

Research Article

Statistical Analysis of Flame Oscillation Characterization of Oxy-Fuel in Heavy Oil Boiler Using OH Planar Laser-Induced Fluorescence

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The present work investigated the flame structures and oscillations of oxy-fuel combustions in a heavy oil boiler using OH planar laser-induced fluorescence imaging. Combustion instabilities, such as flame oscillation and combustion fluctuation, can assess the performance of an industrial burner in the boiler. The peak position variation in OH concentration was associated with the change of the reaction zone that corresponded with the fluctuation of the heat-release zone in the combustion chamber, which provides a valuable reference for the design of the combustion chamber. The experimental results suggest that the phenomenon of stratified flame combustion is related to the characteristic of flame oscillation. The substitution of N₂ with CO₂ will not significantly influence the flame oscillation frequency but increases the number of flame surface. As O₂ concentration increased in the O₂/CO₂ atmosphere, the phenomenon of stratified flame combustion disappeared, and the flame presented an island-like structure. The bimodal oscillation of the combustion center was demonstrated by means of the probability density method; CO₂ played a role in the extension of the combustion center. The combustion fluctuation of inner regions was quantitatively described; CO₂ could maintain interregional stabilization to some extent. Compared with traditional measurement methods, PLIF technology has great advantages in evaluating burner performance and optimizing the design of the combustion chamber.

1. Introduction

In the context of energy saving and emission reduction, heavy oil, which has the advantages of abundant reserves and low costs, has been the focus of much attention [1–3]. The oxy-fuel combustion process has been proposed as a promising technology for controlling CO₂ emissions, thus presenting an important option to address the environmental issues [4–6]. Therefore, the combustion system of heavy oil is combined with oxy-fuel combustion process in order to reduce carbon dioxide emissions while offering a more efficient use of heavy oil resources [7]. However, the successful implementation of O₂/CO₂ technology in heavy oil boilers requires a comprehensive understanding of the

changes caused by the replacement of N₂ with CO₂ in the combustion atmosphere. In addition, the consequent stability problems of the combustion system also cannot be ignored [8]. In view of the performance evaluation of industrial-type burners, combustion instabilities during the combustion process are important for assessing the quality of the burners.

Previous experience with the study of industrial combustors suggests that combustion instability may exist in scramjet engines and gas turbines [9–12]. Both the type of fuel and the injection mechanism have an impact on acoustic motion and flame oscillation. The characteristics of frequency oscillation, both experimentally and analytically, were investigated [13–15]. Combustion instabilities

including flame oscillation and combustion fluctuation are also of great significance in the combustion efficiency and even the safety of combustion system, although the problem of heavy oil boilers has not been recognized and explored thoroughly. The research on the instability of combustion system published mainly focuses on the measurement of temperature and pressure. The traditional measurement methods are implemented by means of temperature and pressure sensor with high precision [16–18]. However, due to the limitation of installation positions, the spatial resolution of the measurement is low. At present, modern optical measurement techniques are applied to the combustion experiments increasingly, achieving the measurement of many important combustion parameters such as concentration, velocity, and temperature [19–21]. High-speed PLIF visualization measurement technology possesses the characteristics of high spatial and temporal resolution, which can not only present the spatial structure of flame but also provide the time characteristic information of flame. The peak position variation in OH concentration was associated with the change of the reaction zone that corresponded with the fluctuation of the heat-release zone in the combustion chamber. The flame fluctuation can be tracked in real time, so combustion instability reflected by flame fluctuation can be investigated without spatial and temporal limitations.

Over recent years, the high-speed PLIF (planar laser-induced fluorescence) measurement system has been widely used in laboratory small-scale combustion devices [22, 23], but its application in industrial combustors bench, such as scramjet engines and boilers, is still rare [24, 25]. The harsh bench test environment and high requirements on the performance of laser, detector, and optical system limit its engineering applications. Considering complex test environment, a set of high-speed PLIF measurement system with high reliability and environmental adaptability is independently developed. This system consisted of modular design, temperature, and humidity control and vibration isolation device possesses extremely high environmental adaptability.

The aim of this paper is to report the characteristics of flame structures and oscillations under the oxy-fuel combustion conditions. In the experiment, the flame structure of oxy-fuel combustion of heavy oil was reported applying a 400 Hz OH-PLIF. In our previous ignition experiments of heavy oil combustion in the boiler, including autoignition and forced ignition, the temporal resolution of 400 Hz was sufficient to track the temporal evolution of the flame in boilers. A deep understanding of the combustion instabilities is beneficial to understand comprehensively the operating performance of industrial burner, especially providing a valuable reference for boiler design.

2. Experiment Details

2.1. PLIF Measurement Apparatus. A schematic diagram for OH-PLIF measurements is shown in Figure 1, as previously described in [26]. The laser system consisted of a pulsed Nd:YAG laser and a dye laser with a frequency-doubling BBO crystal. The second harmonic ($\lambda = 532$ nm) of the Nd:YAG

laser was used to pump the dye laser with rhodamine 590. For the excitation of OH radical, $Q_1(8)$ line of $A^2\Sigma^+ - X^2\Pi(1, 0)$ transition at 283.553 nm was adopted to reduce temperature dependence of the fluorescence signal. It is particularly emphasized here that the harsh bench test environments require the measurement system to have good environmental adaptability. In the laboratory environment, temperature and humidity are better controlled and no dust affects. However, in the bench test environment, high temperature and humidity strongly affect the stable operation of the PLIF measurement system. Specifically, the high temperature can affect thermal effects of laser crystal and reduction of frequency-doubling efficiency, and the high humidity may cause crystal deliquescence. In addition, the fluctuation of laser energy and drift of laser wavelength are also caused by complex test environment. The pumping source was developed independently for the PLIF system to overcome complex experimental environment, including moisture proof and antivibration. The optics consisted of a concave lens ($f = -8$ mm), collimating lens ($f = 240$ mm), and focus lens ($f = 800$ mm). The sheet forming optics generated a 10.5 cm laser sheet, and the sheet reaching the observation window was nearly 12.3 cm. A large scale of laser sheet can provide enough visualization area of radicals as a foundation of studying combustion fluctuation.

