Experimental Study on Combustion Stability of a Gas Turbine Model Combustor under Oxygen-Lean Conditions

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Abstract: Flue gas recirculation has emerged as a promising low-NOx emission technology in advanced gas turbines, while the slower oxidation rate induced by the low oxygen content could potentially cause combustion instability. We conducted an experimental investigation in a single-nozzle swirl combustor to examine the impact of oxygen content, inlet flow rate as well as temperature on combustion instability under oxygen-lean conditions. The results show that reducing oxygen content from 23.3% to 21% leads to reduced amplitudes of pressure pulsation and exothermic pulsation, indicating improved combustion stability. However, further reduction in oxygen content to 18.6% causes a decrease in the combustion reaction rate, which leads to the deterioration of flame root stability and an increase in the amplitude of pressure pulsation. As the oxygen content drops to below 18.6%, the flame becomes unstable and suspends downstream of the combustion chamber, leading to a reduction in exothermic intensity and causing the flame to gradually approach extinguishment, which results in a decrease in the amplitude of pressure pulsation. Besides, under oxygen-lean conditions, increasing the inlet temperature is conducive to reducing the amplitude of pressure pulsation and enhancing combustion stability. Additionally, as the incoming flow rate increases from 7.4 to 9.9m/s, the refined fuel atomization and improved uniformity of oil-gas mixing contributed to increased flame root stability and decreased pressure pulsation amplitude. Nonetheless, when the incoming flow rate further increases to 12m/s, flame root stability deteriorates, leading to increased amplitudes of exothermic and pressure pulsations.

Keywords: Swirl Combustor; Flue Gas Recirculation; Oxygen Lean; Combustion Instability.

Combustion instability is a frequent problem in turbine combustion chamber[1-4]. When the flow field fluctuates, a large amount of exothermic pulsation may occur leading to unstable combustion[5-7], which will cause severe engine vibration, damage key components of combustion chamber, and seriously affect engine performance[8-11]. Therefore, combustion instability is one of the main technical challenges in the development of engines. To address this issue, engineers need to thoroughly investigate combustion instability during the design and testing process to ensure the reliability and good performance of the engine.

Specifically, flame morphology has an important impact on combustion instability, unstable fluctuations in the flame surface can cause heat release fluctuations in the combustion chamber. Meier[12] measured the flame shape of swirl flames in a gas turbine model combustor under different conditions, and investigated the difference between turbulent combustion and combustion instability through spectrum measurements. Their study implied that combustion instability is the result of the coupled effects of flame surface and several different flow structures. Taamallah[13] studied the relationship between flame shape and combustion stability in a lean premixed swirl combustor. Their results showed that as the equivalence ratio increase, the combustion chamber gradually transitions from stable state to unsteady state, and the overall flame structure develops from V-shape to M-shape. They found that the presence of flames in the recirculation zone outside the combustion chamber is key to the transition from stable to unstable combustion. Additionally, the flame structure is flatter and the heat release is more concentrated, which makes self-excited combustion instability more likely to occur.

Operational parameters also have significant impacts on combustion stability. Fritsche[14] conducted an experimental study on the combustion stability characteristics of a single-nozzle swirl combustor under different inlet temperatures and equivalent ratios. Their results suggested that the flame stability deteriorates with increasing equivalence ratio under fuel-lean conditions, while it is enhanced with increasing equivalence ratio under the fuel-rich condition. Bonciolini[15] studied the effect of fuel flow rate on combustion instability of single-nozzle swirl combustor. They found that changes in the fuel flow rate show a great impact on combustion instability. As the fuel flow rate increases, the exothermic heat in the combustion chamber increases, and the combustion stability first deteriorates and then improves. Besides, oil/gas ratio also shows great influences on the combustion stability, but the range of fuel-gas ratio for stable combustion is quite different when increasing fuel quantity and when decreasing fuel quantity, i.e., combustion stability shows hysteresis. Vignat et al.[16] adjusted the pressure loss of the combustion chamber by changing the geometry of the swirler, and explored the effect of pressure loss on combustion instability. Their results showed that, as the pressure loss decreases, the operating range of combustion instability becomes narrow and the amplitude of pressure pulsation increases. Preethi[17] carried out a study on the influences of fuel types on the combustion instability in an annular combustor, and found that the amplitude and frequency of combustion instability depend on the fuel injection models and fuel type, and the injection of liquid fuel can cause a change in the ignition delay time, which leads to a change in the unstable region. The results show that the largest instability domain is obtained for premixed propane. In comparison, the instability contour shrinks in the case of heptane, revealing a larger stable region. The stability of the system is further augmented when it is operated with dodecane. Furthermore, many researches[18-28] have examined the influence of fuel composition on combustion stability. Figura et al.[29] investigated the effect of fuel components in CH4/H2 mixtures on combustion instability for a lean premixed combustion chamber. Their results showed that fuels of different components have different stable combustion conditions. The lower heat release rate of hydrogen and the lower combustion chamber temperature will result in the reduction of sound pressure intensity and the decrease of the main frequency for combustion instability.

As shown above, although combustion instabilities have been extensively studied by experiments and numerical simulations, most studies have focused on the influences of operational and geometric parameters on combustion instabilities under 21% constant oxygen content. Few studies have been conducted on the effects of oxygen content, especially under oxygen-lean conditions, on the combustion instability in gas turbine combustion chambers. With the increasingly strict environmental protection regulations, low pollution technologies such as the dilution of flue gas recirculation technology[30, 31] have been developed rapidly. However, dilution of flue gas recirculation technology reduces the oxygen content in the combustor resulting in the reduction of combustion reaction rate and flame propagation speed[32-34], which may cause new combustion instability issues. Therefore, we carried out an experimental study on the stability characteristics of a single-nozzle swirl combustor under lean oxygen conditions to highlight the influence of inlet speed, temperature and oxygen content on the flame structure, exothermic pulsation and pressure pulsation. This study may help better understand the laws and mechanisms of operational parameters on combustion stability under lean-oxygen conditions.

