ISSN: 2414-1895 DOI: 10.6919/ICJE.202201_8(1).0059

Research on Homogeneous Ignition of Coal by Pulse Ignition Technique

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Abstract

In this work, homogeneous ignition of eight kinds of coal sample have been studied by means of the pulse ignition technique. For all coal samples, flame color appears yellowish red, which are due to the removal of functional groups during pyrolysis. The homogeneous ignition temperature is in the range of 390~500oC and decreases with the decrease of particle size of coal particle. Moreover, the ignition delay time decreases along with the decrease of particle size. Furthermore, an expression was derived on the homogeneous ignition temperature based on energy balance and thermal explosion theory. The resultant expression accords with the physical meaning of ignition of coal to a great degree and can provide a reference to design of boiler firing coal.

Keywords

Coal, Pulse Ignition, Homogeneous Ignition, Pyrolysis.

1. Introduction

At present, biomass is thought as a carbon-neutral and renewable energy resource, which holds a great potential to act as an alternative energy resource to address the challenging of global warming and worldwide energy crisis[1,2]. Comparing to other conversion technologies, co-firing with coal are thought to be the most efficient approach for biomass utilization to generate heat and power[3, 4]. Ignition is an important preliminary step in combustion and has a critical influence over flame stability, pollutants formation and emissions, security during transportation and storage[4, 5]. Ignition can be investigated via pulse ignition, continuously flow ignition, thermogravimetric, direct measurement of particle temperature at ignition, laser-induced ignition, etc.[6]. Most studies on ignition focus on ignition mode and ignition delay time, which depend on several factors, such as the particle size, its composition and combustion atmosphere. Ignition mode plays an important role in intensifying combustion and reducing pollutants emissions. Particles of coal can ignite in ways of homogeneously, heterogeneously, or a combination of the two[7]. Anthracite and most of the semi anthracite coal ignited heterogeneously while bituminous coal particles from different sources ignited homogeneously. The ignition mode of lignite depends on its fragmentation tendency and switches to a mixed heterogeneous/homogeneous behaviors[8]. Besides that, the ignition temperature and the ignition delay time are the key parameters on ignition of coal as well. Combination of them two is capable to evaluate the reactivity of coal[9]. Ignition temperature is not a characteristic parameter but depends on fuel rank, experimental technique, and surrounding conditions. The measured ignition temperature is different from different experimental technique[1-5]. However, it seems more important to identify the ignition tendency according to the measured ignition temperature, rather than its absolute value. For a specific experimental technique, the resultant ignition temperature decrease along with the increase of sample mass and the oxygen concentration in surrounding gas, and decreases with the decrease of particle size. Moreover, the moist content also has important influence on coal ignition. Along with the increase of moist content, the ignition temperature increases under the lower temperature conditions and decreases under the higher temperature conditions. The ignition delay time is related to fuel type, temperature conditions, O2 concentration, etc.[9]. Its measurement can be obtained by shock tube, rapid compression machine.

Obviously, homogeneous ignition have an important influence on several design parameters, including the ratio of primary air, the swirl number of its burner, and the self-ignition risk of preparation system of pulverized coal. Therefore, it is imperative to develop a model to state quantitatively the relation between ignition behaviors and its action variables. Up to now, the ignition indicators adopted in boiler design include the homogeneous ignition temperature, the stable ignition index, or the flammability index. At present, the flammability index are adopted in China standard (JB/T 10440-2004), where the ignition models take the volatiles content as the action variable and do not take into account of the effect of moist content on the homogeneous ignition. Moreover, it is difficult to isolate combustion time of the volatiles from its devolatilization time because the two processes overlap. Therefore, it is of greater practical interest to measure homogeneous ignition delay time.

This work aimed to investigate homogeneous ignition of coal. The ignition is studied by means of pulse ignition technique and the sample mass was about 1g, to know the particles group behaviors at ignition. In experiment, the homogeneous ignition temperature, the homogeneous ignition delay time and the fuel reactivity are obtained and can be applied to represent ignition behaviors of particles group. Secondly, in view of the dominant role of homogeneous ignition temperature for ignition behavior of the evolved volatiles, an expression on homogeneous ignition temperature was derived through a thermal balance analysis.

2. Experimental

2.1 Materials

In this work, 8 samples of coal, supplied by power plants in Henan province, were chosen. All coal samples were milled and analyzed for proximate using GB/T 212-2008. Table 1 shows the properties of coal sources used in this work. Moreover, to know the effects of particle size on the homogeneous ignition, all samples were screened into four groups by the standard sieve. The particle size of the four-group samples were in the range of 180~380 μm, 150~180 μm, 120~150 μm and less than 120 μm, respectively.