Considering typically fluorescing components, interferences from soot and Mie scattering from the oil spray can be blocked by the combination of simrock 315/15 and UG11 mounted in front of the ICMOS camera. To minimize contributions of OH* chemiluminescence and flame luminosity, the detection gate was set to 30 ns. Postprocessing included off-resonant background subtraction, a correction of the inhomogeneous laser sheet profile, and pulse-to-pulse energy variation. As a result, the signals from PLIF images correspond to the OH radical emission. Concentrations of OH radicals can be demonstrated qualitatively by OH fluorescence signals. In the paper, the short-time fast Fourier transform (FFT) revealed the frequency-domain characteristics of flame oscillations, and the statistical probability density method was applied to study interregional combustion fluctuation. The statistical sample extracted from time-resolved sequences of OH-PLIF images. For each transient image, the position where the maximum OH intensity occurs was used to represent high OH concentration position at that time; meanwhile, the mean OH intensity in a given region corresponds to the combustion state of the region.

2.2. Flame Conditions. The oxy-fuel combustion system refers to the work of Wang et al. [7]. The oxy-fuel experimental conditions are shown in Table 1. The excess air coefficient is the ratio of the practical oxygen supplement to the theoretical oxygen consumption. In addition, the experiment burner is a commercial burner, whose model was RIELLO40-G10LC (RIELLO, Legnago, Italy). The maximum output is 2.5 GPH (10 kg/h). The jet was a solid nozzle (Steinen S) with an output of 1.0 GPH (3.73 kg/h), and the atomization angle was 60. The oil pump pressure was 12 bars. In the experiment, only the turbulent flame

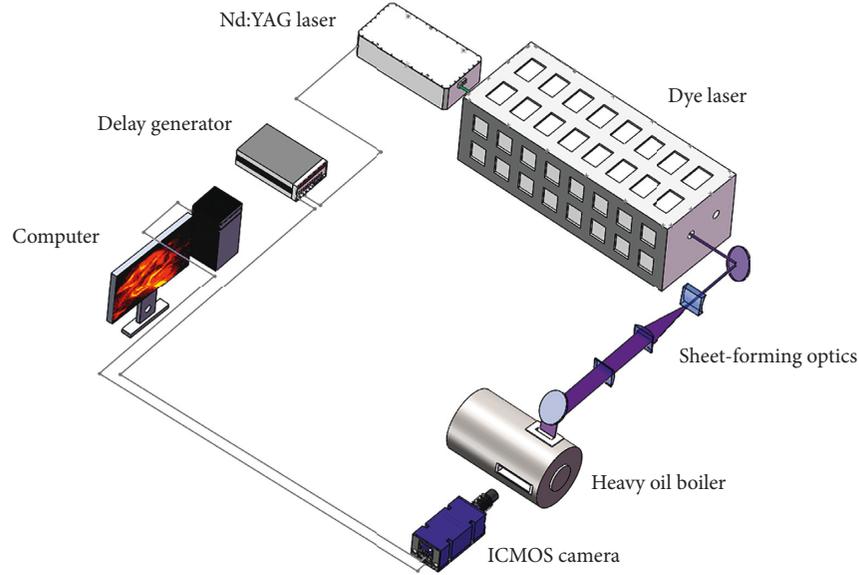


FIGURE 1: Experimental setup schematic diagram.

TABLE 1: Oxy-fuel experimental conditions.

Condition	O ₂ concentration	Coefficient of excess air α	Composition of gas supply (L/min)			
			Air	O ₂	CO ₂	Total gas flow
A1	33	1.652	573	103		676
A2	33	1.652		223	453	676
A3	37	1.852		250	426	676

structures involving the oil-gas combustion process attracted our attention to assess the application of an industrial burner in the boiler and optimize the design of the combustion chamber.

3. Results and Discussion

3.1. Flame Oscillation. Experiments were conducted to study the flame oscillation characteristic in the heavy oil boiler under three oxy-fuel combustion conditions. In terms of flame structure, the flame surface exhibited relatively large differences, as shown in Figures 2(a)–2(c). In the O₂/N₂ atmosphere, the phenomenon of stratified flame combustion was investigated, which may play an important role in stabilizing combustion. In Figure 2(b), using CO₂ instead of N₂ in the air as the diluent, it is interesting to find that the number of the flame surface increased and the combustion zone was clearly expanded. As mentioned earlier, spray combustion creates a turbulent environment in the combustion chamber. The flame is not continuous during the turbulent combustion process; instead, it is a process comprising extinction and reignition [27]. The number of the flame surface could strengthen the process of heat and mass and then improve combustion stability. As the concentration of O₂ increased in the O₂/CO₂ atmosphere, the phenomenon of stratified flame disappeared and the flame presented an island-like structure, as is shown in Figure 2(c).

