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Non-equilibrium Plasma Assisted Combustion of Low Heating Value Fuels

Hongbin Hu, Quanbin Song, Yanji Xu, Gang Li, Chaoqun Nie

Institute of Engineering Thermophysics, Chinese Academy of Sciences, P.O. Box 2706, Beijing 100190, China

This paper describes the effects of non-equilibrium air plasma generated by a dielectric barrier discharge (DBD) on the combustion of low heating value fuels. The experimental results indicate that addition of a very small amount of energy to the air flow in the form of DBD significantly improves the flame stability. Moreover, main combustion characteristics such as flame propagation speed, combustion intensity and lean blow-off limits are also enhanced by the effect of plasma. Some active radicals such as excited O atom and excited N_2 molecule are observed by spectrograph in the discharge area. Based on the results of numerical investigation we can conclude that these active radicals generated in discharge area can accelerate the production rate of active OH radical which plays a key role in the oxidation process of low heating value fuel, and thus the whole combustion process is accelerated.

Keywords: Low heating value fuels; Non-equilibrium plasma; Combustion stability; Active radicals

Introduction

Low heating value fuels such as blast furnace gas (BFG) and converter gas are by-products of steel enterprises. They are very important secondary energy. At present most of the blast furnace gas is burned in a boiler to produce high-temperature steam to drive a steam turbine, the thermal efficiency is as low as 25%. The steel enterprises are urgent to find a solution of using low heating value fuels more efficiently. As the development of gas turbine technology, it is possible to use low heating value fuels in a gas turbine combustor. The heat efficiency can achieve as high as 42% in a gas turbine-steam turbine combined cycle. It seems the best way of using BFG currently, thus it is very attractive to the steel enterprises.

When a gas turbine combustor burns BFG instead of natural gas, some important problems must be solved, including: 1) flame instability; 2) narrowed stable flame range; 3) low combustion efficiency and large CO emission at low load condition [1]. Traditional solutions of these problems are as follows: 1) adding coke oven gas (COG) into BFG to increase the initial fuel heating value; 2) using COG as a pilot to maintain the flame at low load condition. But it will consume a large amount of COG which is already lacking in the steel mill. Steel enterprises have the demand of burning BFG in gas turbine combustors while reducing COG consumption at the same time.

Flame stabilization through the use of non-equilibrium plasma generated by an electrical discharge might be a more practical and efficient means in comparison with the above-mentioned methods. The main advantages of this technology can be listed below. a) The discharge device is relatively simple, and easy to integrate into the combustor design. b) Active feedback control is possible, because the discharge time scale is smaller than the flow and chemical time scales of the combustion system. c)

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The parameters such as voltage, frequency and duration are controllable and can be precisely adjusted. d) The production of atoms, ions, and active radicals can significantly promote the process of chemical reactions, and e) the relatively low temperature of non-equilibrium plasma provides a longer life time of electrodes and lower energy cost [2].

The idea to use non-equilibrium plasma assisted combustion is not new [3]. Many researchers obtained positive results in the generation of active radicals [4], reduction of ignition time delay [5], extension of flammability limits [6], and flame stabilization at various fuel-air mixed flows [7]. However, all these studies were conducted on high heating value fuels such as CH_4, C_3H_8 etc. The main purpose of this paper is to investigate the effect of non-equilibrium plasma assisted combustion of low heating value fuels. Combustion characteristics of low heating value fuels such as combustion stability, flame propagation speed and lean blow-off limit will be tested and compared. These works may be helpful to explore the mechanism of plasma assisted combustion.

Experimental Setup

A schematic diagram of plasma discharge device and Optical Emission Spectroscopy (OES) measurement equipment is shown in Fig.1. An AC power supply with peak voltage of 20kV and typical frequency range of 20~30 kHz was used for discharge power source. Information on voltage and frequency at the electrode is collected by a high–voltage probe with a voltage reduction ratio of 1/1000, and read by an Oscillograph. This type of discharge is so-called dielectric barrier discharge (DBD) for generating uniform and concentrated non-equilibrium plasma at atmospheric pressure or higher pressure.