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

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

2.2 Experiment

The experimental rig is shown in Figure 1 and is comprised of an electrical furnace, a temperature controller, a pulse igniter, copper container and exhaust hood. The heating component of the furnace is resistance wire with circular cross section and arranged in helix form. A temperature controller, XMT-700 Model, is used to regulate the furnace temperature via two K-type thermocouples. The temperature controller takes an electric relay as the drive circuit. Two slide wire rheostats, 150 Ω, are connected in series to heat the furnace up to 800～850℃. A cooling fan is installed at the bottom of the furnace to make its temperature more stable. A mercury thermometer, WNG-01 model, is used to calibrate the K-type thermocouple. A high energy igniter, GNQ-20, constitutes the ignition unit with ignition frequency, 6~12 Hz. A camera, Nikon D5600 model, is installed near outlet of the container to detect the flame formed by volatiles evolved and determine ignition delay time through photography.

The experimental procedures are described as follows:

Loaded sample into the container and hold materials level even with half height of the container. The amount of loaded sample is about 1g.

When the furnace was electrically heated to a selected temperature, $TF=Ti$, plugged the container into the electrical furnace. At the same time, open the camera to record the ignition process.

Ignite the volatiles near outlet of the container by means of the high energy igniter. If flame appears and continues for longer than 5s, reduce the furnace temperature to a lower temperature, $TF=Ti+1$. Then step 1 and step 2 were repeated until there is no flame or the flame continues shorter than 5 s.

If no flame appears or the flame continued shorter than 5 s, regulated the selected temperature, TF, to be half way between Ti and $Ti+1$ and the process was repeated. The process is terminated when |Ti-Ti+1|<5℃.

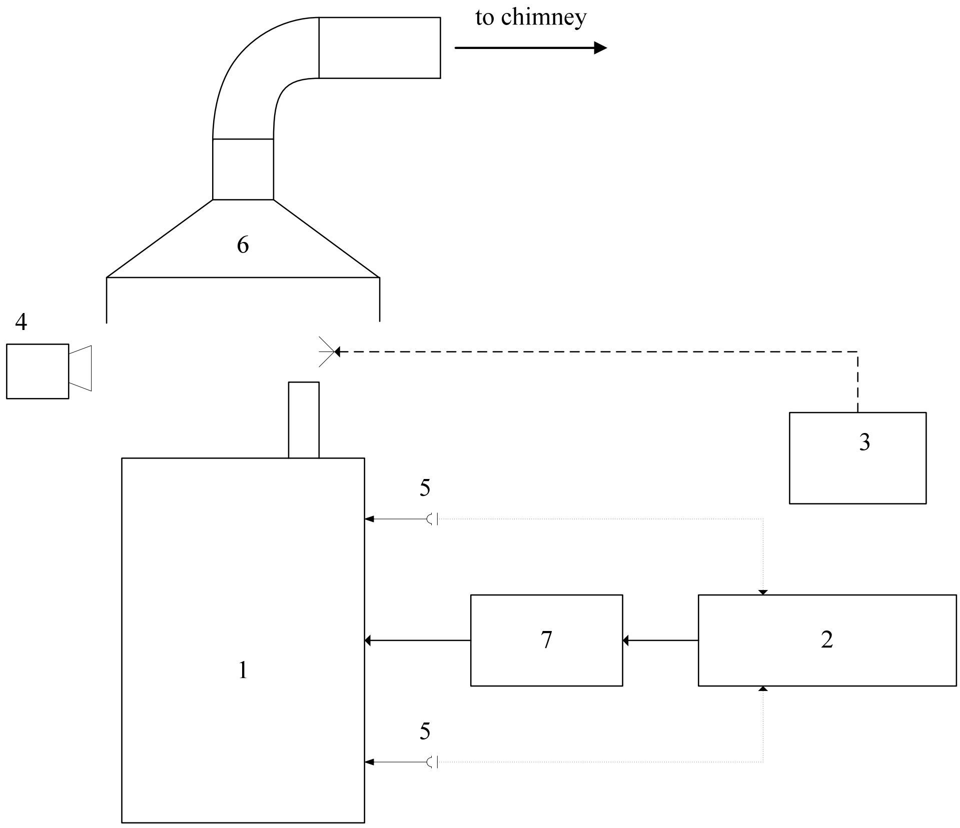


Figure 1. Schematic diagram of the ignition temperature measuring instrument.

