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Experimental Studies on Suppression of Combustion Instability with the Addition of Helium

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ABSTRACT

When combustion instability occurs, fluctuation in the release of heat couples with oscillating pressure, while the sensitivity of flame to acoustic disturbance restricts the oscillation intensity. This paper investigates the efficacy of helium in suppressing combustion instability. The flame structure, its sensitivity to acoustic disturbance and the inhibition of oscillating pressure with the addition of helium were studied by means of open tests, external-excited and self-excited combustion instability experiments. First of all, the addition of helium made larger flame surface area, which shaped the distributed flame, and the heat was such released over a broader space. Then, the external-exited combustion instability experiments confirmed that adding helium to fuel could decrease the sensitivity of flame to acoustic disturbance. Finally, Helium was used in the case of self-excited combustion instability to further investigate its effectiveness on the oscillation suppression. Proper Orthogonal Decomposition (POD) and Dynamic Mode Decomposition (DMD) methods were used to study flame fluctuation intensity. The results showed that the amplitudes of oscillating pressure were greatly reduced by the added helium. For 250Hz mode, adding helium with 20% of fuel flow could significantly reduce the flame pulsation and reduce the pulsation pressure by more than half. However, for the 160hz mode, more helium should be added to achieve better results. When the helium flow exceeded 80% of fuel flow, the combustion instability could be converted to stable combustion.

Keywords: Combustion instability suppression; Fuel dilution; Flame fluctuation; POD; DMD.

NOMENCLATURE

DMD	Dynamic Mode Decomposition	FFT	Fast Fourier Transform
FAR	Fuel-Air-Ratio (mass flow)	POD	Proper Orthogonal Decomposition

1. INTRODUCTION

Combustion instability is a common phenomenon that often occurs in combustion systems, including gas turbines, rocket engines and combustion furnaces. Under specific conditions, small disturbances generated by various mechanisms are magnified via complex feedback mechanisms and further lead to the coupling procedure of heat release fluctuation and acoustic wave. The flame can release an oscillating pressure wave with large amplitudes in a combustion instability environment. Usually, the amplitudes of dynamic pressure are used to characterize the stability of combustion. In the case of combustion instability, pressure fluctuation has negative impacts on the combustion system (Huang and Yang 2009). Combustion instability is a complex physicochemical process in which fluid, acoustics and combustion are coupled, and it is usually studied by experiment (Harvazinski *et al.* 2015) and numerical simulation (Zhao *et al.* 2019; Sun *et al.* 2022). As for the mechanisms of combustion instability, the excitations have not yet been fully understood (Murayama and Gotoda 2019). Researchers often attribute the combustion's lack of stability to the coupling of heat release and acoustic waves. In this situation, the oscillation reaches the cycle state limit when the driving energy is equivalent to the dissipation. In the development of civil aviation and ground gas turbines, more and more attention is paid to pollutant emission. For example, the developed lean fuel combustion shows good low emission characteristics. In the pursuit of low-pollution emissions, persistent combustion instability has been encountered in many cases. This is because the lean fuel combustion will lead to the combustion at the limitation of lean flameout, which makes the flame pulsation more sensitive to disturbances such as sound waves.

Changing fuel properties has important impacts on suppression of combustion instability. For instance, adding aluminum agent to the fuel of rocket engine can effectively reduce the amplitudes of combustion instability. In addition, some scholars also improve the combustion instability by adjusting the fuel supply strategy and changing the temperature pattern in the combustor. Compared to gas turbines, rocket engines encountered combustion instability earlier, the mechanisms of which and suppression methods in solid and liquid rocket engines have been studied by many scholars (Ji *et al.* 2020; Xue *et al.* 2020; Nguyen and Sirignano 2019; Ji and Wang 2019; Wang *et al.* 2020; Sehgal and Strand 1964). With the investigation of rocket combustion chambers, it has been discovered that aluminum preparation affects the distribution of flame surface in the combustion process and plays important roles in restraining combustion instability (Povinelli 1967; Price 1971). Therefore, related investigations of the effects of aluminum-containing composite propellants on acoustic damping characteristics have been carried out. For example, particle size of aluminum agent affects the harmonic frequency and condensed combustion products in the flow field (Jin *et al.* 2014). It was also found that the goal of eliminating combustion instability could be achieved by adjusting stabilizer content and particle diameters (Yi *et al.* 2016).