In order to further study flame oscillation characteristic in the whole combustion process, time-resolved sequences of OH-PLIF images were acquired and the normalized mean OH signals were extracted as is shown in Figure 3(a). For oxy-fuel combustion condition A1, intermittent drops and jumps in the signal are demonstrated. The conditions A2 and A3 are similar to A1, so for brevity they are omitted here. Figure 3(b) shows the frequency power spectral of the oscillating OH signals. The low frequency oscillation ranging over 0–50 Hz exists for both conditions A1 and A2, while the amplitude of the latter is slightly lower than the former. For condition A3, there is no dominant frequency in the 0–200 Hz range. The behavior of self-excited oscillating flame may be influenced by the presence of soot under the higher O₂ concentration atmosphere [17].

3.2. Combustion Fluctuation. There is rather strong OH intensity at the flame surface and high temperature. Heat and mass are transferred into the surrounding gas increasing the temperature and decreasing the density, which resulted in a longitudinal density gradient in the combustion chamber. In that case, a vortex structure is formed and extrudes the flame surface, and then flame fluctuation is generated accordingly. The generated vortex separates the flame from the surrounding gas, slows down the diffusion, and lengthens the flame. As a result, the flame is burning away from the nozzle, so the occurrence position of maximum OH intensity appears far from the nozzle. On the

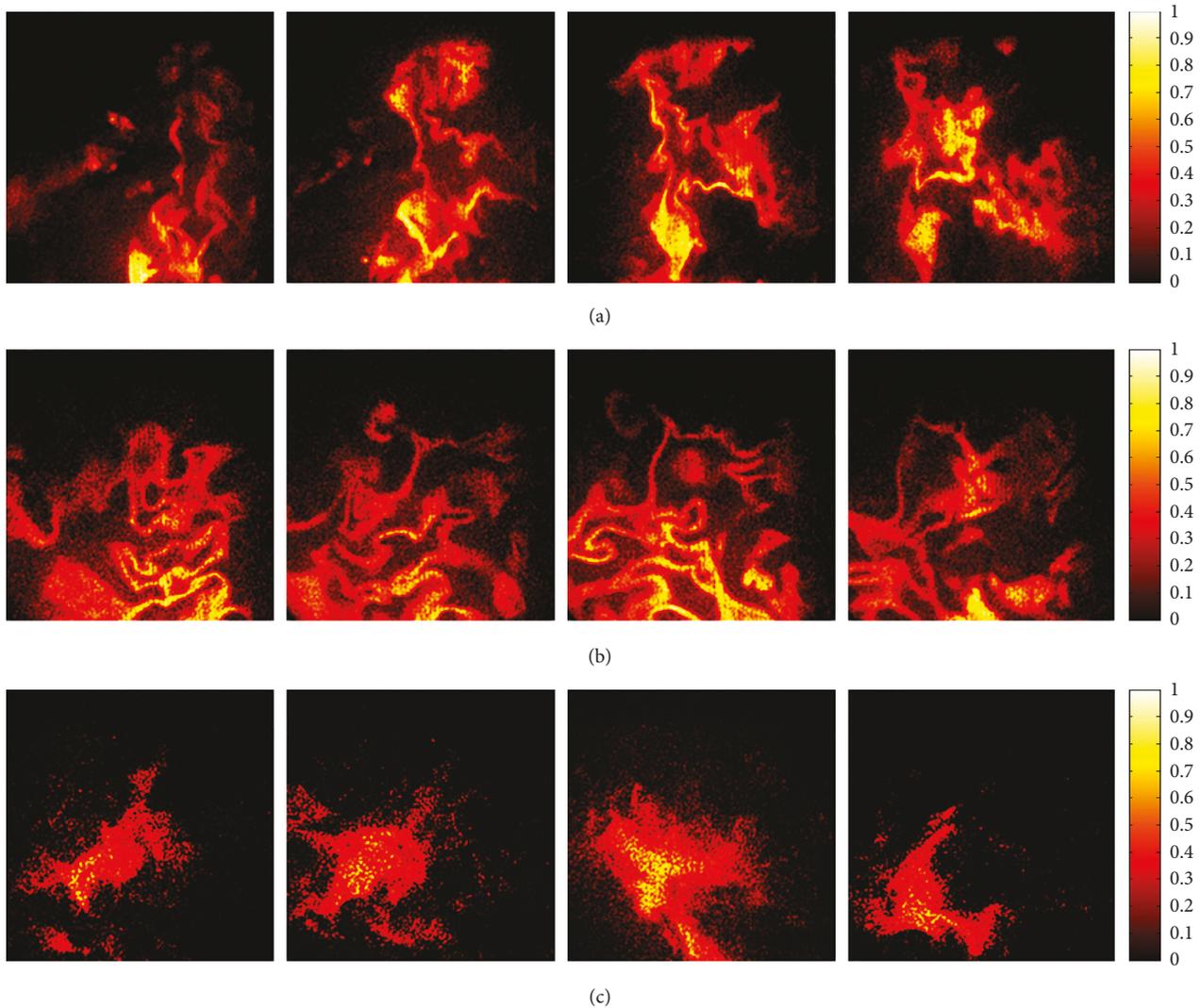


FIGURE 2: Selected sequences of OH-PLIF images. (a) In the O_2/N_2 atmosphere, the oxygen concentration is 33% corresponding to the condition A1; (b) in the O_2/CO_2 atmosphere, the oxygen concentration is 33% corresponding to the condition A2; (c) in the O_2/CO_2 atmosphere, the oxygen concentration is 37% corresponding to the condition A3. The unit scale bar reflects the intensity of the OH signal, which has been normalized.

