

An Experimental Study on High Temperature and Low Oxygen Air Combustion

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(Received 15 December 1999 • accepted 26 April 1999)

Abstract—High temperature preheated and diluted air combustion has been confirmed as the technology, mainly applied to industrial furnaces and kilns, for realizing higher thermal efficiency and lower emissions. The purpose of this study was to investigate fundamental aspects of the above-mentioned combustion experimentally and to compare with those in ordinary hydrocarbon combustion with room temperature air. The test items were exhaust gas components of CO, NO_x, flame shape and radical components of CH, OH and C₂, which we measured with gas analyser, camera and ICCD (Intensified Charged-Coupled Device) camera. Many phenomena, as a result, which appeared in the combustion with the oxidizer, low oxygen concentration and extremely high temperature air, such as expansion of the flammable limits, increased flame propagation speed, looked very strange in comparison with those in existing combustion technology. We confirmed that such extraordinary phenomena were believable through a hot-test experiment.

Key words : High Temperature Air Combustion, Diluted Air, Blue-Green Flame, Radicals NO_x, ICCD Camera, Hot-Test

INTRODUCTION

Recently, much attention has been paid to utilizing highly preheated air up to 1,000 °C through waste gas in industrial furnaces, in which about 15 % of the total national energy in Korea is consumed, because of the high efficiency of energy savings. Moreover, one of three major issues in the fiscal 1996, "Understanding Enhancement of High Temperature Air Combustion" has been studied as successive subject to the Japanese national project to reduce CO₂ for protection of the earth. Introduction of high cycle regenerative combustion system broke through the difficulties of utilizing the highly preheated air with moderate cost. This regenerative combustion technology [Hasegawa and Tanaka, 1997; NEDO, 1996; Katsuki and Ebisui, 1997] was originally developed and commercialized in the United Kingdom in early 1980. In order to commercialize this technology widely in Japan, NO_x emissions, which are predicted to be higher with preheated air temperature above 1,000 °C, must be reduced down to the values limited by the environmental regulation [Katsuki and Ebisui, 1997; Fujimori et al., 1997].

The maximum combustion temperature is significantly affected by the temperature of the fuel and the amount of flue gas recirculation and flue gas temperature. However, since little knowledge is available for the characteristics of high temperature air combustion, special emphasis must be placed on understanding the basic characteristics of the combustion under the condition using diluted high temperature combustion air. One significant test result has been a discovery of a phenomenon called the "Green Flame" effect [Kisimoto, 1997; Tanaka et al., 1994], taking place in the diluted high temperature air combustion condition confirmed with spectroscopic measurement.

The objective of this study is to understand the characteristics of

high temperature preheated and diluted air combustion technology experimentally as a preliminary stage of the commercialization of a high cycle regenerative combustion system and to analyze the phenomena.

THEORETICAL BACKGROUND

The combustion temperature (T_b) in case of high temperature preheated and diluted air combustion can be described as follows, where volume rates and heat contents of preheated air and waste gas are considered. The maximum flame temperature can keep its constant value if the volume rate of the diluted gas increases proportionally along with the increase of preheated air temperature.

$$T_b = \frac{H_u + G_w h_{wO'} + G_D h_{DO'}}{(G_w + G_D) \cdot C_p} + T_o \quad (1)$$

$$\gamma = A \cdot \exp\left(-\frac{E}{RT}\right) \cdot [F]^m [O]^n \left(\frac{1}{1+D}\right)^{m+n} \quad (2)$$

Here m, n : reaction order, γ : reaction rate, H_u : low caloric value, $h_{wO'}$: enthalpy of preheated air, G_w : volume of preheated air, G_D : volume of diluted gas, $h_{DO'}$: enthalpy of diluted gas, D : concentration of oxygen, O : oxidizer, F : fuel

From the viewpoint of reaction rate of fuel and oxidizer, formula (2) can give information on keeping the reaction speed constant, if the diluted air volume rate increases with the increase of air temperature.

In real combustion field internal-recirculation of combustion gas arises from high speed jet stream of combustion air and mixes with combustion air. That combustion, "high temperature preheated and diluted air combustion," is called "high temperature excess enthalpy combustion," which gives a new phenomenon, the "Green flame" effect. The high temperature preheated and diluted flow field can make the temperature inside the furnace homogeneous and prevent the formation of a local overheating

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zone, which can be a problem in the case of high temperature preheated air combustion.