After excited by high voltage electric field, the air flow became the air-plasma flow which contains various active radicals. The light of the air-plasma was observed by a spectrograph, and then the data of the optical emission spectroscopy was analyzed by computer. The focal length of the spectrograph is 500 mm and the scan range is 0~1400 nm. The resolution of the CCD is 0.09 nm.

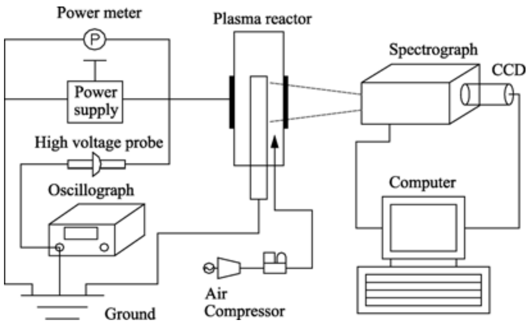


Fig. 1 Schematic of plasma discharge device

A schematic diagram of the combustion system is shown in Fig. 2. The fuel flow consisted of CO flow, H_2 flow, and N_2 flow which were supplied by high-pressure bottles. A shutoff valve and a flash arrester installed in each fuel supply line enabled quick flow shutoff and prevented flame propagation into the bottles. The air flow was supplied by room air compressed by an air compressor. A mass flowmeter was installed in each flow to measure and control the mass flowrate precisely. The flow ranges of CO flow, H_2 flow, and N_2 flow are 0~50 SLM, and the flow range of air flow is 0~250 SLM. The accuracy of these flowmeters is 2%. Fuel flow enters the inner electrode while air flow enters the discharge gap between quartz tube and inner electrode.

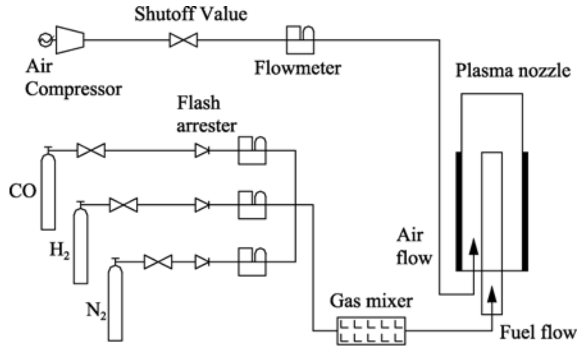


Fig. 2 Schematic of plasma assisted combustion facility

Detailed structure of the plasma nozzle is shown in Fig.3. As we can see, the plasma discharge is integrated into the nozzle design. Fig.3 (a) is a non-premixed jet flame nozzle. Fig.3 (b) is a non-premixed swirl flame nozzle, the swirl number is 0.88.

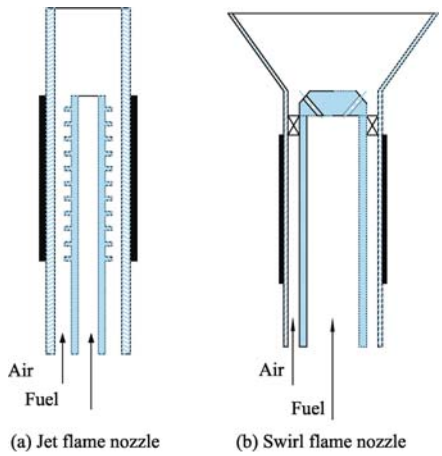


Fig. 3 Structure of plasma nozzles

A schematic diagram of PLIF (Planar Laser Induced Fluorescence) measurement system is shown in Fig.4. A Nd: YAG solid-state laser was used to generate three times pumped laser. The basic parameters of the laser are:

wavelength 355 nm, pulse width 3 ns, single pulse energy 250 mJ, pulse frequency 10 Hz.