contrary, when the vortex breaks away from the flame, the flame interacts more closely with each other, making the flame shorter, which represents the position of maximum OH intensity appears near the nozzle. Therefore, the flame intensity fluctuates along the direction of the airflow in the turbulent combustion. To our knowledge, the cumulative average method is frequently applied to deal with the issues related to turbulent combustion, especially turbulent burning speed and flame brush [28]. However, when involving in the combustion field instability, several problems come with it. Typically, the cumulative average method will erase the flame transient information, so the fluctuation of the flame in the combustion field cannot be learned. The information of flame fluctuation is of significance in evaluating the performance of industrial burner.

The maximum OH positions from the burner exit were extracted according to the time-resolved sequences of OH-

PLIF images under the three experiment conditions, as is shown in Figure 4(a). It can be seen the fluctuation area satisfies a certain range and better consistency, and then the statistical method is applied to study the oscillating data. In Figure 4(b), the probability density distribution is shown to illustrate the oscillating correlation. In the O_2/N_2 atmosphere, there exist two oscillating peaks in the probability density distribution. The phenomenon of two peaks explained the leading flame mainly distributed in these two regions. In the O_2/CO_2 atmosphere, the oxygen concentration kept the same as the former. The results showed that two oscillating peaks still existed, while the peak away from the burner exit got weak. It should be noted that the oscillating peaks moved away from the burner exit, meaning that the center of combustion may move to the rear of the combustion chamber. The substitution of N_2 with CO_2 in the oxidizer with the same oxygen concentration resulted in an

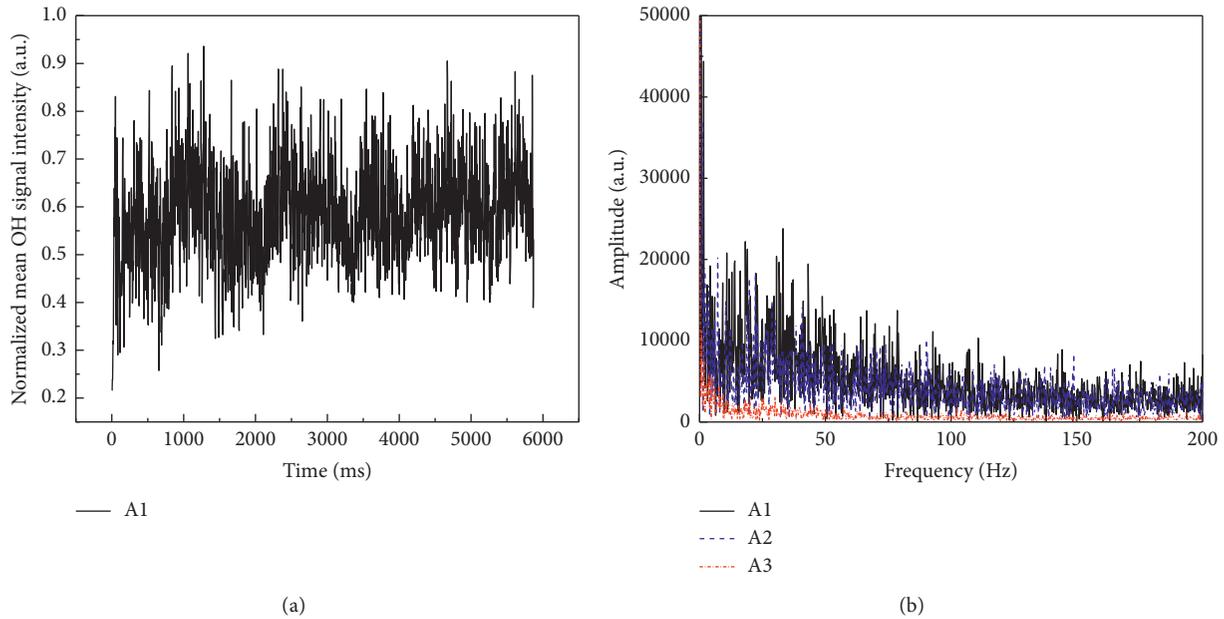


FIGURE 3: Oscillation curves of the normalized mean OH intensity. (a) Time-domain distribution of OH intensity. More than 2400 data are acquired, and the time interval is 2.5 ms. (b) Frequency-domain distribution of OH signals.

increase in the distance between the two peaks, corresponding to a more severe fluctuation of combustion center. The results also illustrated the expanding combustion zone in the O_2/CO_2 atmosphere. As the oxygen increased (up to 37%), surprisingly, the phenomenon of two oscillating peaks disappeared and the position of intense burning distributed more concentrated. In other words, the fluctuation degree of combustion center is weaker than before.

The temperature distributions across the central axis are shown in Figure 5(a), already studied by Wang et al. [7]. In the O_2/CO_2 atmosphere, the temperature field distribution changed and the high temperature area was far from the burner exit compared with the O_2/N_2 atmosphere. However, the reaction zone represented by OH concentration did not change when CO_2 was used to replace N_2 in the oxidizer as shown in Figure 5(b). The reasons can be explained that CO_2 changed the temperature distributions by influencing the transport and thermal properties of the mixture rather than directly participating in chemical reactions [29]. As the oxygen increased, the highest temperature positions moved towards the burner exit and the temperature conditions tended to be similar to that of the O_2/N_2 atmosphere at low oxygen concentration. However, the reaction zone was not moving in the direction of the high temperature zone, but similarly away from the burner exit. It was shown that the reaction zone represented by OH concentration deviated from the high temperature zone, which is necessary to understand deeply the combustion state of the boiler.