1. Electrical furnace. 2. Temperature controller. 3. Pulse igniter. 4. Camera. 5. K-type thermocouple. 6. Exhaust hood. 7. Drive circuit.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202201_8(1).0059

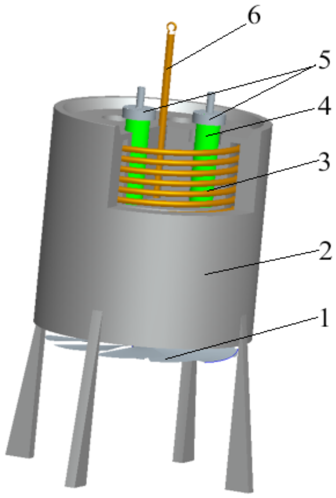


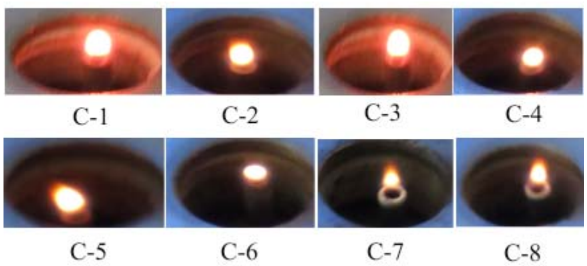
Figure 2. The ignition temperature measuring instrument.

1. Fan. 2. Furnace body. 3. Electrical resistance wire. 4. Container. 5. lid. 6. Mercury thermometer.

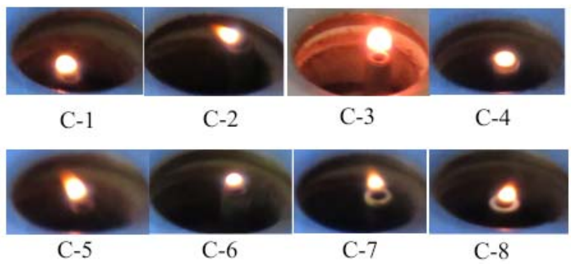
3. Results and Discussion

3.1 Flame Phenomena at Ignition

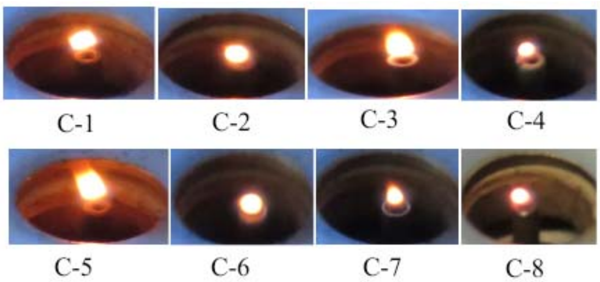
As shown in Figure 3, flame phenomena at ignition were recorded by Nikon D5600 camera under several conditions, with particle size respectively ranging in 180~380μm, 150~180μm, 120~150μm and less than 120μm. It can be seen that the flame is bright, which is resulted from the removal of functional groups, such as C=O, CH2, O-CH3, in pyrolysis. Moreover, the yellowish part for coal at ignition indicates that there exists incomplete combustion to a great degree. Those phenomena can be interpreted as that, due to the amount of volatiles released from coal is in a lower level and its flow velocity from the container is lower and unable to entrain enough air to meet with complete combustion.



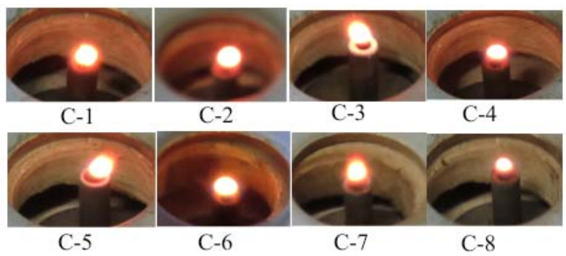
(a) Particles size in the range of 180~380μm



(b) Particles size in the range of 150~380μm



(c) Particles size in the range of 120~150μm



(d) Particles size less than 120μm

Figure 3. The flame at ignition of coal with different particle size.