EXPERIMENTAL APPARATUS

The experimental apparatus consisted of a hot gas generator and a combustion chamber as shown in Fig. 1. An electric heater constructed with Kanthal wire in 10 kW was used as a hot gas generator to make high temperature air; it was 500 mm in diameter and 500 mm long. A thermocouple was inserted at the center of the flow passage between the hot gas generator and the combustion chamber to measure the temperature of preheated and diluted air. The combustion chamber was mounted on the exit of the hot gas generator. The chamber was 180 mm in diameter and 300 mm long. The flow passage was surrounded by castable. The gas fuel was injected from the nozzle at the center of the test section. The nozzle as shown in Fig. 2 was installed axially or radially to vary a flow pattern. A water-cooled stainless steel sampling probe was mounted 300 mm downstream of the convergent chamber exit to get the concentration of the exhaust gas. The sampling gas was analyzed by the chemiluminescence NO/NO_x analyzer and the paramagnetic O₂ analyzer. To observe and take a picture of flame, the side wall of combustion chamber was replaced by quartz windows. Tests were conducted with LPG fuel over ranges of inlet temperature up to 1,100 °C. The inlet air diluted by N₂ was supplied to the generator. The mixture of air and N₂, after passing through the generator, was allowed to heat up a temperature of about 1,100 °C.

It is reported that much higher levels of NO_x are obtained with N₂ as the dilution gas than CO₂ at any degree of air preheat [Kishimoto, 1997]. This shows the importance of chemical composition of gas for controlling NO_x in highly preheated air combustion.

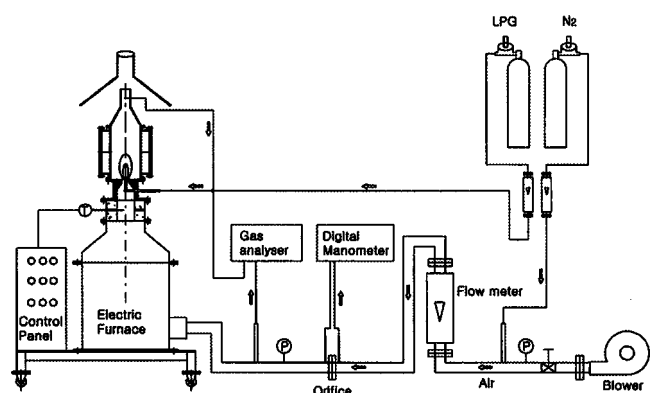


Fig. 1. Experimental apparatus.

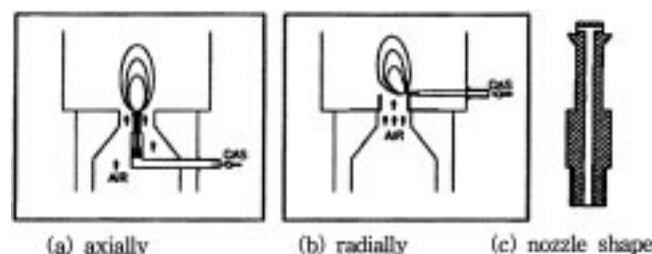


Fig. 2. Location of gas nozzle in combustor.

Table 1. Experimental conditions

Items	Contents	Remarks
Fuel	LPG	Hu=12,000 kcal/kg
Heater input	10 kW	
Gas flow rate	1.5-2.5 l/min	ΔP=200 mmAq
Diluter	N ₂	
Air temperature	200, 400, 600, 800, 1,000 °C	
O ₂ [%; dry]	5, 10, 15, 21	
Air velocity [m/s]	about 1.0	

tion. Thus in a combustion process, the use of burned gases (natural products of combustion) can be more effective to control NO_x in addition to the amount of oxygen in the combustion air. However, N₂ dilution method was preferred for this study under consideration of tougher combustion circumstances.

EXPERIMENT

The experimental conditions examined on this combustion test are given in Table 1.