Due to the high spatial and temporal resolutions of the PLIF measurement system, the field of view is divided into 10 regions along the direction of the airflow as shown in Figure 6(a). The aim of region segmentation is to study the combustion fluctuation of inner regions. As previously studied, the displacement velocity of the flame surface is

about 4 m/s. The time interval is 2.5 ms, so the divided area is enough to capture a full flame surface at a certain time with sufficient precision. Taking the region F in Figure 6(a) as an example, the mean value of the OH signal in this region was selected during the whole combustion process, and then the fluctuation samples of the OH signal value were obtained, which reflected the combustion condition in this region. The probability density distribution of statistical samples was calculated. In Figure 6(b), the correlation coefficient of Gaussian fitting is above 0.99. The half height width, i.e., FWHM, was selected to quantitatively represent the fluctuation of the combustion field. In other words, it can also reflect the fluctuation of temperature field because of OH intensity change. In addition, the value of X_C in the Gaussian curve represents the x -coordinate of the peak position, which reflects the center of fluctuation and it can quantitatively express the intensity of the combustion.

In Figure 7(a), the OH signal expresses a narrow distribution and a high amplitude near the nozzle region. Besides, the OH signal increases along the direction of airflow, indicating that it is getting closer to the area of intense combustion. The combustion field presents a strong center and weak sides. In Figure 7(b), CO_2 replaces N_2 in the air as the diluent. It showed that the substitution of N_2 with CO_2 in the oxidizer would change the combustion distribution, in which the combustion near the nozzle burned more intensely. Because of different thermodynamic properties between N_2 and CO_2 , the diffusion rate of O_2 in CO_2 was lower than that in N_2 [29, 30]. The variation of thermal and transport properties may result in a different flame distribution in the combustion chamber. It is worth noting that the distribution of the OH signal is more compact between regions, possessing a high degree of similarity, as shown in Figure 7(c). As the oxygen