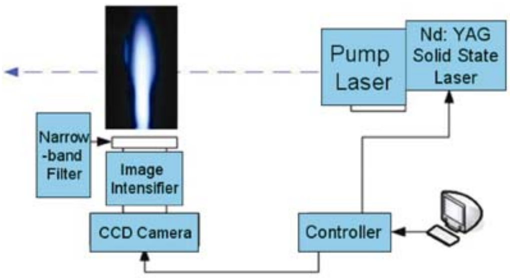


Fig. 4 Schematic of PLIF measurement system

Experimental Results and Discussions

OES of Discharge Process

Optical emission spectroscopy of radicals produced in the air plasma discharge process is shown in Fig.5. The results reveal that the electron impact process by application of high voltage is the dominant chemical reaction which produces various activated radicals in the air. Major species produced in a typical DBD discharge are excited oxygen atoms and excited nitrogen molecules. N_2+ decreases rapidly while active O atom decays relatively slowly. The key chemical reactions during discharge process might be as follows:

A. oxygen molecules impacted by high energy electrons:

$$e + O_2 \rightarrow e + O + O$$

B. nitrogen molecules impacted by high energy electrons:

$$e + N_2 \rightarrow e + N_2(v > 1)$$

C. unstable intermediate products during discharging process will convert to more stable species as follows:

$$N_2(v > 1) \quad + O_2 \rightarrow N_2 + O + O$$

$$e + O + O_2 \rightarrow e + O_3$$

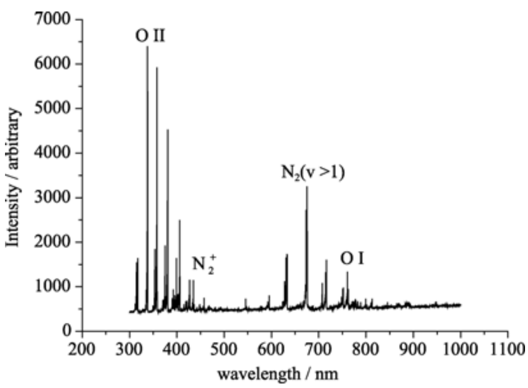


Fig. 5 OES of radicals in plasma discharge process

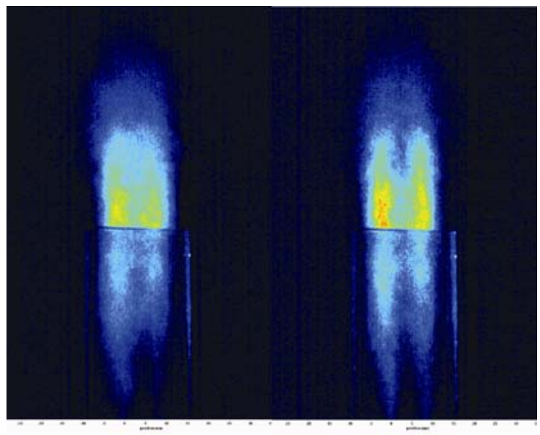
Plasma Effect on Flame Structure

Fig.6 shows the average images of OH radical distribution of jet flame measured by PLIF system. The experimental conditions are shown in Table 1. As we can see from Fig.6a, the flame lifted from the nozzle at the bottom area, and the luminous intensity was very low in this area. This characteristic means that, without plasma assistance, the flame was unstable. However, when the plasma power was turned on in Fig.6b, the flame propagated downstream and attached on the nozzle quickly, and the luminous intensity of this area was higher.

According to the comparison of the results, it is clear that non-equilibrium plasma can improve the flame propagation speed and flame stability. The enhancement of luminous intensity indicated that more OH radical was produced with plasma assist; hence the combustion efficiency was improved.

Table 1 Experiment conditions of jet flame

Volume Composition			Heating Value / MJ / Nm^3	Equivalence Ratio
H_2 / %	CO / %	N_2 / %		
10	40	50	6.1	0.24



(a) Plasma off (b) Plasma on

Fig.6 Average images of OH-PLIF of jet flame

Fig. 7 shows a series of photos of swirl flame which were taken as a function of time. All these pictures were taken under the experimental conditions shown in Table 2, except the plasma power was turned down slowly. According to these pictures, it is obvious that the swirl flame can be maintained very well at high plasma power. However, as the plasma power was turned down, the swirl flame became extremely unstable, and finally quenched.