1 Experimental setup

1.1 The model combustion chamber

The model combustor is shown in Figure 1. It is mainly composed of an air intake system, a rectification section, a combustion section, an exhaust section and a measuring system, etc. Among them, the air intake system includes an air pipe and a nitrogen pipe, which can be separately adjusted by an electric regulating valve and a mass flowmeter, so as to control the test intake flow and oxygen content. Additionally, the inlet gas temperature can be controlled by adjusting the power of the electric heater. The combustion section is mainly composed of a square combustor, a swirler, a venturi tube and a centrifugal nozzle. The single-nozzle swirl combustor is shown in Figure 2 (a). Its length is 380mm and the cross-section size is 152mm×152mm, tapered outlet structure is connected at the tail end. The swirl combustor is designed with a quartz glass window with a size of 140mm×90mm, with high-frequency pressure sensor arranged along the wall. Through the measurements of photomultiplier tube and high frequency pressure sensor, the flame exothermic rate pulsation and pressure pulsation in the combustor under different operation conditions can be obtained, respectively, with which the combustion dynamic stability can be assessed.

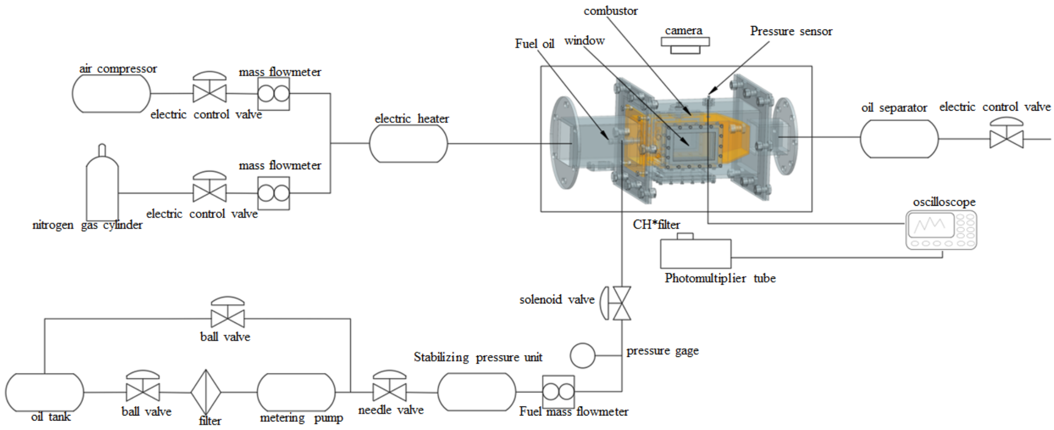


Fig. 1 Schematic diagram of the model combustor test rig

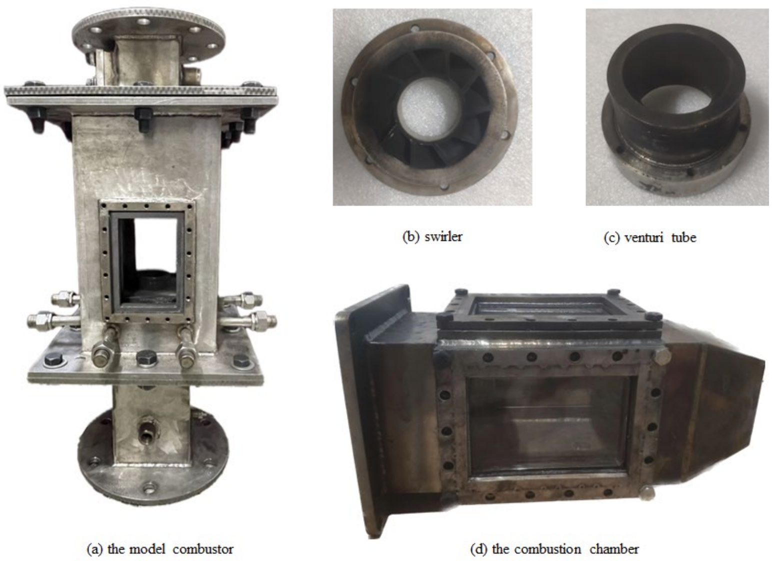


Fig. 2 Schematic diagram of the model combustor

The swirler and venturi tube are presented in Figure 2 (b) and Figure 2 (c) . The combustion chamber adopts single-stages swirler with 8 blades. The blade stagger angle is 41.5°, the swirl number is 0.6, the inner diameter of the swirler is 27.2 mm and the outer diameter is 88.3 mm. The inlet diameter and outlet diameter of venturi tube are 88.3mm, the angle of contraction section is 45°, the diameter of throat is 30mm, the angle of expansion section is 45°, the length of expansion section is 14mm. The solid nozzle is located in the center of the swirler, the diameter of the nozzle is 0.5mm and the spray cone angle is 60°.

1.2 Measurement system and data processing method

To obtain the exothermic rate pulsation of the flame, a photomultiplier tube (Hamamatsu CR131) is used to measure the light intensity signal of the whole flame after it passes through the CH* filter, as shown in Figure 3. A high-frequency pressure sensor (PCB-112A22) is used to measure the pressure pulsation in the model combustor. Considering that it is difficult to directly measure the exothermic rate of flame, and the main focus is on the change amplitude of the exothermic rate pulsation, we use the flame light intensity signal filtered by CH* as the flame exothermic rate pulsation. The measurement results are collected and recorded by an oscilloscope (WaveSurfer 3022) with a sampling frequency of 10,000Hz. The flame is photographed with a SLR camera (Nikon D500).