The location of gas nozzle installations was varied according to the flow direction of combustion air, axially(case a) or radially(case b) as shown in Fig. 2. The test items were exhaust gas components of CO, NO_x, flame shape and radical components of CH, OH and C₂, which we measured with gas analyser, camera and ICCD camera. The ICCD camera was used especially for qualitative analysis of the flame, in which the radical components (OH, CH and C₂) inside the flame play an important role in understanding the structure of the flame. The OH component, which is known as the intermediate product of combustion, exists in the reaction zone. CH and C₂ radicals emit spontaneous chemilumi-

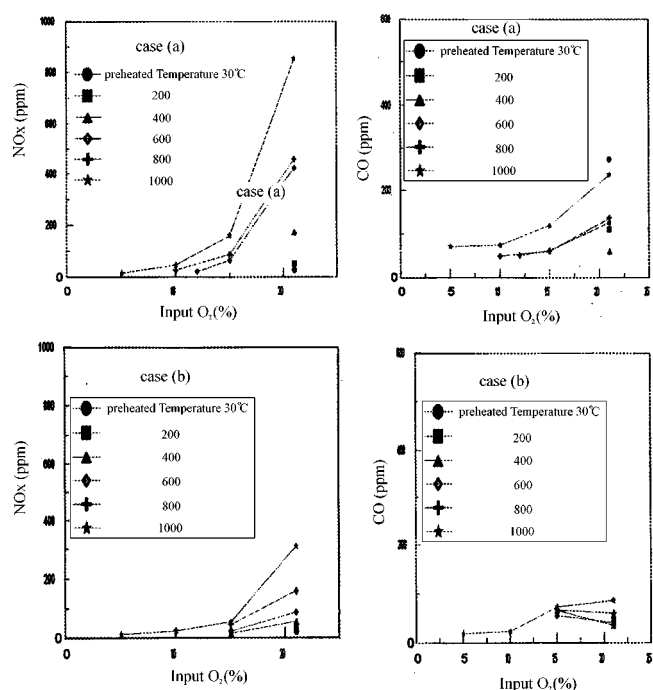


Fig. 3. NO_x and CO emissions depending on location of gas nozzle.

nescence under the decomposing process of hydrocarbon fuel and have their own source of color, blue and green, respectively. All tests were carried out under the condition of 2 l/min for fuel gas flow rate and 4.7 m³/h for air flow rate including N₂ dilution gas.

RESULTS AND DISCUSSION

1. NO_x and CO Emissions

The influence of both air temperature and oxygen concentration on the NO_x and CO emissions was studied with two locations of gas nozzle, and the selection of the gas nozzle location was done at the same time. The results of both cases presented in Fig. 3 show a significant influence of the dilution gas composition on NO_x and CO emission levels. Generally, case (b) has better performance compared with case (a). That is considered due to good mixing mechanism of air and fuel for reaction. The emission of CO in case (b) was found to be less than 100 ppm, and this suggests the presence of good and stable combustion conditions. As predicted, the values of NO_x and CO emissions increased with the increasing temperature and oxygen concentration. It can be explained that thermal NO_x, as main NO_x depends considerably on oxygen concentration and flame temperature coupled together. Finally we can say that lower oxygen concentration reduces NO_x and CO emissions remarkably, though the preheated air temperature goes higher. Hereafter case (b) was preferred for the next tests.