In engineering applications, Helmholtz resonator is an effective passive acoustic absorption structure commonly used to suppress combustion instability (Cora *et al.* 2014), however, its absorption bandwidth is narrow. Then, Ye *et al.* proposed an improved structure of Helmholtz resonator, which can effectively solve the defect of narrow bandwidth of traditional structure (Ye and Yang 2022). In addition, fuel classification and mechanical structure modification are commonly used for suppressing oscillation pressure. For instance, the change of temperature distribution in combustors (Lieuwen and Yang 2005) and added microspores air jets (Zhou *et al.* 2020) have successfully reduced the amplitudes of oscillating pressure. Similarly, changing the distribution of heat sources in space has an important impacts on pressure oscillation (Du *et al.* 2019). The modification of the Fuel-air-ratio (FAR) surrounding a flame can also absorb the oscillation by adding to secondary fuel supplication (Tachibana *et al.* 2006; Steinberg *et al.* 2010; Dhanuka *et al.* 2011). It also promotes the same effects by changing the flame shape in bluff body-stabilized combustion system. It has been confirmed that the geometry of a bluff body has important impacts on combustion instability (Gutmark *et al.* 1995). In addition, the flame front distribution can significantly affect the stability of premixed hydrogen/oxygen combustion (Pizza *et al.* 2009). In recent years, fuel composition has become a research field to investigate the effects on pollution emissions, flame kinetics and combustion instability (Karlis *et al.* 2019). At first, dilution fuel combustion was used to solve the problem of reducing pollutant emissions (Arghode and Gupta 2010; Khalil *et al.* 2012; Khalil *et al.* 2014), and it was found that fuel dilution flame can also reduce the unstable boundary and oscillation pressure amplitudes. For instance, the turbulent diffusion flame in a jet flow under specific methane additions that make the combustion reaction more stable (Diao *et al.* 2016). Khalil *et al.* studied the influence of carbon dioxide dilution on flame stability and noise emissions. The results indicate that combustion instability could be eliminated by adding a proper amount of carbon dioxide to fuel-air mixture. The results also showed that although the pulsation intensity of heat release did not significantly change, the amplitude of pressure pulsation was greatly reduced (Khalil and Gupta 2017). Moreover, the combustion instability boundary was narrowed when a proper amount of carbon dioxide was added to the fuel supplement (Li *et al.* 2018). Recently, experiments on the effects of annular N2/O2 and CO2/O2 jets on combustion instabilities in lean-premixed methane flames were conducted. Results indicated that the CO2, N2 and O2 concentration could effectively change the instability characteristics and reduce oscillation amplitudes (Zhou and Tao 2020; Liu *et al.* 2021a; Liu *et al.* 2021b). In addition, air humidity and fuel composition also presented excellent ability to inhibit combustion instability (Cadavid *et al.* 2021). In general, the thermoacoustic system in a turbulent combustor is viewed as a complex system, the theoretical prediction and suppression methods are extremely complex. In a complex turbulent combustor, Sujith *et al.* discuss the recent developments of system approach to mitigate thermoacoustic instability based on complex system theory (Sujith and Unni 2020).

As an inert gas, helium has relatively stable characteristics and is widely present in natural gas. Helium has stable physical and chemical properties that do not significantly affect chemical reactions (McDonald 1995). In fact, it is necessary to consider the cost of helium dilution to inhibit combustion instability. This paper primarily focuses on the resistance of flame to acoustic disturbance and combustion instability. Cheap inert gas may be selected as an alternative dilution gas in the future. In this paper, to study the influence of inert gas on combustion instability, helium is added to the fuel supplement. Open tests, self-excited and extra-excited combustion instability experiments are also conducted to investigate the above-mentioned characteristics. The FFT, POD and DMD methods are respectively used to discover the dominant frequency and corresponding amplitudes of oscillating pressures and pulsating flame. These methods are indispensable to investigating the effects of helium addition on the suppression of combustion instability.