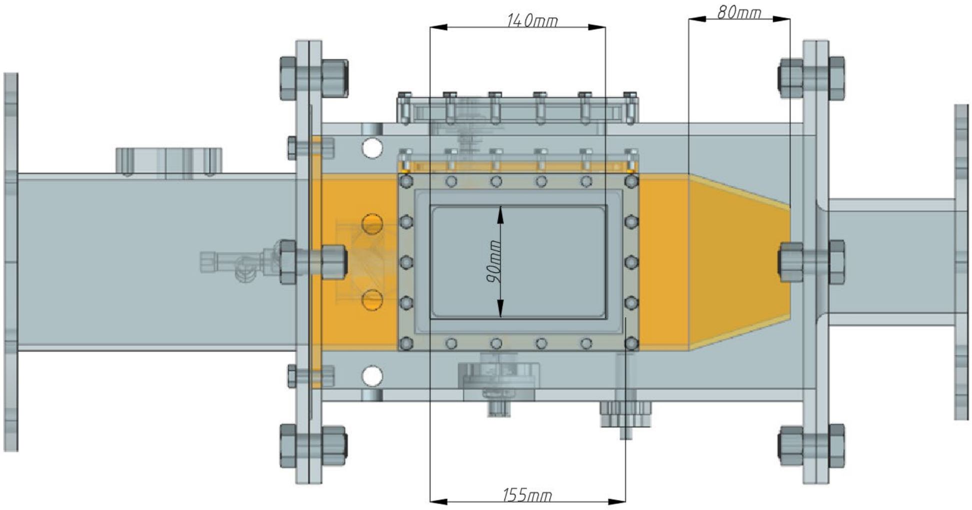


Fig. 3 Schematic diagram of measurement location

The influences of lean oxygen on combustor pressure pulsation are assessed by the PCB high-frequency pressure sensor. The influence of lean oxygen on combustor exothermic pulsation is detected by the photomultiplier tube. The influence of lean oxygen on combustion flame structure is monitored by the camera. Among them, the pressure signal and the exothermic signal are time-related data. It is necessary to use the Fourier transform to convert the time-domain data into frequency-domain data so as to obtain the main frequency and amplitude of pulsations. The mathematical formula is shown in Eq. (1). FFT (Fast Fourier Transformation) is a fast algorithm of DFT (Discrete Fourier Transform), is obtained by improving the algorithm of DFT according to the odd, even, imaginary, real and other characteristics of DFT.

$$f(x) = a_0 + \sum_{1}^{\infty}\left(a_n \cos\frac{n\pi x}{L} + b_n \sin\frac{n\pi x}{L}\right) \tag{1}$$

2 Results and discussion

2.1 Case summary

In this study, both the inlet gas and oxygen contents are adjusted by controlling the nitrogen mass flow and air mass flow, and the inlet flow temperature is adjusted by a 30kW electric heater. The model combustor works under the atmospheric pressure. The fuel is diesel, the fuel temperature is 298K. All the cases are summarized in Table 1.

Table 1 Experimental operational conditions

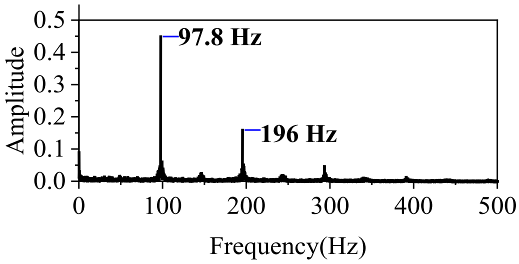
Case No.	Inlet Temperature （K）	Inlet Gas Velocity （m/s）	Oxygen Content （%）	Oil-Gas Ratio
A1	298	9.4	23.3	0.06
A2	298	9.4	21.0	0.06
A3	298	9.4	18.6	0.06
A4	298	9.4	16.3	0.06
B1	298	9.4	18.6	0.06
B2	350	9.4	18.6	0.06
B3	375	9.4	18.6	0.06
B4	385	9.4	18.6	0.06
C1	325	7.4	18.6	0.06
C2	325	9.0	18.6	0.06
C3	325	9.9	18.6	0.06
C4	325	12.3	18.6	0.06

2.2 Effect of oxygen content

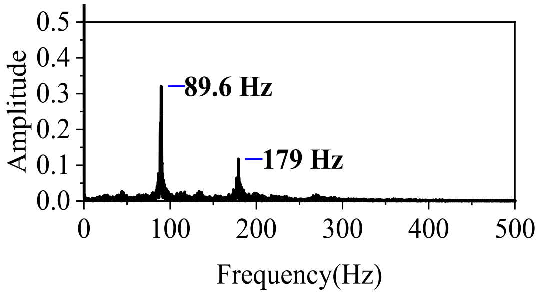
The oxygen content has an important impact on the combustion stability of the gas turbine combustor. In this section, the influence of the oxygen content on the spectral characteristics of the exothermic pulsation and pressure pulsation is studied at the inlet air temperature 298K and speed 9.4m/s, and the oxygen mass fraction changing from 16.3% to 23.3%.

Figures 4~6 depict the impact of oxygen content on the frequency and amplitude of pressure pulsation and exothermic pulsation. It is seen that the amplitude and frequency of flame pulsation varies regularly with the oxygen content. When the oxygen content decreases from 23.3% to 16.3%, the dominant frequencies of pressure pulsation and exothermic pulsation reduce by the same amount, which implies a coupling relationship between these two quantities. The pulsation is mainly distributed in the frequency band within 200Hz. As the oxygen content further decreases, the dominant frequency and amplitude of the exothermic pulsation decrease, meanwhile the harmonic frequency amplitude also decreases and finally disappears. It is worth noting that the decrease of exothermic pulsation amplitude is mainly caused by the decrease of chemical reaction rate and the gradual weakening of exothermic intensity in the model combustor.