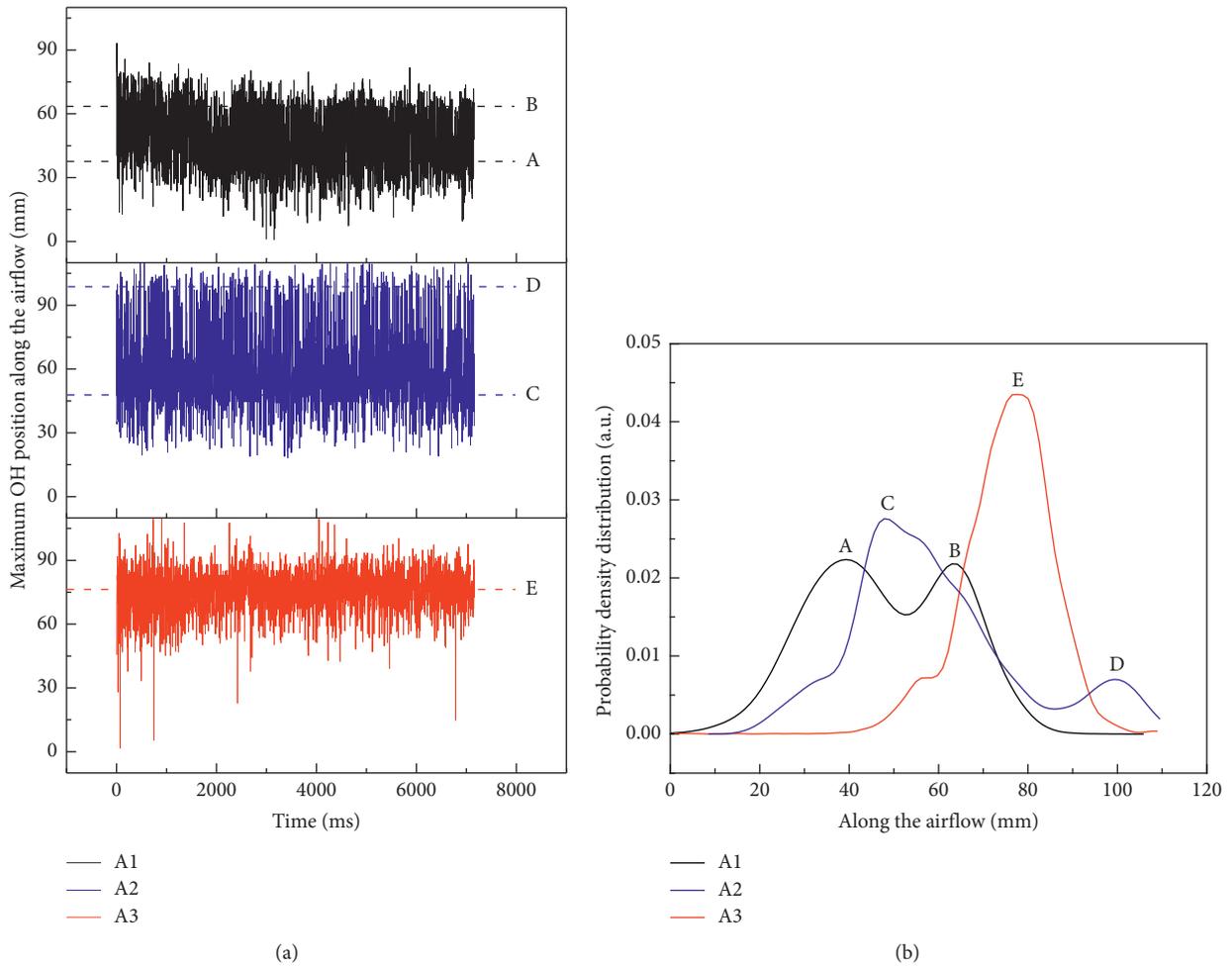


FIGURE 4: (a) Oscillation curves of the strongest burning position under three oxy-fuel conditions. The dash indicates the peak position of probability density distribution. (b) Probability density distribution of the oscillation data. A-E express the oscillation peaks.

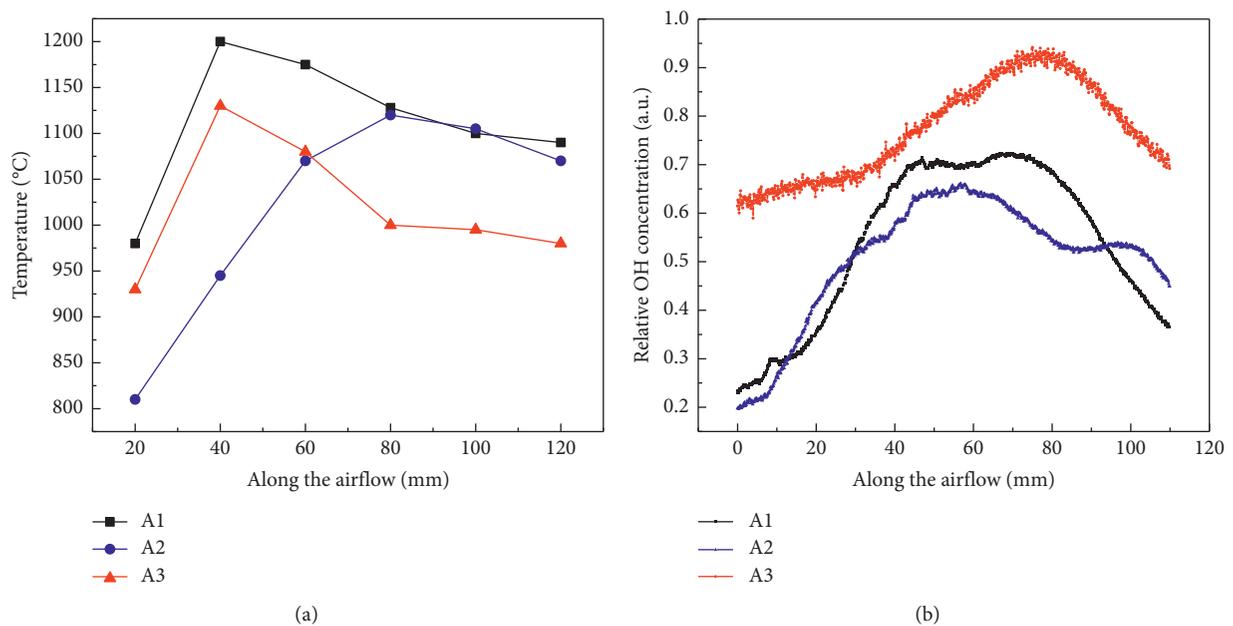


FIGURE 5: (a) Temperature distributions across the central axis; (b) distribution of relative OH concentration along the airflow.