ISSN: 2414-1895
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3.2 Effects of Particle Size on Homogeneous Ignition Temperature

Homogeneous ignition temperature is a dominant factor and have an great influence on ignition of the evolved volatiles, regardless of the presence of oxygen. Its impact factors are complex and include fuel properties, particles size, heating rate, atmosphere conditions. Figure 4 gave the homogeneous ignition temperature of coal with different particle size. It can be seen that the homogeneous ignition temperature is in the range of 390~500oC. The cause lies in that coal is rich in alkyl side chain and bridged bond, such as COOH, C=O, CH2, O-CH3, etc. Among them, removal of COOH is at about 200oC and produce CO2 and H2O, which are helpless for homogeneous ignition. Therefore, homogeneous ignition of coal seems due to the removal of functional groups, such as C=O, CH2, O-CH3, etc. and produces CO, CH4, and H2, etc.

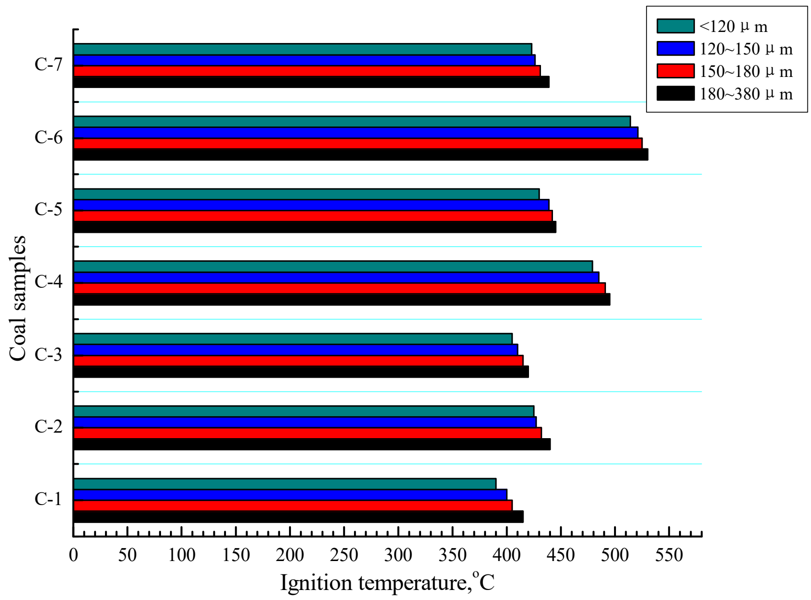

Figure 4. The homogeneous ignition temperature of coal samples with different particle size

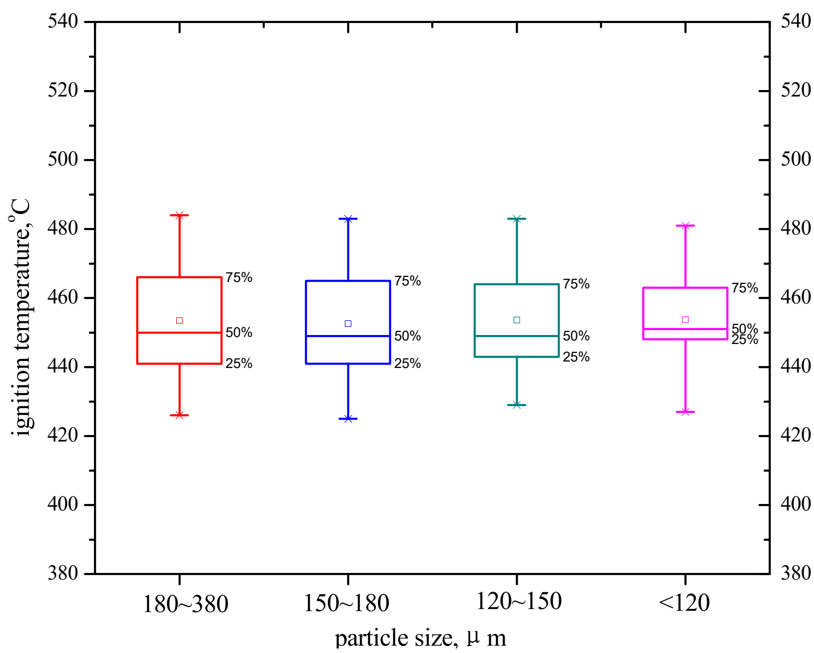

Figure 5. Effect of particle size on the homogeneous ignition temperature

Volume 8 Issue 1, 2022
DOI: 10.6919/ICJE.202201_8(1).0059

Secondly, from Figure 4, it can also be seen that homogeneous ignition temperature relates to particle size. Figure 5 gives the average value of homogeneous ignition temperature with different particle size. From Figure 5, it can be seen that homogeneous ignition temperature decreases along with the decrease of particle size. These phenomena can be interpreted to be that, the sample mass loaded into the container increases along with the decrease of particle size, which results in the decrease of heating rate of particles and the increase of released amount of the volatiles. In turn, flow velocity of the released volatiles from the sample container increases, which intensifies to entrain the ambient air yield enough to form combustible mixture. As a result, homogeneous ignition occurs at a lower temperature, which is in accordance with the opinions in literature [9].