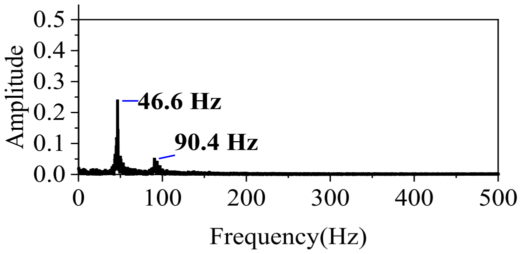
Interestingly, with the decrease of oxygen content, the dominant frequency of pressure pulsation decreases monotonically, but the amplitude does not follow the same trend. The amplitude peaks at 18.6% of oxygen content. As the oxygen content reduces from 21.0% to 18.6%, the flame stability becomes poorer due to the coupling between the pressure pulsation and the exothermic pulsation. Since the exothermic pulsation has a certain incentive effect on the pressure pulsation, it causes the increase of the pressure pulsation in the combustor. With further reduction of the oxygen content, the exothermic intensity of the flame decreases, the incentive effect of exothermic pulsation on pressure pulsation falls, and thus the pressure pulsation amplitude decreases. Particularly, when the oxygen content reduces, the exothermic intensity in the model combustion chamber is gradually weakened due to the reduction of the chemical reaction rate. As a result, the peak temperature reduces, and the sound speed slows. This extends the time for the pressure wave to propagate from the inlet to the outlet, reducing the natural frequency of the system. Consequently, both the exothermic pulsation frequency and the pressure pulsation frequency decrease.



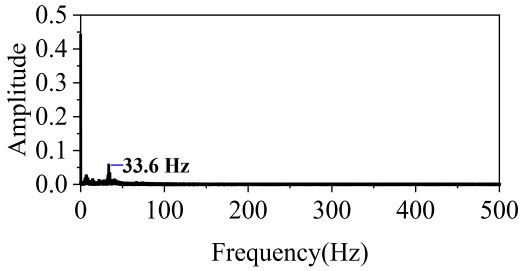
(a) 23.3%



(b) 21.0%

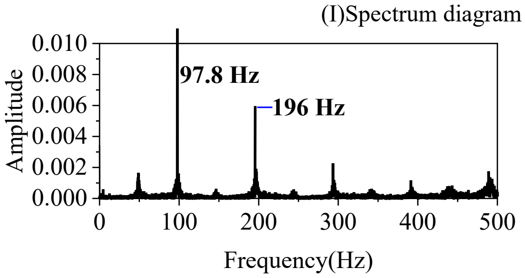


(c) 18.6%

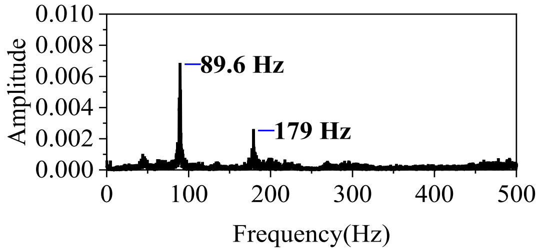


(d) 16.3%

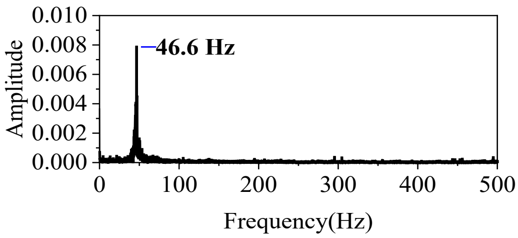
(I)Spectrum diagram of exothermic pulsation



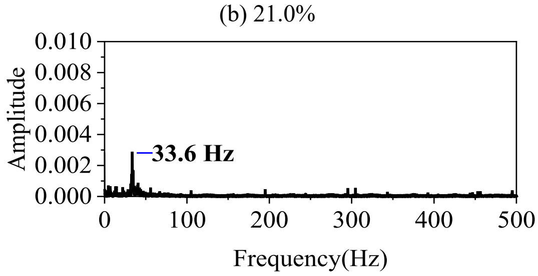
(a) 23.3%



(b) 21.0%



(c) 18.6%



(d) 16.3%

(II)Spectrum diagram of pressure pulsation

Fig. 4 Effect of oxygen content on exothermic pulsation and pressure pulsation of combustor

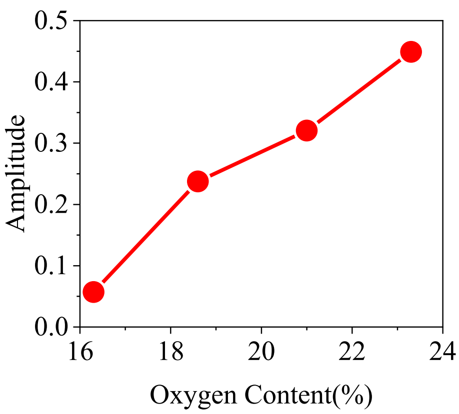


Fig. 5 Effect of oxygen content on the amplitude of exothermic pulsation

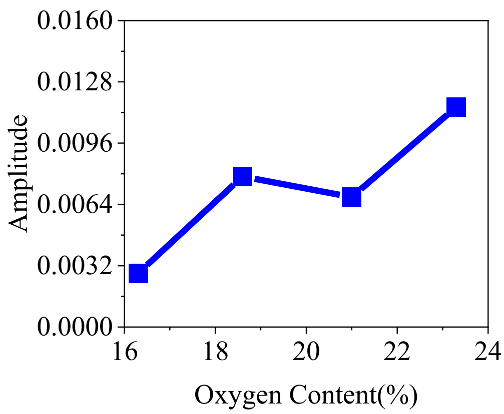


Fig. 6 Effect of oxygen content on the amplitude of pressure pulsation

To further explore the effect of oxygen content on combustion stability, time photos of flame were taken through the combustor visualization window under different operational conditions, as shown in Figure 7. It is observed that a decrease in oxygen content results in the reduction in flame brightness and distribution area. Additionally, the flame's position shifts towards the combustor's outlet and undergoes a color change from bright white to blue. This phenomenon may be due to the decrease of both the chemical reaction rate and the exothermic intensity, which leads to the reduction of flame temperature and brightness. Simultaneously, due to the constant oil-to-gas ratio, the equivalence ratio at the head of the combustor is excessively high at the oxygen-lean condition. This is unfavorable for the combustion reaction and prevents ignition at the flame root, ultimately resulting in the formation of a blue lifted flame. Furthermore, as unburned high-temperature oil and gas mix with fresh gas and undergo chemical reactions downstream of the combustor, the flame position shifts backward.