2. EXPERIMENTAL SETUP AND SAMPLING SYSTEM

The experimental setup is shown in Fig. 1, and the used equipment including the technical characteristics is shown in Table 1. The combustion instability system with swirlers stabilizing the flame includes an air supplement, air flow measurement, fuel supplement, fuel flow measurement, combustor, dynamic pressure measurement and other pipes. In the central axis direction, the antidromic pressure gradient caused by the swirling centrifugal force is helpful for producing the central recirculation zone, in which the successive flame resides. In this circumstance, the swirl-stabilized flame does not extinguish under a wide range of inlet conditions. The flame is fed with butane and atmospheric air. The inlet temperature is 290 K.

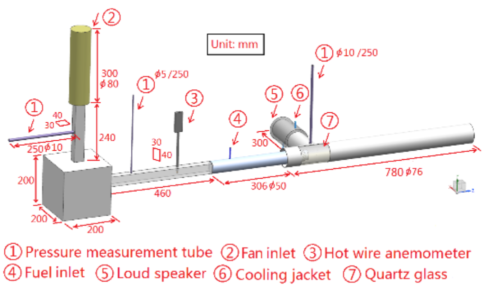
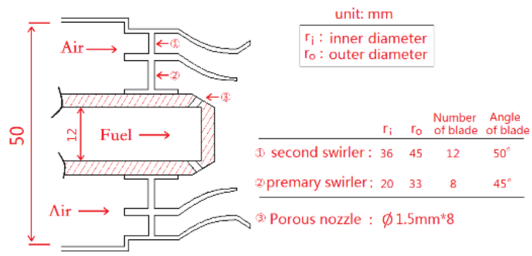


Fig. 1. Combustion instability experiments system.

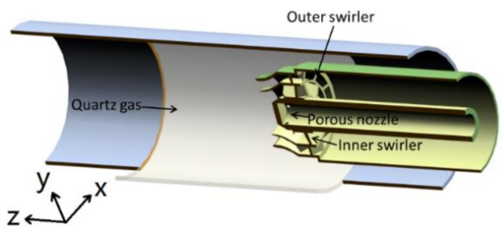
Table 1. Technical characteristics of used equipment

Used equipment	Technical characteristics	Supplementary notes
Hot wire anemometer	Monitor the air flow	Calibrated with thermal mass flowmeter with accuracy of 0.5
Rotameter	Monitor the gas flow	Calibrated using drainage method
Loud speaker	Produce disturbing acoustic waves	Frequency range: 80~2000 Hz
Fan	Produce air flow	Flow range: 0~10 g/s
High speed camera	IDT Co. Y5 type	2072×2072 pixel
lens	50 mm focal length	Nikon Co., fixed focus lens
Pressure sensor	Aire Sensor Tech. Co. AE-H type	Range: -3~3 kPa; Frequency response range: 0~20 kHz

Figure 2(1) shows that the counter-swirling air jets form a shear layer in which the shear stress can promote the entrainment of air with fuel. Fig. 2(2) shows a three-dimensional half-section. There is a large swirling flow velocity in the venturi, and the flame velocity is difficult to balance with the air velocity. In the process of flowing out of the venturi, the fuel is gradually mixed with air, and then burned at the head of the combustor. At this time, the flame in the combustor is mainly blue, accompanied by a small amount of orange flame. The combination of porous fuel nozzle and swirling air jets makes the flame partly premixed, and the swirling flame is sensitive to the disturbance. Since the experimental components are made of stainless steel, the photographing region is mainly concentrated behind the sleeve. Due to the high velocity of swirling jets, the flame mainly exists behind the venturi. There is indeed a small part of flame in the sleeve that cannot be captured by the camera. The blind zone is relatively small compared to the whole flame area. In addition, this paper mainly focuses on the pulsation amplitude of flame under different working conditions, so the small blind zone has little effect on the results. The combustion chamber adopts porous nozzle, as is shown in Fig. 2. When helium is added to the fuel, the fuel and helium are mixed in the external mixing chamber in advance, and then the mixed fuel is supplied to the inlet of the fuel nozzle. The swirl numbers of primary and secondary swirler are 1 and 0.8, respectively. Detailed geometric parameters are shown in Fig. 2.



(1)



(2)

Fig. 2. Setup of swirlers and fuel nozzle.