2. Combustion Stability Limits

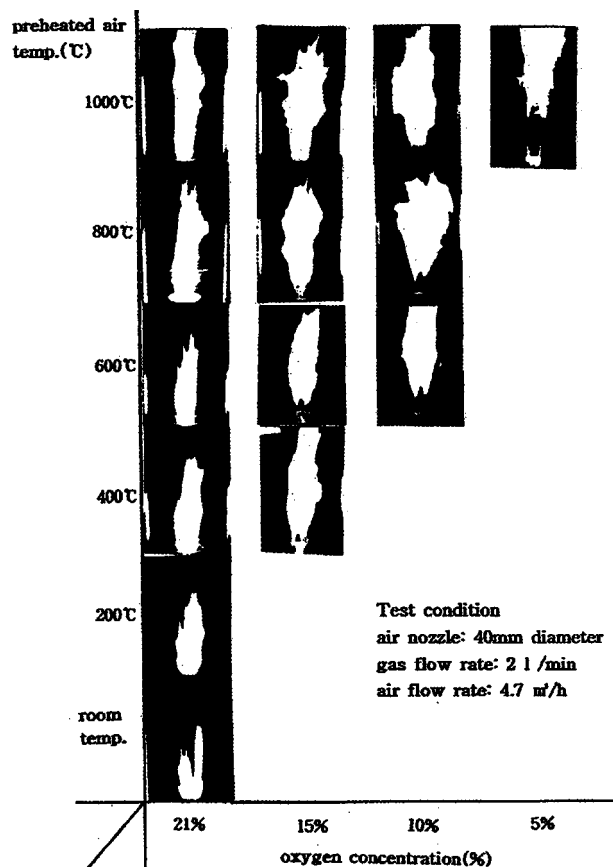


Fig. 4. Combustion stability limits.

The stability limits of the flame with LPG fuel were obtained by normal photography under various conditions of air preheat temperature and oxygen concentration of the air. The results presented in Fig. 4 are in good agreement with those of the published report from Japan, and they confirm stable flame combustion conditions with low oxygen concentrations of air of more than 5 % for air temperatures above 900 °C. However, for air temperatures below 900 °C the flame stability was significantly affected at less than 10 % oxygen concentration in the combustion air. As an example, a stable flame at 400 °C could only be achieved at a much higher oxygen concentration of about 15 %. The physical appearance of the flame (e.g., flame color, size, shape and global flame structure) was found to be significantly changed when the concentration of oxygen was decreased from 21 % (by volume) to 3 % while the air temperature was maintained constant at about 1,000 °C. The global flame features observed under conditions of 21 % O₂ and 25 °C air temperature were found to be a short and compact flame having the expected flame luminosity and blue color. In contrast, the flame observed with air having 3 % O₂ and 1,010 °C had extremely low luminosity and a very large volume. The color of the flame was found from bluish green to green depending on the input conditions of the air. The cause may be that

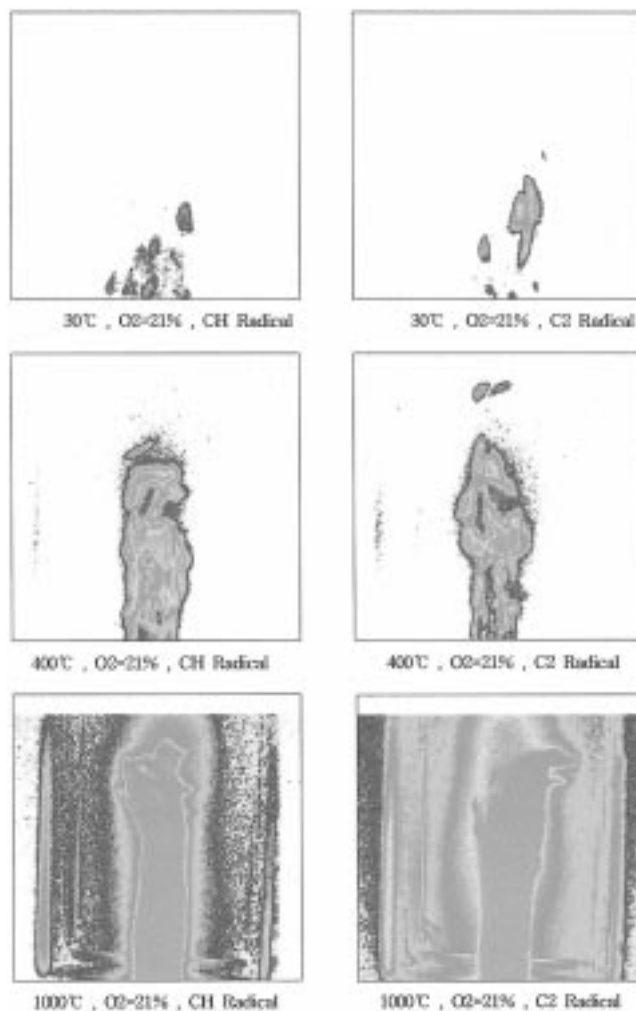


Fig. 5. Influence of air temperature on CH & C₂ radicals.

combustion under high temperature and low oxygen concentration provides lower heat release rates per unit volume compared to those of the flame obtained with 21 % oxygen in the combustion air.