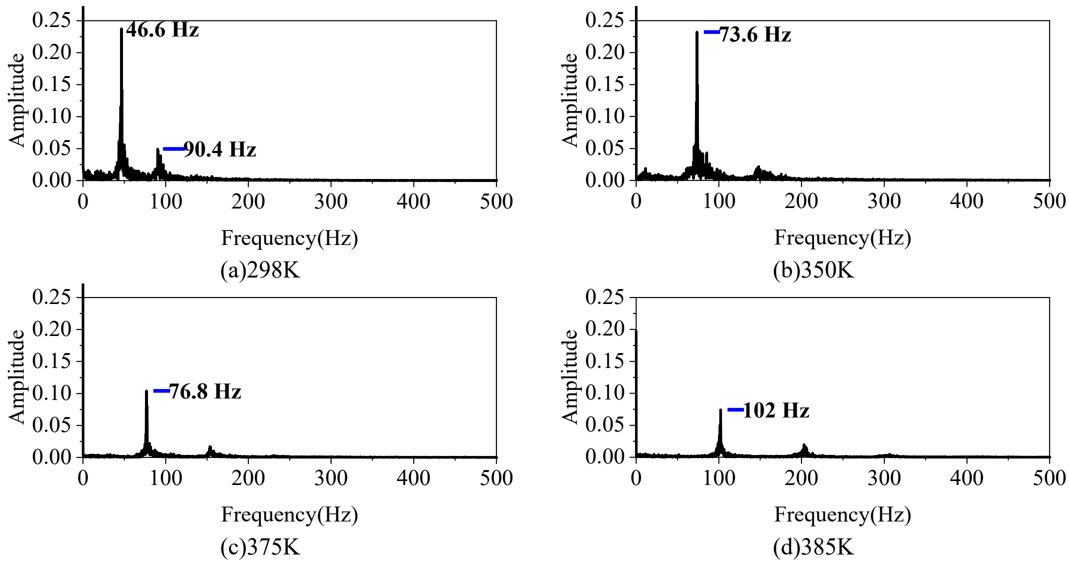
(a) 23.3% (b) 21.0%

(c) 18.6% (d) 16.3%

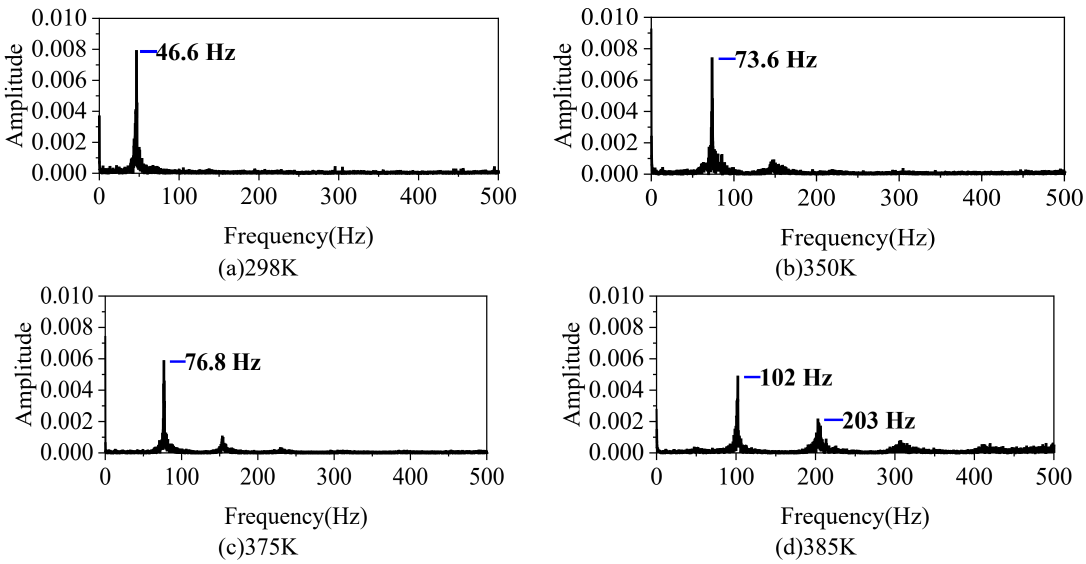
Fig. 7 Effect of oxygen content on flame morphology

2.3 Influence of inlet temperature

In this study, the incoming gas temperature varies from 298 K to 385 K, while the inlet flow rate of the combustor is fixed as 9.4 m/s, the oxygen mass fraction is fixed at 18.6% and the oil-gas ratio is fixed at 0.06. The spectra of combustor exothermic pulsation and pressure pulsation at different inlet temperatures under oxygen-lean condition are shown in Figures 8~10. It is seen that the dominant frequencies of both pressure pulsation and exothermic pulsation keep equal when the inlet temperature of the combustor varies between 298K and 385K, and the pulsation is predominantly distributed within a frequency band of 200Hz. The same trend is observed in the pulsation amplitudes. With the increase of inlet temperature, the main frequencies of exothermic pulsation and pressure pulsation gradually increase from 46.6Hz to 102Hz. Concurrently, the amplitude of exothermic pulsation decreases by 68.7%, and the amplitude of pressure pulsation decreases by 38.5%. This is because that with the increase of inlet temperature, the fuel particle size decreases, resulting in improved fuel atomization performance and enhanced stability of the combustion reaction exothermic in the combustor. In addition, the increase of combustor temperature elevates the natural frequency of the system, leading to an increase in the main frequencies of exothermic pulsation and pressure pulsation.