Under these specific conditions, flame can produce positive feedback to the various disturbance, with the amplitudes of acoustic wave and heat release fluctuation then increasing and approaching saturation. First, inlet air flow is measured using a hot-wire anemometer, which is previously calibrated by a thermal flowmeter with an accuracy rate of 0.5%. Uncertainty of hot-wire anemometer is 1%. Therefore, the comprehensive accuracy of inlet air flow is about 1.51%. The fuel flow is measured using a rotameter, which is previously calibrated by a counting cup using drainage method. Reading error of counting cup and rotameter is 2%, comprehensive accuracy of fuel supply is 4.04%.

At the outlet of fan, there are dominant frequencies in the spectrum analysis of dynamic pressure and square tank is used to eliminate the above-mentioned fan pulsation. The side pipe with a length of 300 mm is attached to the combustor for the convenience of loud speaker installation. In the external-excited combustion instability experiments, the loud speaker produces an acoustic wave with different amplitudes and frequencies. To avoid damage caused by the high temperature, pressure sensors are installed at the end of pressure measurement tubes, whose length and inner diameter are 250 mm and 10 mm, respectively.

An Y5 series high-speed camera from the IDT Company was utilized to sample flame images. A lens with a 50 mm focal length was employed, which has a large amount of light input and can increase the flame brightness with a short exposure time. The exposure time is 400 μs and sampling time is 1 s. AE-H-type high-frequency dynamic pressure sensors made by Aire Sensor Technology Co., Ltd were used to sample the oscillating pressure. The measuring range was -3~3 kPa, the comprehensive accuracy 0.5% (full scale) and the measuring frequency response range was 0-20 kHz. The flame images and oscillating pressure were acquired with a sampling frequency of 2000 Hz.

3. EXPERIMENTAL METHODS AND DATA PROCESSING

3.1 Experimental Methods

Three experimental methods including open test, external-excited and self-excited combustion instability procedures were used to study the effects of helium dilution on combustion instability. In open test, there is no serious acoustic reflection at combustor outlet, and the distribution of the flame shape is studied. In external-exited combustion instability test, it is necessary to ensure that the working condition parameters are within the stable combustion boundary. In the external-excited experiment, to study the effects of mixing helium in the fuel on sound waves of different frequencies, the externally excited sound wave is introduced to interfere with the flame. In self-excited test, the self-excited combustion instability needs to be generated without the interference of external excitation, so the working condition parameters should fall within the oscillation boundary. Therefore, the above experimental conditions are different owing to the existence of combustion instability boundary. In the self-excited combustion instability, the oscillation frequency of combustion instability is fixed, which is affected by the acoustic characteristics of the system. Therefore, the suppression results of self-excited combustion instability by mixing helium in fuel are mainly studied.

3.1.1 Open test

To study the influence of fuel dilution on flame appearance, an open test was designed wherein the burned gas is directly discharged into the atmospheric environment after passing through the sleeve of swirlers. There is no acoustic reflection and there will be no significant acoustic response for the flame because most of the disturbing energy is dissipated into the atmosphere. Therefore, the open test can be used to investigate the influence of helium dilution on the flame structure. The open tests are conducted under two working conditions with different FAR, with the parameters shown in Table 2.

Table 2. Open test working parameters.

case	Reynolds number	Air flow(g/s)	FAR	ϕ
1	5000	2.66	0.015	0.234
2	5000	2.66	0.030	0.469

3.1.2 External-excited combustion instability

The acoustic response should be introduced to study the helium dilution affecting combustion instability. In the external-excited combustion instability experiments, a loud speaker was used to produce acoustic wave to disturb the flame. The acoustic wave produces heat release fluctuation, which will further lead to oscillating pressure. However, the combustion will return to stability as soon as the disturbance source is removed. The above-mentioned phenomena are attributed to the difficulty in the equilibrium of the driving and dissipation energy. The amplitude of the external-excited acoustic wave at the flame position is stable at 200 Pa. The acoustic-excited experiments should run outside the boundary. The inlet Reynolds number is 3500, air flow is 1.86g/s and FAR is 0.025, ϕ is 0.391. The span of acoustic disturbance frequency is 100~700 Hz.