3. Flame Colors Corresponding to Combustion Conditions

Fig. 5 shows the influence of preheated air temperature on flame colors based on CH and C_2 radicals. Various colors, namely white, red, blue, green, yellow are expressed in accordance with flame intensity. The color intensity of flame was stronger and brighter and the area of flame intensity was wider as the preheated air temperature increased.

Fig. 6 reveals the comparison of CH and C_2 radicals at a temperature of 1,000 °C through the variation of oxygen concentration 21, 10 and 5 %. As it is known that the color of premixed hydrocarbon flame changes with the equivalence ratio at 1 atm, namely, the color of flame is violet for fuel lean condition and it changes into blue for near-stoichiometric and blue-green for fuel rich condition. This phenomenon was confirmed through this test [Kishimoto, 1997; Sato, 1997]. By the spectroscopic studies, it is thought that the reason of color change of flame into green for fuel rich condition is the decrease of CH emission (425–432 nm) and the increase of C_2 swan band (516.5 nm). Even the flame which we observed is a non-luminous diffusion flame, the color change from luminous or blue into green-blue was observed with de-

creasing oxygen concentration. By spectrum analysis of the flame, the reason for the greenish changes is confirmed that C_2 intensity grows more intense than CH. At oxygen concentration of 21 % CH and C_2 radicals appeared upstream of the flame, but with decreasing oxygen concentration the appearance of CH and C_2 radicals moved to the downstream.

Moreover, its flame size would be larger and voluminous. This can be explained due to the delay of reaction by reduction of reaction rates. Fig. 7 shows the influence of air temperature and oxygen concentration on OH radical intensity of flame. It's widely known that OH radical is generated in the combustion reaction zone, mainly high temperature area [Katsuki and Ebisui, 1997; Fujimori et al., 1997]. In the case of oxygen concentration of 21 % the area of OH radical appeared larger and the color also brighter as the temperature went up. On the other hand, the intensity of the OH radical showed weaker as oxygen concentration changed from 21 % to smaller amount 5 %. These phenomena can be described as the reason from reduction of reaction through smaller reactant input.

Generally speaking the whole thing for this test, local intensity of chemiluminescence was comparably decreased corresponding to decreasing oxygen concentration and luminous region was drawn to downstream and spreaded.