The experimental results on jet flame and swirl flame indicated that non-equilibrium plasma can significantly improve the combustion stability and combustion velocity.

Table 2 Experiment conditions of swirl flame

Volume Composition			Heating Value / MJ / Nm^3	Equivalence Ratio
H_2 / %	CO / %	N_2 / %		
2	40	58	5.27	0.29

Fig. 7 Plasma effect on swirl flame as a function of time

Plasma Effect on Lean Blow-off Limits

Fig.8 and Fig.9 show the lean blow-off limits of jet flame and swirl flame. The experiment was conducted at variable fuel compositions shown in Table 3 and Table 4. In order to obtain the blow-off limits, the fuel flowrate was kept constant and the air flowrate was increased slowly until the flame quenched. The lean blow-off limit was defined as the equivalence ratio at the moment of blow-off. From the experimental results, it is clear that lean blow-off limits were increased in each fuel composition with the support of plasma, and the stable flame range was extended greatly. This means the flame can be held below the lean flammability limit by the support of plasma.

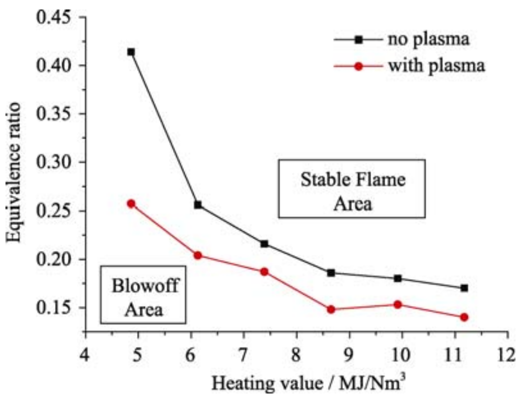


Fig. 8 Lean blow-off limits of jet flame

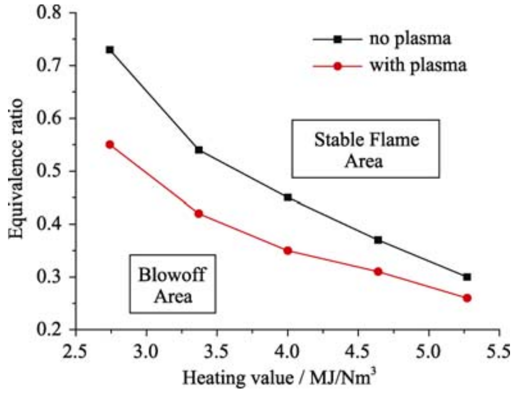


Fig. 9 Lean blow-off limits of swirl flame

Table 3 Experiment conditions of jet flame

Volume Composition			Heating Value / MJ / Nm^3
H_2 / %	CO / %	N_2 / %	
10	30	60	4.9
10	40	50	6.1
10	50	40	7.4
10	60	30	8.6
10	70	20	9.9
10	80	10	11.2

Table 4 Experiment conditions of swirl flame

Volume Composition			Heating Value / MJ / Nm^3
H_2 / %	CO / %	N_2 / %	
2	20	78	2.74
2	25	73	3.37
2	30	68	4
2	35	63	4.64
2	40	58	5.27

Numerical Analysis

Numerical Model

Numerical model is based on a 0-Dimension, closed, homogeneous, perfect-stirred reactor in CHEMKIN. To reduce the calculation, the following necessary assumptions were made:

(1) Flow effect was neglected compared with rapid chemical reactions in a discharge region.

(2) Concentration of active radicals is spatially uniform in discharge field.

(3) The effect of active O atom on combustion was only considered while the other radicals generated in air

plasma was neglected.

(4) Initial concentration of active O atom is 10^{-5}.

(5) Initial volume composition of air is $N_2:O_2 = 4:1$.