3.1.3 Self-excited combustion instability

Unlike external-excited experiments where an external acoustic source is used to sustain combustion instability, the self-excited instability system is self-sufficient, with the flame playing the role of an acoustic source. The flame is interfered with by the initial disturbance and further produces fluctuation in heat release, and so the combustion instability is self-excited and does not require external energy input. After amplification and saturation, the amplitudes of oscillating pressure become stable. The self-excited combustion instability experiments are essential for inspecting the effectiveness of helium suppression on oscillation. The influence of added helium on oscillating flame and pressure under three typical working conditions is investigated. The operating parameters of the self-excited combustion instability experiments are shown in Table 3.

Table 3. Operating parameters of self-excited combustion instability

Case	Reynolds number	Air flow (g/s)	FAR	ϕ
A	4700	2.50	0.0158	0.247
B	5500	2.96	0.0172	0.269
C	6500	3.47	0.0206	0.322

3.2 Data Processing

To characterize the oscillation characteristics as amplitudes of oscillating pressure and pulsating intensity of flame, several dynamic processing methods are employed in this paper, including FFT, POD and DMD. The latter two methods are described in detail below.

3.2.1. POD

POD is an effective dynamic analysis method that obtains the main pulsating axis by singular decomposition and captures the primary fluctuation characteristics of numerous samples. POD decomposes the samples into several modes, including spatial pulsation distribution, temporal distribution and singular values. The flame shows periodic pulsation process under combustion instability environment. POD decomposes the pulsation process into spatial structure and time pulsation. The spatial structure represents the flame pulsation region, while the time mode represents the time evolution process of the corresponding spatial structure, which is a one-dimensional signal. At the same time, the spectrum analysis of time mode can be carried out to obtain the dominant frequency of flame pulsation. Generally, the primary mode with the maximum singular value can be selected for analysis. The spatial and temporal modes are unitary, while the singular value represents the pulsating energy of the flame image vectors. Therefore, the singular values represent the pulsating energy and has no clear physical unit. In addition, a detailed solution process of the POD can be found in (Liu *et al.* 2019), and will not be discussed here.

3.2.2 DMD

DMD is a mode decomposition method for multidimensional vector samples, and was first proposed by Schmid (Schmid 2010). Some scholars have also applied it to the processing of unstable data of self-excited oscillating combustion (Huang *et al.* 2013; Quinlan and Zinn 2017). Firstly, sample matrix of flame images V_1^n is described as $\{\vec{v}_1, \vec{v}_2, \vec{v}_3, \cdots, \vec{v}_n\}$. In a linear system, the development of sampled vectors follows linear mapping theory. Mapping matrix A represents the evolution of the system, while the sampled vectors satisfy the following relationships: $A\vec{v}_i = \vec{v}_{i+1}$. According to linear algebra theory, with the increasing of n, the sampled vectors will be linearly correlated when n exceeds a certain threshold. Then, $\vec{v}_n$ can be expressed as a linear combination: $\vec{v}_n = a_1\vec{v}_1 + a_2\vec{v}_2 + \cdots + a_n\vec{v}_n + \vec{r}$ or $\vec{v}_n = V_1^{n-1}\vec{a} + \vec{r}$, where $\vec{r}$ is the error vector. Therefore, formula (1) is established as follows:

$$AV_1^{n-1} = V_2^n = V_1^{n-1}S + \vec{r}\vec{e}_{n-1}^T \quad (1)$$

where $\vec{e}_{n-1}$ is unitized with the dimension of n. The above equation shows that the evolution of the system can be discussed by analyzing the eigenvalues and eigenvectors of matrix S. Schmid has proposed a more robust full matrix $\tilde{S}$, which is similar to S. Firstly, $V_1^{n-1} = U\Sigma W^H$ is derived from the singular value decomposition of matrix V_1^{n-1}, while $\tilde{S}$ is then defined as $\tilde{S} \equiv U^H AU$. λ_i is defined as the singular value and $\vec{y}_i$ the eigenvector of matrix $\tilde{S}$, respectively. Then, $\tilde{S}\vec{y}_i = \lambda_i\vec{y}_i$, substitute $\tilde{S}$ as $U^H AU$, derive $U^H AU\vec{y}_i = \lambda_i\vec{y}_i$, yielding formula (2):