(I) Spectrum diagram of exothermic pulsation



(II) Spectrum diagram of pressure pulsation

Fig 8 Effect of incoming flow temperature on exothermic pulsation and pressure pulsation of combustor

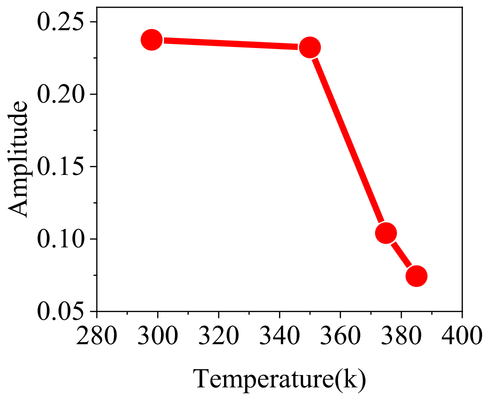


Fig. 9 Effect of temperature on the amplitude of exothermic pulsation

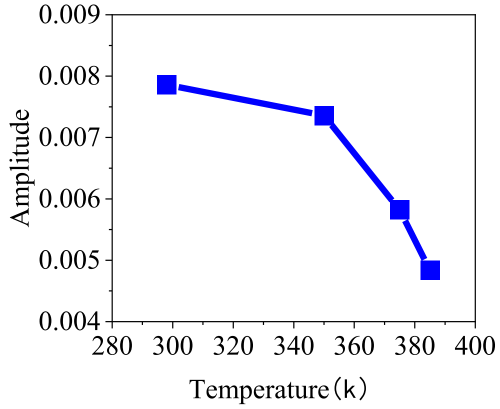
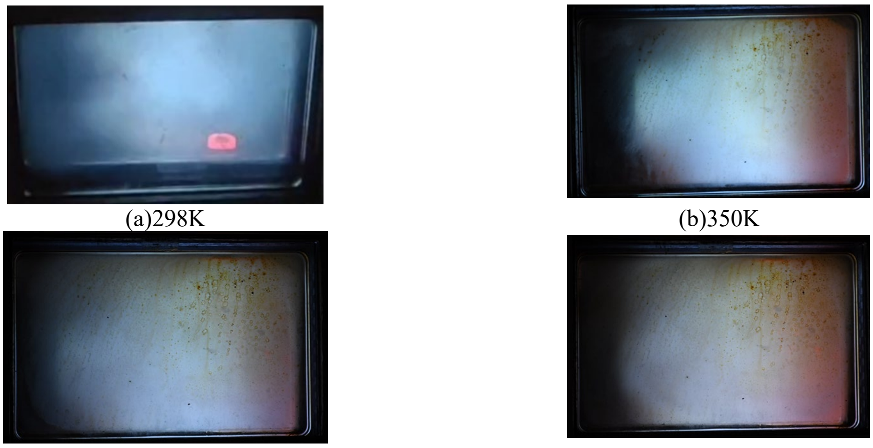


Fig. 10 Effect of temperature on the amplitude of pressure pulsation

The influence of inlet temperature on flame shape is shown in Figure 11. It can be seen that the flame structure varies considerably at different inlet temperatures, and both the flame brightness and distribution area increase with the increase of inlet temperature. As the inlet temperature rises from 298K to 385K, the blue flame in the combustor gradually turns into a bright red flame due to a more complete combustion reaction and increased flame temperature. It can also be found that when the inlet temperature is lower than 375K, the flame temperature is lower due to incomplete combustion, and the flame root is a light blue flame with narrow width, which can’t form a stable ignition point and may cause unstable pulsation of the flame. When the inlet temperature increases to 375K, significant changes are observed in the flame characteristics at the outlet of the swirler. The flame angle at the outlet of the swirler increases substantially, altering the flame shape and widening the flame root. Additionally, the brightness of the flame intensifies, indicating a more vigorous combustion reaction and enhanced flame stability. These are consistent with the phenomenon in which the amplitude of exothermic pulsation in the combustor changes significantly when the inlet temperature increases from 350K to 375K.