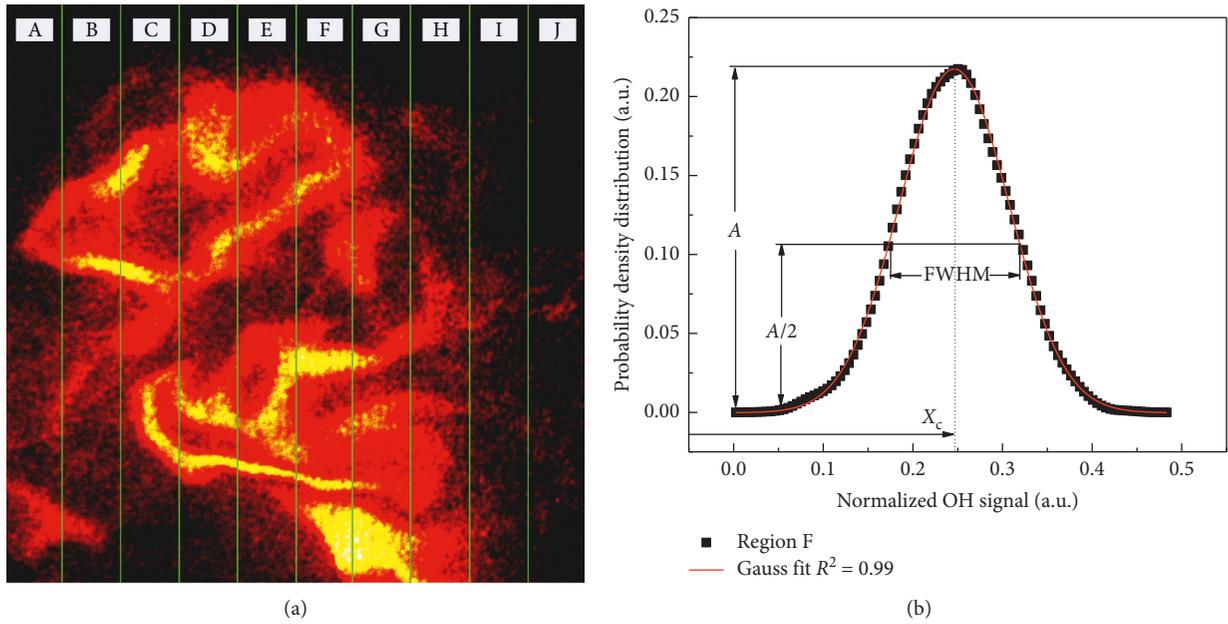


FIGURE 6: (a) Region segmentation diagram, field of view = 110 mm × 110 mm. The airflow is from the right to left. The nozzle is on the right. (b) Probability density distribution of oscillation data of the F region.

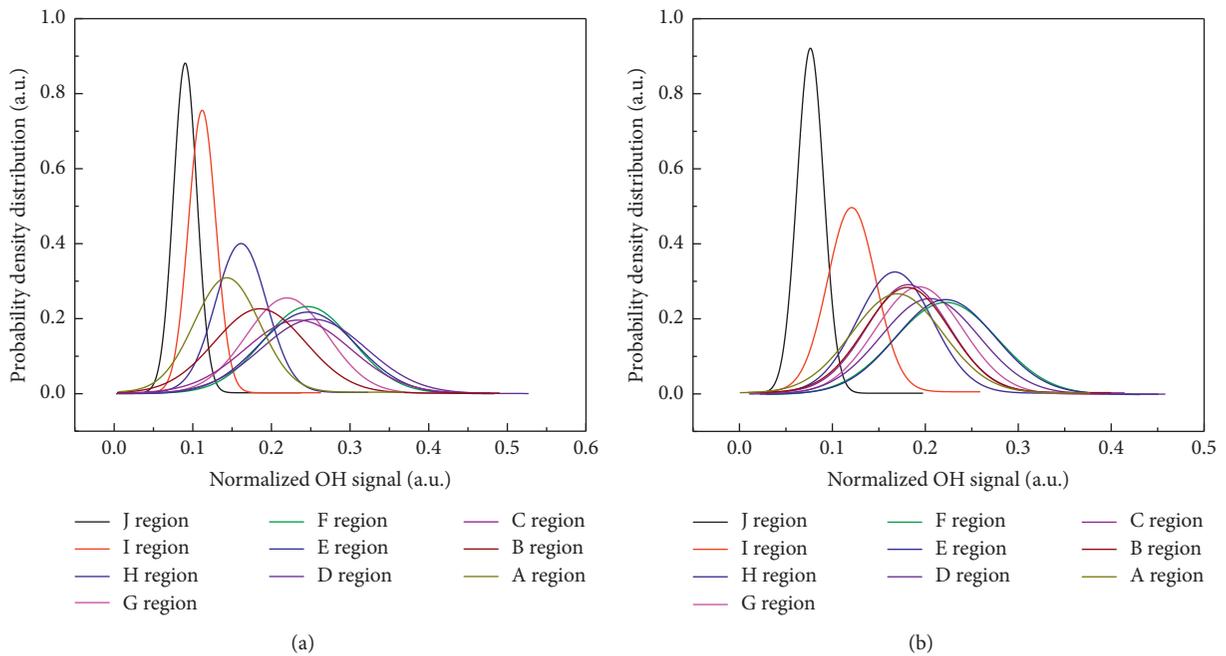


FIGURE 7: Continued.

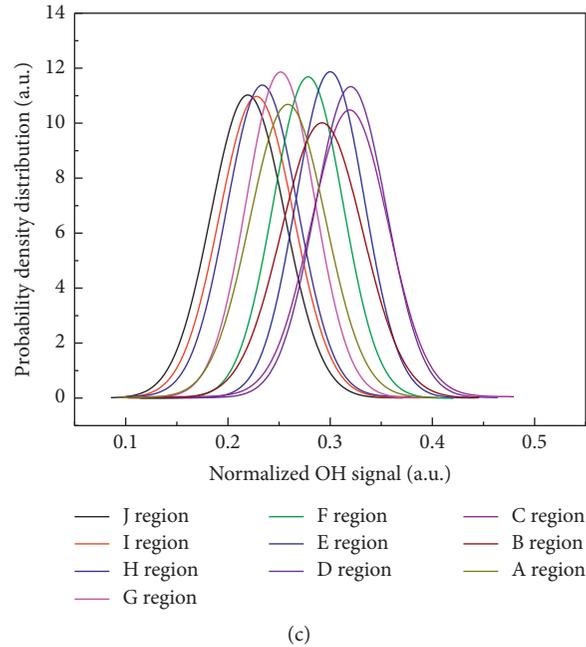


FIGURE 7: Probability density distribution of oscillation data of various regions, corresponding to the conditions (a) A1, (b) A2, and (c) A3.

concentration increases, the temperature of the reaction gas rises, which compensates for temperature reduction due to low diffusivity.