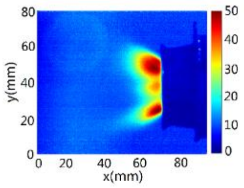
$$A(U\vec{y}_i) = \lambda_i(U\vec{y}_i) \quad (2)$$

where λ_i and $U\vec{y}_i$ are the singular value and eigenvector of matrix A, respectively. Define $\vec{\varphi}_i = U\vec{y}_i$ as the mode of the dynamic system. The eigenvalue value can be described as $\lambda_i = a + bi = \sqrt{a^2 + b^2}e^{i\theta}$, $\theta = \arctan(b/a)$, define $\gamma_i = \log(\lambda_i)/\Delta t = \log(\sqrt{a^2 + b^2} + i\theta)$, and then its real part reflects the stability of the corresponding mode: the positive number means unstable, negative numbers mean attenuation and zero represents a steady periodic fluctuation. Moreover, the imaginary part represents the fluctuation frequency. To sum up, the right side of the equation can be divided into three parts: the spatial mode $[\vec{\varphi}_1, \vec{\varphi}_2, \cdots, \vec{\varphi}_r]$, time evolution $\mathrm{diag}(\lambda_1^k, \lambda_2^k, \cdots, \lambda_r^k)$ and amplitudes (remaining parts). Both POD and DMD involve energy effect, which represents the importance of decomposed modes. The energy is usually represented by the eigenvalue of matrix decomposition. Similarly, DMD also needs to decompose flame matrix. In general, the energy effect can be understood as the pulsation amplitude of flame image vectors.

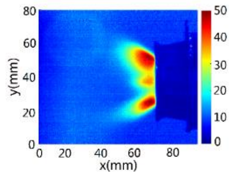
4. RESULTS ANALYSIS

4.1 The Influence of Helium on Flame Structure (Open Test)

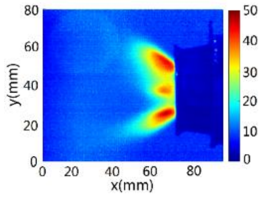
Figure 3 and Figure 4 show the time-average flame brightness (luminous intensity of flame) in case 1 and case 2. In the experiment, flame shape is photographed by a high-speed camera, and gray value images are obtained. Therefore, the color bar in Fig. 3 and Fig. 4 represents the brightness of gray value images, and the average of multiple transient flame structures is obtained. The helium flow rate should be normalized with the fuel flow rate. Helium volume content is defined as Q_h/Q_b, Q_h is helium volume flow rate, and Q_b is butane volume flow rate. When no helium is added, the helium volume content is 0, while when the addition amount is the same as that of fuel, the volume content is 1. The results indicates that the flame structure presents typical asymmetry. This is caused by the installation of the blades of two-stage swirlers and the manufacturing and installation errors of components. In order to increase the discrimination, only a few results of helium ratio are given here. It has a shorter length for the flame at small FAR, fuel is burned in a small space within the sleeve and its outlet. The helium has almost no effect on the flame structure when its helium volume content is less than 50%. The flame will not change significantly until the helium approximates the same volume flow as fuel. As helium is added to the fuel, the overall brightness of the flame decreases, the length of the flame increases and the brightness distribution is more uniform. This means that after helium is mixed into the fuel, the jet entrainment ability is stronger, so that the combustion chemical reaction is distributed in a wider space. The larger flame front and the lower distributed temperature attenuates the concentration of flame pulsation, which is beneficial to combustion instability. More fuel supplementation makes it



Helium volume content: 0

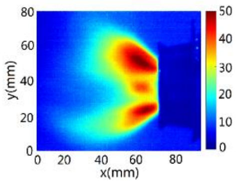


Helium volume content: 0.5

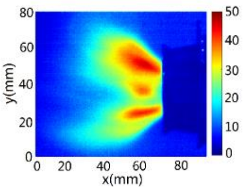


Helium volume content: 1

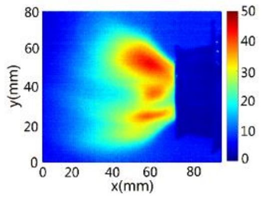
Fig. 3. Time-average flame brightness under different helium content (case 1).