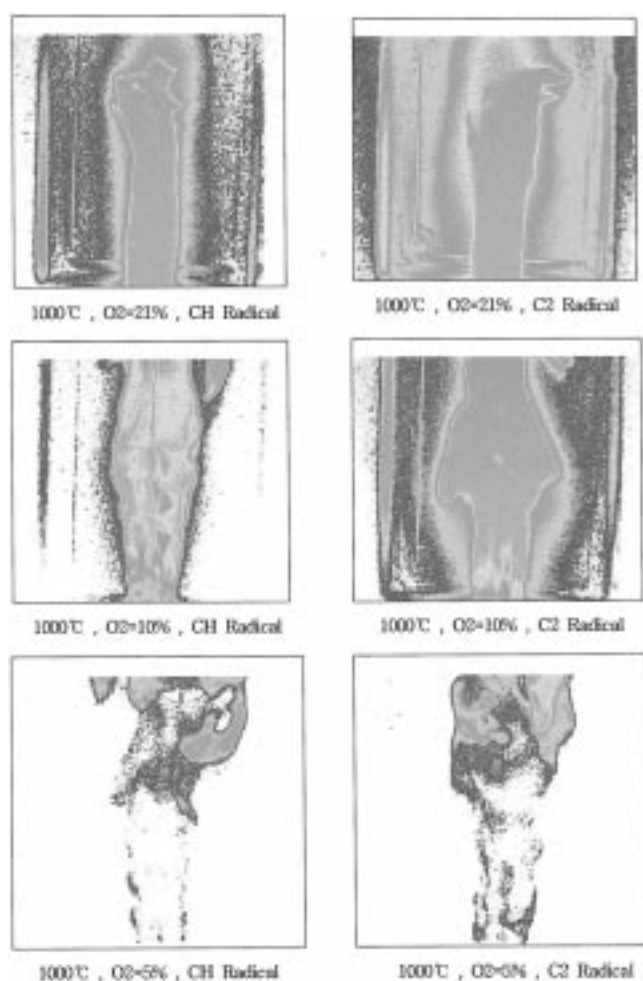


Fig. 6. Influence of oxygen concentration on CH & C_2 radical.
July, 1999

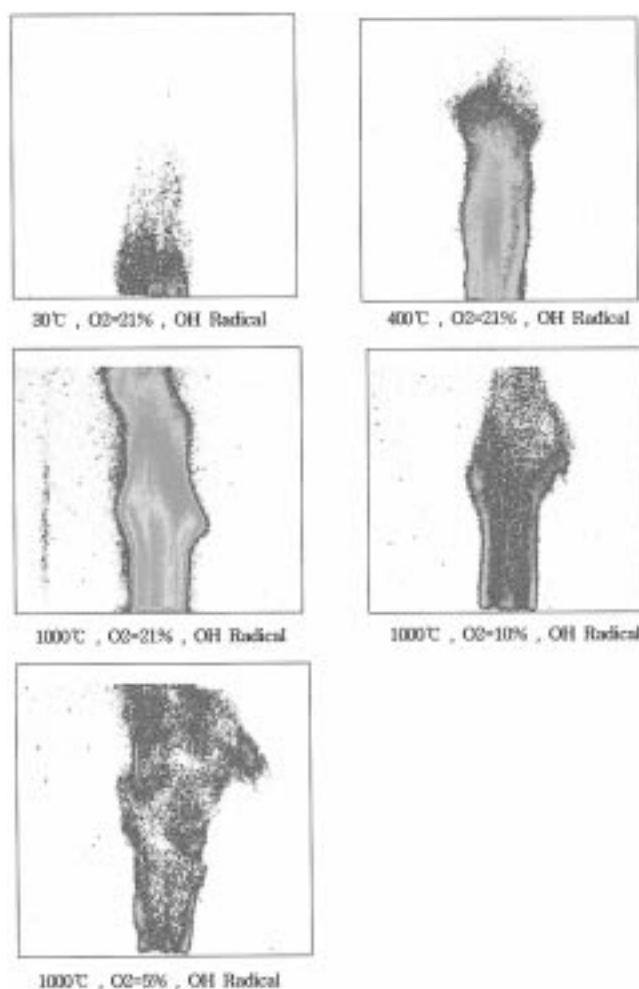


Fig. 7. Characteristics of OH radical.

For ordinary diffusion flame, the color of flame changes along the stream because the local mixing intense changes along the flow. But, according to the above discussion, for the change of flame color for high temperature preheated and diluted air combustion extended to the whole region of flame, it must be difficult to think that the color change into greenish was only due to the equivalence ratio. We guess that the mixing process or chemical process may be varied with preheated temperature, but in the future we intend to elucidate this for reliable answers.

Furthermore, flame with low oxygen concentration may have a comparably longer ignition delay than that of 21 %, and its root could not seat on a nozzle jet. This means that the long ignition delay makes enough time to mix nozzle fluid with the main air stream. But the air preheating could suspend the flame in space stably. This phenomenon may be new flame stabilization without the obstruction of flow, and partially premixing due to long delay must affect the NO_x emission characteristics and other combustion characteristics.

CONCLUSION

After consideration and discussion about high temperature preheated and diluted air combustion, we can summarize some results as follows :

1. Through the experimental test we had a confirmation of the lean-air combustibility under the circumstances of high temperature combustion air. That can be achieved under the condition that the higher the temperature of preheated air for combustion is, the lower the concentration of oxygen in air is. The results showed that a decrease of oxygen concentration lifted up the flame and dragged the flame position to downstream.

2. The tendency in CO and NO_x value from the experiment is thought to be very similar with that from the previous numerical

study, in which CO and NO_x are increasing with the preheated temperature and the oxygen concentration in combustion air to be increased.

3. One significant test result has been a discovery of a phenomenon called "Green Flame" effect, taking place in the diluted high temperature air combustion condition confirmed with spectroscopic measurement. It is thought that the reason for the color change of the flame into green for fuel rich condition is the decrease of CH radical and the increase of C_2 radical.

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