeneous ignition temperature of coal with different particle sizes

Moreover, from figs. 3 and 4, we can find that particle size also influences the ignition temperature. Figure 5 gives the average value of the ignition temperature of samples with different particle sizes. From fig. 5, it can be seen that the ignition temperature decreases with the decrease of particle size. The cause lies in that the sample mass increases with the decrease of the particle size, which results in increasing amount of the released volatiles. Therefore, the flow velocity of the volatiles increases and is helpful to entrain surrounding air enough to form an explosive mixture.



Figure 5. Effect of particle size on the homogeneous ignition temperature of biomass samples

Model development

Derivation on homogeneous ignition temperature

The stabilization of a non-premixed flame depends on the premixed flame segment, which is adjacent to the rim of the outlet of the burner. In this work, the released volatiles are mixed with the surrounding air to form a combustible mixture with a stratified composition ranging from lean to rich contents [15]. Meanwhile, the released heat in the reaction zone is conducted partly into the premixed zone and preheats the mixture from the initial temperature, T_0 , to the ignition temperature, T_i . So, the thermal balance for the premixed segment can be expressed:

$$\lambda \left. \frac{\mathrm{d}T}{\mathrm{d}x} \right|_{\delta_{a}} = m_{R} c_{p,R} (T_{i} - T_{0}) + m_{I} c_{p,I} (T_{i} - T_{0}) \tag{1}$$

where λ denotes the thermal conductivity, m_I and m_R – the mass flux of the inert and the combustible, respectively, and $c_{p,R}$ and $c_{p,I}$ – the specific heat capacity of the combustible and the inert, respectively. Considering heat conducted into the premixed zone being from the reaction zone, the left hand of eq. (1) can be rewritten:

$$\lambda \frac{\mathrm{d}T}{\mathrm{d}x}\Big|_{\delta_{p}} = \alpha k m_{R} Q \tag{2}$$

where α denotes the portion of reaction heat transferred into the premixed zone, Q – the reaction heat, and k – the rate constant. Combining eq. (1) with eq. (2), an expression can be obtained:

$$T_i - T_0 = \frac{\alpha k m_R Q}{m_R c_{p,R} + m_I c_{p,I}} \tag{3}$$

According to expression: $T_i - T_0 = RT_0^2/E$, R denotes gas constant. Equation (3) can be rewritten:

$$T_i^2 = \frac{\alpha k m_R Q E}{\mathcal{R}(m_R c_{p,R} + m_I c_{p,I})} \tag{4}$$

For the sake of simplification, we substitute M for m_I and V for m_R . As a result, eq. (4) can be rewritten:

$$T_i^2 = \frac{\alpha k m_R Q E}{\mathcal{R}(V c_{p,R} + M c_{p,I})}$$
(5)

Regression analysis

Using natural logarithmic form, eq. (5) could be written:

$$\ln T_i = a_3 \ln V + a_2 \ln(a_1 M + a_0 V) \tag{6}$$

where a_i (i = 0, 1, 2, 3) is undetermined parameters. According to eq. (6), a non-linear expression can be obtained to know the effect of M and V on T_i . Moreover, a simpler linear expression can be obtained by ignoring the difference of specific heat capacity between M and V:

$$\ln T_i = a_2 \ln V + a_1 \ln(M + V) + a_0$$
(7)

Starting from eq. (6), a non-linear model was obtained through the least squares method. After 15 iterations, a non-linear model (hereinafter termed as NLM) was obtained:

$$T_i = \exp[-3.544\ln V + 3.167\ln(0.449M + 10.089V)]$$
(8)

Coefficients of determination and adjusted coefficients of determination of NLM are 0.922 and 0.900, respectively.

Based on eq. (7), we consider $\ln T_i$ as the dependent variable and $\ln V$ and $\ln (M + V)$ as the independent variables, a quasi-linear model (hereinafter termed as QLM) can also be obtained:

$$\ln T_i = 7.320 - 0.526 \ln V + 0.149 \ln(M + V) \tag{9}$$

For eq. (9), the coefficient of determination and the adjusted coefficient of determination are 0.922 and 0.909, respectively, which means that the cross-validation of QLM performs better than NLM.

The physical meaning of QLM and NLM

Figure 6 gave the effect of volatile matter on T_i from QLM and NLM. From fig. 6, it can be seen that T_i decreases with an increasing amount of the volatiles. This can be explained: Firstly, the higher the outlet velocity is, the more the surrounding air is entrained into the premixed zone, the process is helpful to form the combustible mixture and to reduce the ignition temperature. Secondly, there exists a gradual transition of T_i from an accelerating decrease in the early stage to a decelerating decrease in the late stage. For the solid fuel with a high rank, its volatiles are comprised of gas with excellent flammability, such as H₂ and CH₄. Therefore, T_i decreases with an increasing amount of the volatiles in the early stage. However, for the solid fuel with low rank, its volatiles are comprised of gas with poor flammability, resulting in a decelerating decrease in the late stage.

Figure 7 gives the effect of the moist content on T_i . From fig. 7, it could be seen that T_i increases with an increasing amount of the moist. Moreover, there exists a deviation between the predicted values. The influence of the moist matter on T_i has to consider the following two countering properties. When the moist content increases, heat to ignite the combustible mixture increases. But on the other hand, its porosity also increases, which can promote the release of the volatile matter. Therefore, it can be concluded that QLM performs more valid than NLM from fig. 7.



Figure 6. Effects of the volatiles content on T_i according to QLM and NLM

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Conclusion

Homogeneous ignition of biomass and coals is studied by the pulse ignition technique. The flame brightness of biomass is fainter than that of coals. The flame color appears in faint bluish violet for biomass and yellowish red for coals. The ignition temperature is in the range of 270~310 °C for biomass and 390~500 °C for coals. The ignition temperature decreases along with the decrease of the particle size. An expression is derived based on the thermal balance and the thermal explosion theory. Starting from the expression, a quasi-linear model and a non-linear model are developed by the least



Figure 7. Effect of the moist content on ignition temperature

squares algorithm. Combining several statistic indexes with its physical meaning concludes that the quasi-linear model performs more validly than the non-linear model does.

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