(a)298K (b)350K

(c)375K (d)385K

Fig. 11 Effect of inlet temperature on flame shape

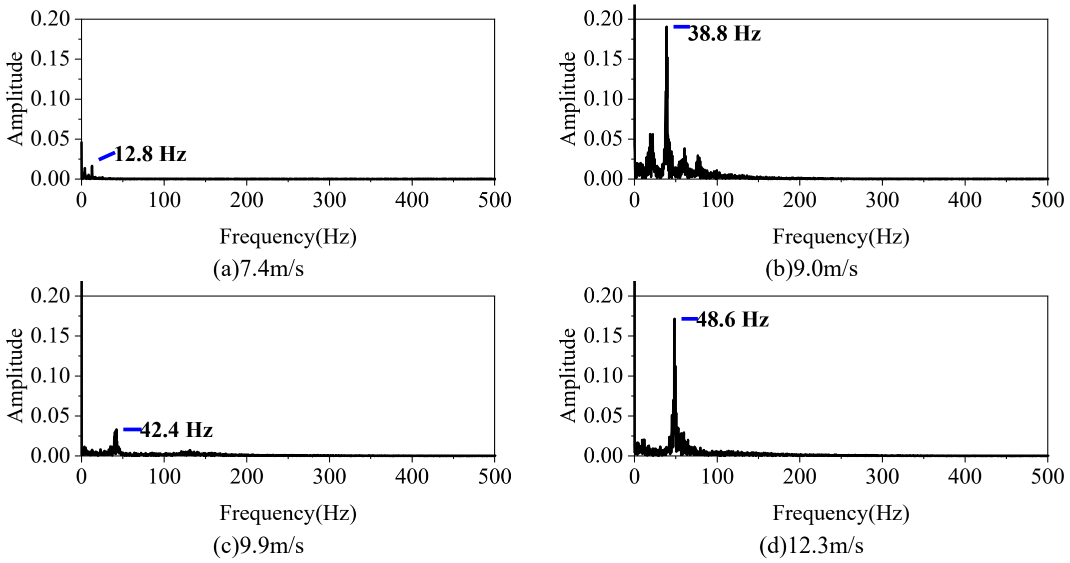
2.4 Effect of inlet flow rate

The inlet flow rate of the combustor affect many physical and chemical processes such as fuel atomization, fuel-air mixing, combustion reaction rate, etc[35]. In this section, the influence of incoming flow speed (7.4m/s~12.3m/s) on combustion stability of the gas turbine model combustor is studied at the inlet temperature of 325K, the oxygen content of 18.6% and the oil-gas ratio of 0.06.

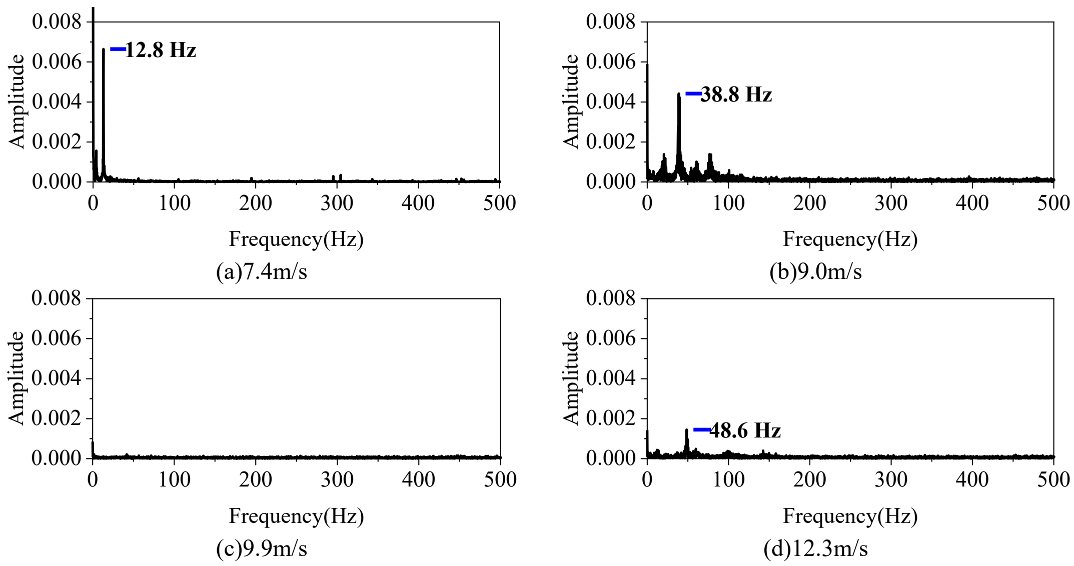
The effects of inlet flow rate on exothermic pulsation, pressure pulsation and flame shape are depicted in Figures 12~14, respectively. As the incoming flow velocity increases, it can be found that the dominant frequencies of combustor exothermic pulsation and pressure pulsation are identical, and the pulsation is predominantly distributed within a frequency band of 50Hz. However, the trends in pulsation amplitude do not exhibit complete consistency and significant changes are observed in the flame shape. When the inlet flow rate is 7.4 m/s, the dominant frequencies of exothermic pulsation and pressure pulsation in the combustor are 12.8 Hz. While the amplitude of pressure pulsation is considerable, the amplitude of flame exothermic pulsation is small, and the peak value of pulsation is not prominent. It can be observed from Figure 15a that the flame separates from the swirler, suspends near the exit of the combustor, and exhibits an irregular shape, blue color, and low brightness, which indicates that the flame temperature is low, the combustion is insufficient, and the flame stability is poor. It should be noted that a small inlet flow rate and low nozzle pressure result in a poor fuel atomization performance and an uneven oil-gas mixture. As a result, the combustion is inadequate and flame stability is extremely poor. Additionally, a large oil area in the venturi tube can easily induce low-frequency unstable combustion. However, due to the low combustion intensity and weak overall exothermic intensity of the flame, the change in exothermic pulsation amplitude is minimal.

With the inlet flow rate increased to 9m/s, the dominant frequencies of exothermic pulsation and pressure pulsation increase to 38.8Hz, and the amplitude of exothermic pulsation increases significantly, while the amplitude of pressure pulsation decreases. In addition, the flame brightness increases, the distribution area of flame expands and the main reaction zone moves upstream of the combustion chamber. This can be attributed to the fact that with the increase of inlet flow rate and turbulence intensity, the atomization performance of fuel in the combustor is enhanced, and the mixture of oil and gas is more uniform, which makes the combustion more sufficient, resulting in a significant improvement in flame stability and a reduction in pressure pulsation amplitude. Meanwhile, due to the significant impact of combustion intensity on the amplitude of exothermic pulsation, the sharp increase in flame temperature increases the amplitude of exothermic pulsation.