In order to intuitively reflect the interregional fluctuation conditions, the values of FWHM in ten regions above were extracted along the airflow, as shown in Figure 8. The behavior of the global flame is controlled by the local flame. The fluctuation of inner regions is caused by the intensity change of the local flame in the inner region, so the local fluctuation information is beneficial to understand the global flame behavior deeply. It can be seen the value of FWHM increases first and then decreases in the O_2/N_2 atmosphere, corresponding to the fluctuation of temperature. Besides, the peak is behind the field of view, namely, away from the nozzle direction. In the O_2/CO_2 atmosphere, the peak gradually moves to the nozzle and the value of FWHM decreases slightly. In other words, the degree of temperature fluctuation in the O_2/CO_2 atmosphere was not as violent as the former. With the O_2 concentration increasing, up to 37 percent, it can be found that a nearly constant FWHM value was presented, which means fluctuation differences between regions are weak.

According to the change trend of the X_C value in Figure 9, good agreement was obtained for the center of fluctuation of both N_2 diluent and CO_2 diluent, meaning that the substitution of N_2 with CO_2 in the oxidizer with the same oxygen concentration would not significantly change the center of fluctuation. A comparison of 33 percent O_2 concentration and 37 percent O_2 concentration in the O_2/CO_2 atmosphere obviously illustrates that the latter greatly is superior to the former. Analysis of the image suggests that the O_2 concentration plays a role in the intensity of the combustion, while the diluent characteristic has no obvious effect. The soot in the reference case with higher oxygen concentration participates

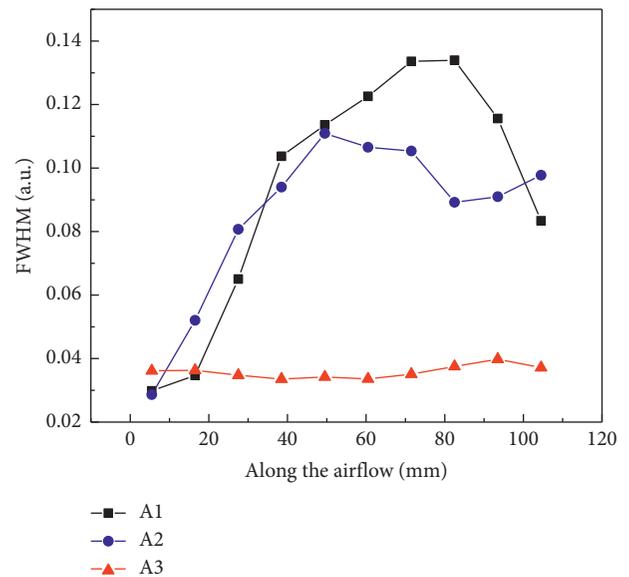


FIGURE 8: FWHM data of three oxy-fuel conditions in different regions.

in the radiation heat transfer, causing a higher temperature level in the whole combustion chamber [17]. In terms of combustion fluctuation, both the O_2 concentration and the diluent characteristic contribute to it. In addition, it can be found that the distribution of fluctuation center of the inner region is consistent with the results representing overall combustion intensity shown in Figure 5(b).

It is true that CO_2 could inhibit combustion to some extent; besides, it is superior to N_2 in maintaining combustion zone stability. On the contrary, as the O_2 concentration increased, more intensely combustion could be

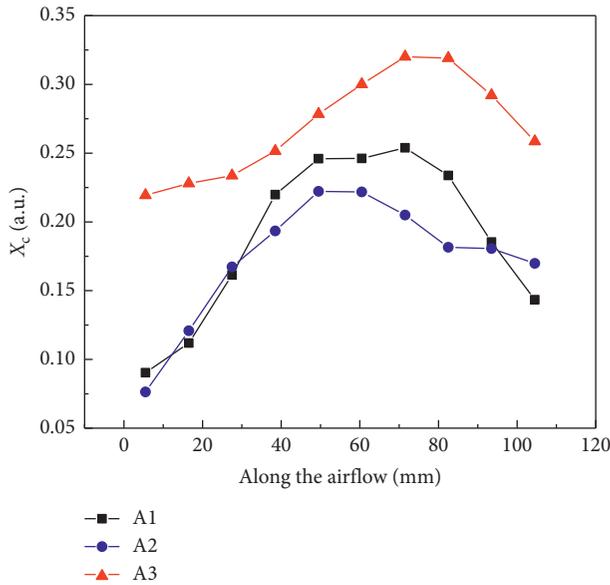


FIGURE 9: X_C data of three oxy-fuel conditions in different regions.

found; meanwhile, the stability of combustion region was significantly improved.

4. Conclusions

The flame structures of oxy-fuel combustion in the heavy oil boiler using 400 Hz OH-PLIF have been investigated in the present work. The phenomenon of stratified flame combustion is related to the characteristic of flame oscillation. Low-frequency oscillation of the flame can be found in the oxy-fuel combustion of heavy oil, although the frequency characteristic disappeared with higher O_2 concentration (up to 37 percent). Interregional combustion instabilities were demonstrated by the statistical probability density method; besides, the values of FWHM and X_C were extracted to quantitatively demonstrate the combustion fluctuation. The fluctuation of combustion center was affected by the type of diluent and the concentration of oxygen. The bimodal oscillation of the combustion center was demonstrated; CO_2 played a role in the extension of the combustion center. The fluctuation degree of the combustion region reflected by the value of FWHM expressed strong center and weak sides. Furthermore, by analyzing the change in X_C values, CO_2 could inhibit combustion and reject combustion instability to some extent. When it comes to the effect of oxygen concentration on combustion instability, it can be found that the combustion was obviously improved and the fluctuation differences of the inner region were greatly reduced.

In further study, the improvement of laser repetition frequency is of significance in investigating combustion instability with higher precision. Compared with traditional measurement methods, PLIF technology has great advantages in evaluating burner performance.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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