3.3 Effects of Particle Size on Reactivity

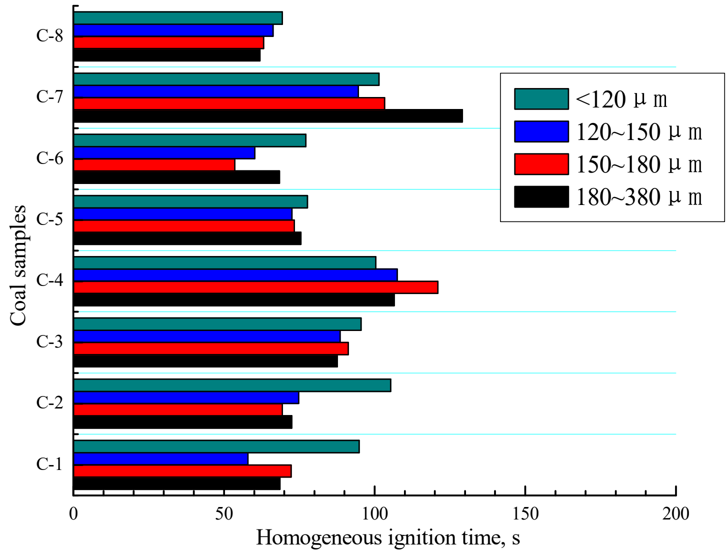

Figure 6 Effect of particle size on the homogeneous ignition time

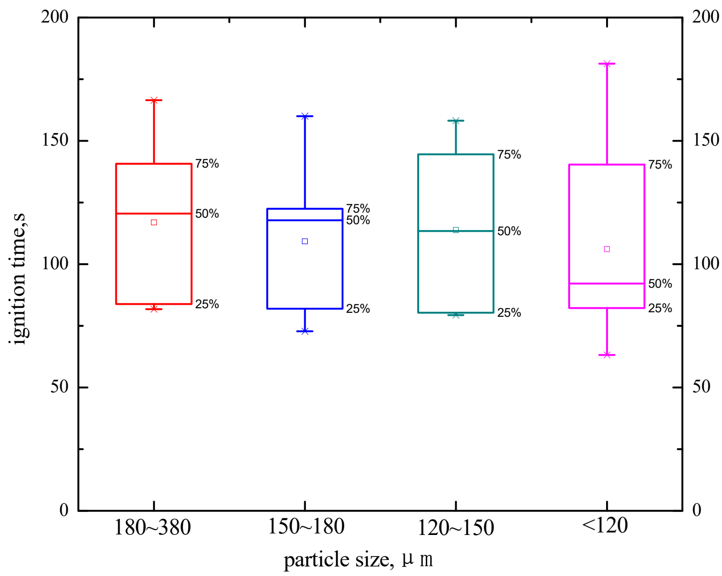

Figure 7 Effect of particle size on ignition delay time of coal samples

The reactivity is also an important indictor for combustion control. According to the expression in ignition, i.e., T0lnτ∝E, it is necessary to measure the ignition delay time. In this work, photography method was adopted for measuring homogeneous ignition delay time. The homogeneous ignition delay time measured includes devolatilization time and the time to ignite its volatiles. In practical, it is difficult to isolate the combustion time from the devolatilization time because the two processes

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overlap. Figure 6 and Figure 7 gave the homogeneous ignition delay time and its average value respectively. Comparing Figure 6 with Figure 7, it can be found that the ignition delay time decreases along with the decrease of particle size, which accords with the opinions in literature [11-13].

4. Derivation of Expression on the Homogeneous Ignition Temperature

The evolved volatiles due to pyrolysis constitute the inert component and the combustible component. The inert component is comprised of carbon dioxide (CO2) and water vapor (H2O). The combustible component is comprised of carbon monoxide (CO), methane (CH4), hydrogen (H2). Therefore, it is necessary to derive an expression to represent the effect of the moist and the volatiles on ignition. As shown in Figure 3, it can be seen that the bulk of flame is essentially attributed to non-premixed flame. So, the flame stabilization is controlled by the stabilization of its premixed flame segment. Where fuel and oxidizer mix immediately and create a mixture with a stratified composition ranging from fuel lean to fuel rich, as shown in Figure 8[13].