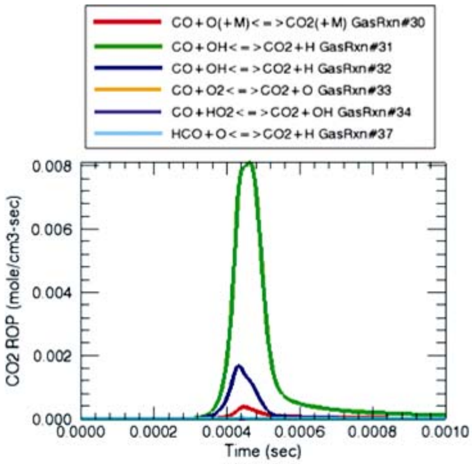
(6) Initial volume composition of fuel is $H_2:CO:N_2 = 1:4:5$.

(7) Initial temperature is 300K, pressure is 1 atm.

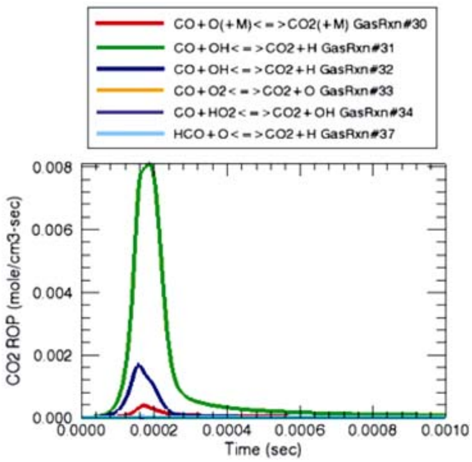
(8) Detailed chemical reactions are referred to literature [8].

Sensitivity analysis of chemical reactions

Sensitivity analysis of a problem solution allows quantitative understanding of how solution depends on various parameters contained in a model. Fig.10 and Fig.11 show normalized sensitivity coefficients as a function of time for the reactions that have the largest effect on the production of CO_2 and H_2O. Fig.12 shows the sensitivity coefficients as a function of time for the reactions that have the largest effect on the production of OH. From these three Figs, it is clear that: 1) the largest sensitivity always occurs near the time of ignition; 2) the ignition delay time is decreased by plasma effect; 3) but the plasma effect on the tendency of reaction sensitivity can be neglected.

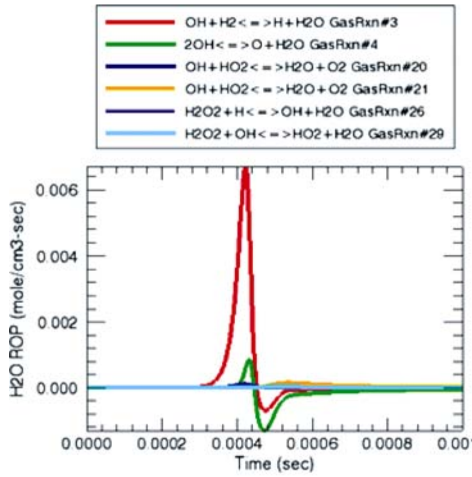


(a) No Plasma

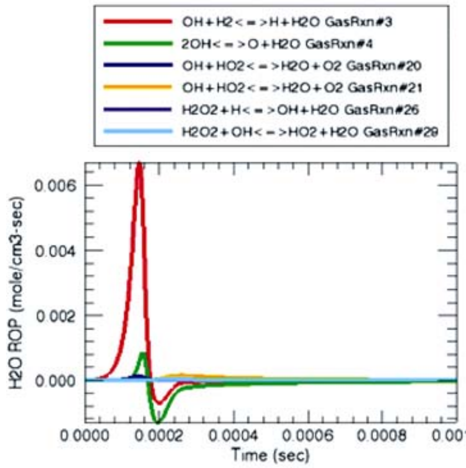


(b) Plasma on

Fig.10 Time evolution of CO_2 production sensitivity



(a) No Plasma



(b) Plasma on

Fig.11 Time evolution of H_2O production sensitivity

Fig.10 and Fig.11 show that the dominant reactions for determining the production of CO_2 and H_2O during ignition are as follows:

$$CO + OH \rightarrow H + CO_2$$

$$H_2 + OH \rightarrow H + H_2O$$

One may see that OH radical plays a very important role in the fuel oxidation process. Fig.12 shows that the dominant reactions for determining the production of OH during ignition are as follows:

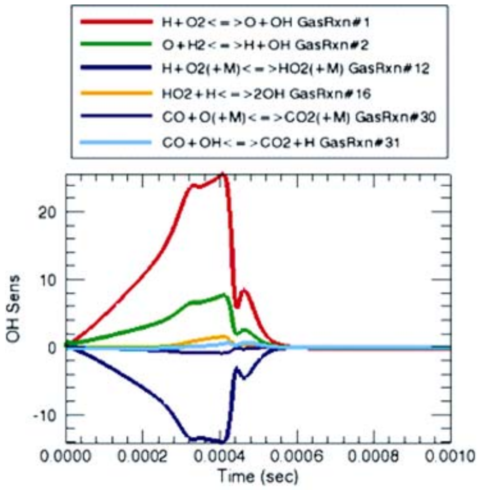
$$H + O_2 \rightarrow OH + O$$

$$H_2 + O \rightarrow OH + H$$

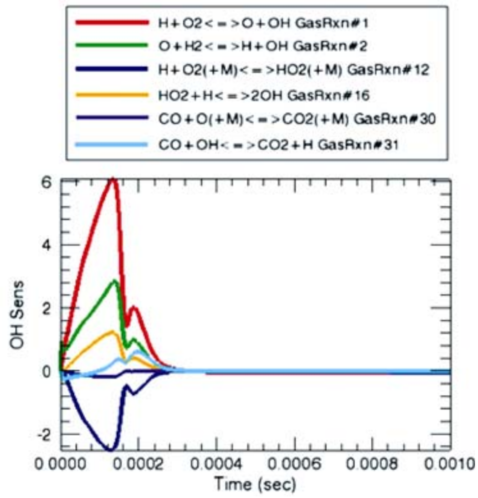
It is obvious that active O_2 molecules and active O atoms are very helpful to the production of OH radicals.

Plasma-Chemical Reaction Analysis

According to our previous work, the mechanism of plasma assisted combustion can be concluded as heating



(a) No Plasma



(b) Plasma on

Fig. 12 Time evolution of OH production sensitivity

effect and chemical effect [9]. Plasma-heating effect means an increase in temperature of reactant molecules due to the high-energy electrons impact.

Plasma-chemical effect means an increase in chemical reaction rates due to the active radicals generated in the discharge process. According to the combustion theory, the chemical reaction rate of the fuel oxidation process is determined by the concentration of initial active radicals. Therefore, if active radicals are produced in the un-burnt area before or during the combustion process, the fuel oxidation reaction rate could be increased remarkably.

Judging by the experimental and numerical analyses, the dominant chemical reactions of plasma assisted combustion of low heating value fuels may as below:

1. Active radicals produced in air discharge process:

$$e + O_2 \rightarrow e + O + O$$

$$e + N_2 \rightarrow e + N_2(v > 1)$$

$$N_2(v > 1) + O_2 \rightarrow N_2 + O_2(v > 1)$$

2. Production rate of OH radical is accelerated by active radicals produced in air plasma:

$$H_2 + O \rightarrow OH + H$$

$$H + O_2(v > 1) \rightarrow OH + O$$

3. Fuel oxidation process is accelerated by the accelerated production of OH radical:

$$CO + OH \rightarrow H + CO_2$$

$$H_2 + OH \rightarrow H + H_2O$$

The above reactions are the basic mechanism of plasma-chemical effect. As the low heating value fuel oxidation process accelerated, the whole combustion rate is accelerated.

Conclusions

Experimental and numerical analyses were conducted to investigate the effect of non-equilibrium air plasma on the combustion of low heating value fuels. The results obtained in the present study are as follows:

(1) Excited O atom and N_2 molecule are produced in air plasma discharge process.

(2) Combustion characteristics such as flame stability, flame propagation speed and combustion efficiency are enhanced by non-equilibrium plasma greatly.

(3) Basic mechanism of plasma-chemical effect is obtained by numerical analyses.

Acknowledgements

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