When the inlet flow rate rises from 9m/s to 9.9m/s, the dominant frequencies of both exothermic and pressure pulsation rise to 42.4 Hz. Meanwhile, their pulsation amplitudes respectively decrease by 82.6% and 101.2%, resulting in small pulsation amplitudes and indistinct pulsation peaks. At the exit of the venturi tube, a V-shaped flame with a brighter flame root can be clearly observed, indicating a further improvement in combustion stability. As the inlet flow rate further increases, it causes a corresponding increase in the dominant frequencies and amplitude of both exothermic and pressure pulsations. Meanwhile, the flame brightness slightly decreases, the flame distribution area expands, and the reaction zone shifts downstream. This can be attributed to the following two reasons: 1) An increase in airflow velocity results in an enhanced shearing effect of the airflow on the droplets. This improves the fuel atomization performance and increases the uniformity of fuel-air mixing, which is conducive to improving combustion stability; 2) Although a high velocity can shorten the fuel-air mixing time, it may also cause an uneven distribution of the equivalence ratio in the combustion chamber, leading to a subsequent decrease in flame stability. With the inlet flow rate increasing from 9.9m/s to 12.3m/s, the penetration depth of fuel decreases and the mixture of fuel and gas is more uneven, which deteriorates the combustion stability and significantly increases the amplitude of flame exothermic pulsation and pressure pulsation. Furthermore, as illustrated in Figure 15, the flame changes from light blue to bright white as the flow rate increases, indicating that an increase in the inlet flow rate induces an elevation in the temperature of the combustor. Consequently, the natural frequency of the system increases, resulting in an amplification of the dominant frequencies of both exothermic and pressure pulsations.



(I) Spectrum diagram of exothermic pulsation



(II) Spectrum diagram of pressure pulsation

Fig. 12 Effect of inlet flow rate on exothermic pulsation and pressure pulsation of combustor

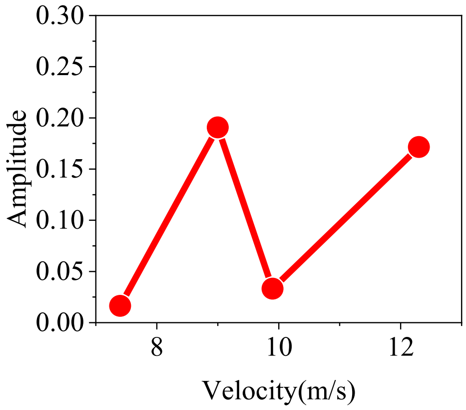


Fig. 13 Effect of oxygen content on the amplitude of exothermic pulsation

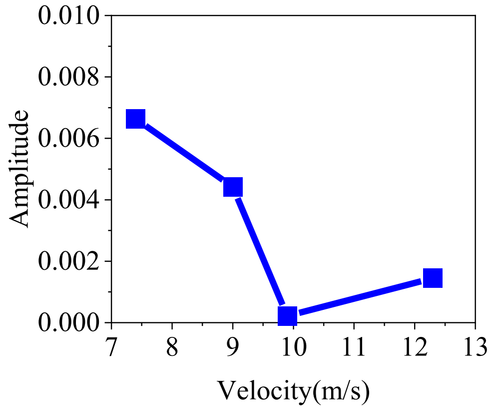
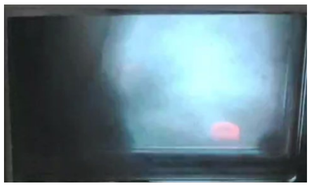
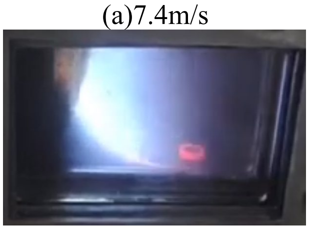


Fig. 14 Effect of oxygen content on the amplitude of pressure pulsation


(a)7.4m/s


(b)9.0m/s


(c)9.9m/s


(d)12.3m/s

Fig. 15 Effect of inlet flow rate on flame shape

3 Conclusion

To shed some new lights on the effects of oxygen depletion on combustion instability, in this study an experimental investigation was carried out in a single-nozzle swirl combustor to elucidate the influences of oxygen content, velocity and temperature on the flame structure, pressure pulsation and exothermic pulsation under the oxygen-lean condition. The major conclusions are as follows:

1) The combustion stability of the single-nozzle swirl combustor is significantly influenced by the oxygen content. Especially, reducing the oxygen content from 23.3% to 21% decreases the amplitude of pressure pulsations and improves

combustion stability. This is because as the oxygen content decreases, both the flame brightness and the exothermic pulsation decrease, leading to a decrease in the driving energy of unstable combustion. However, as the oxygen content further decreases from 21% to 18.6%, the flame root stability deteriorates, and the amplitude of pressure pulsation increases due to the reduced combustion reaction rate. When the oxygen content drops below 18.6%, a further reduction in the combustion reaction rate leads to a decrease in the pressure pulsation amplitude. This causes the lift-off height of the swirl flame to increase and the flame to suspend downstream of the combustion chamber with very low brightness. As a result, there is a significant decrease in both exothermic pulsation and pressure pulsation.

2) Under oxygen-lean conditions, increasing inlet temperature leads to increased flame brightness and reaction zone area. The flame exotherm becomes more uniform and amplitudes of exothermic pulsation and pressure pulsation are reduced, thereby combustion stability is enhanced.

3) Under oxygen-lean conditions, when the incoming flow rate increases from 7.4m/s to 9.9m/s, the flame brightness increases and the flame root stability improves significantly due to the enhanced fuel atomization and oil-gas mixing effect, thus causing the pressure pulsation amplitude to decrease. However, as the incoming flow velocity is greater than 9.9m/s, the flame root stability becomes worse and the pressure pulsation amplitude increases.

4) The present study demonstrates that the reduction in flame brightness results in decreases in the primaries frequency of pressure pulsation and exothermic reaction

pulsation. This could be attributed to that reducing flame brightness leads to a decline in combustion chamber temperature, which in turn reduces the mean flow speed of the combustion chamber, resulting in a lower frequency of airflow oscillations. Consequently, the intrinsic frequency of the system decreases, leading to a reduction in the frequency of heat release pulsation and pressure pulsation.

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