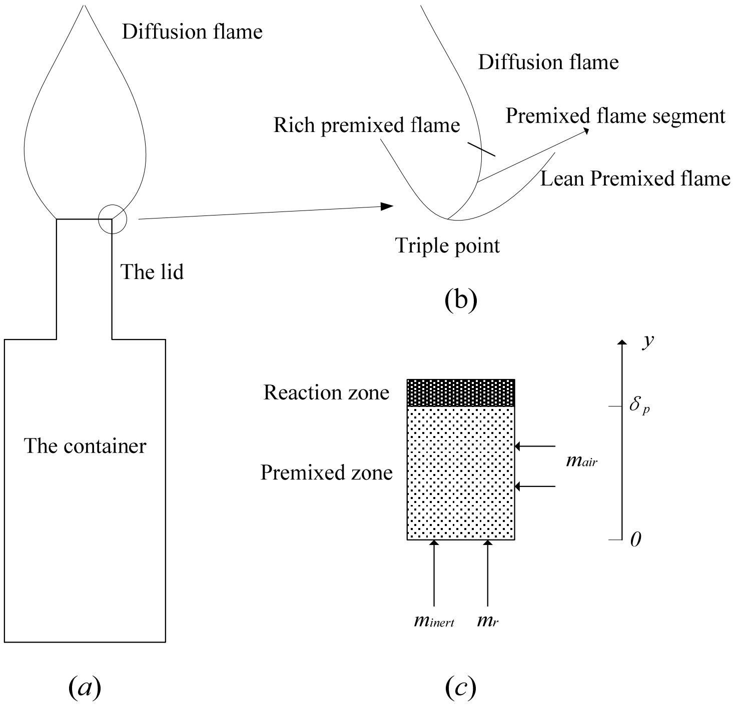

Figure 8 Schematic diagram of flame of the volatiles at ignition

In premixed flame segment, the gas flow from the sample container entrains ambient air and form combustible mixture. According to the feedback mechanism in conventional flame, heat release in reaction zone conducts into premixed zone partly and preheats the combustible mixture in premixed zone from initial temperature, T0, to ignition temperature, Ti. As a result, the energy balance equation on the premixed segment can be expressed as:

$$\lambda \left.\frac{dT}{dx}\right|_{\delta_p} = \dot{m}_R c_{p,R}(T_i - T_0) + \dot{m}_I c_{p,I}(T_i - T_0) \tag{1}$$

Here, heat transferred into the premixed zone equal to a portion of heat release in reaction zone. Thus, the left hand of Eq. (1) can be written as:

$$\lambda \frac{dT}{dx}\bigg|_{\delta_p} = \alpha k \dot{m}_R Q \tag{2}$$

In Eq. (2), chemistry reaction in reaction zone is assumed to be first order[10, 13] and the combustible component in combustible mixture is considered as deficient reactant[10]. According to Eq. (1) and Eq. (2), an expression can be obtained as follows:

$$T_i - T_0 = \frac{\alpha k \dot{m}_R Q}{\dot{m}_R c_{p,R} + \dot{m}_I c_{p,I}} \tag{3}$$

Combined with the relation between Ti and T0: Ti-T0=RT02/E, Eq. (3) can be rewritten as[10]:

$$T_i^2 = \frac{\alpha E / Rk \dot{m}_R Q}{\dot{m}_R c_{p,R} + \dot{m}_I c_{p,I}} \tag{4}$$

From Eq. (4), it can be found that there are many factors involved to affect Ti, and its solution is very difficult. Considering the overriding effects of chemical composition on the ignition tendency of coal[11], we substitute the inert component $\dot{m}_I$ as M, the combustible component $\dot{m}_R$ as V. As a result, Eq. (4) can be rewritten as:

$$T_i^2 = \frac{\alpha E / RkQ \cdot V}{c_{p,R} \cdot V + c_{p,I} \cdot M} \tag{5}$$

5. Conclusion

In this work, homogeneous ignition of coal have been studied by the pulse ignition technique. Flame color of coal at ignition appears yellowish red. Homogeneous ignition temperature of coal is in the range of 390~500oC. The homogeneous ignition temperature decreases along with the decrease of particle size. Homogeneous ignition delay time decreases along with the decrease of particle size. A qualitative expression was developed on the homogeneous ignition temperature based on thermal balance.

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