Helium volume content: 0



Helium volume content: 0.5

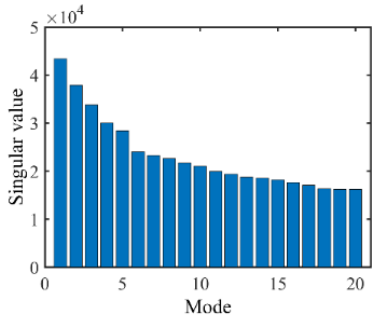


Helium volume content: 1

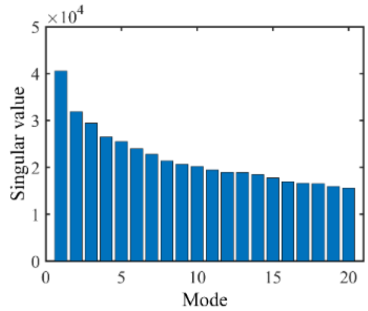
Fig. 4. Time-average flame brightness under different helium contents (case 2).

difficult to burn in a small space. At this point, because of the addition of helium, higher jet velocity and helium entrainment will inevitably lead to flame distribution in a wider space. The velocity of swirling jets is much greater than that of fuel velocity. Fuel jets and air swirling flow mix rapidly in venturi. Therefore, the effects of mixing helium on gas velocity is relatively small, it more affects the fuel concentration distribution in swirling jets. In addition, Helium has similar heat absorption capacity as air with consistent volume flow. It should be noted that the helium flow is very small compared with air flow, the effects of helium on the overall temperature is not very obvious.

To study the effects of added helium on the flame's dynamic structure, POD is used to determine the primary pulsation characteristics of oscillating flame. The distribution of singular values corresponding to the first 20 modes of POD in case 2 is shown in Fig. 5. Open flame does not show obvious periodic pulsation, it presents the characteristics of random pulsation. So, the first few modes do not contribute most of the pulsation energy. In the POD decomposition applied in this paper, firstly, multiple continuously sampled flame images are averaged to obtain the time-average flame structure, and then each flame image is subtracted from the above time-average flame. In this way, the flame samples only contain the pulsation characteristics of the flame. When the helium content reaches 100%, the singular values are generally less than the results without the addition of helium, indicating that adding helium to the fuel can reduce the amplitudes of flame pulsation. From the singular value distribution, the first mode has the largest pulsation energy.



(1) Helium volume content: 0

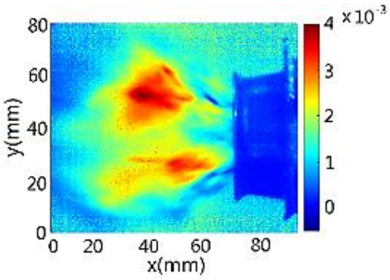


(2) Helium volume content: 1

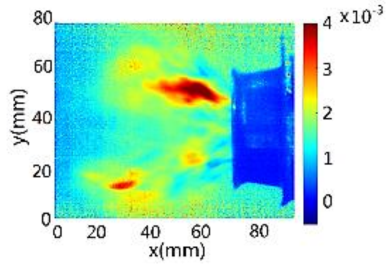
Fig. 5. Singular value distribution of POD.

The comparison results of the spatial distribution of the first mode are shown in Fig. 6. The results show that the flame pulsation is mainly concentrated in the recirculation zone of the combustor under different working conditions. However, in contrast, the addition of helium reduces the energy of flame pulsation (singular values generally decrease), which indicates that helium addition to the fuel makes the flame have less pulsation.

Figure 7 shows the comparison results of radial temperature distribution in the vertical direction and 34mm away from the sleeve outlet. Inlet parameters of the two cases are consistent, the equivalence ratio is 0.469 (FAR is 0.03). The measured temperature is relatively low due to thermal convection and thermal radiation. The result indicates that the center temperature is lower compared to the helium dilution case. This is because the combustion occurs in a wider space when fuel is diluted. Combustion efficiency due to helium dilution can be roughly estimated through the outlet temperature distribution. The average temperature is reduced from 1037.2K to 1027.9K due to the addition of helium. Therefore, it is considered that the overall combustion efficiency is reduced when fuel is diluted with helium, but the degree of the reduction is relatively small.



(1) Helium volume content: 0



(2) Helium volume content: 1

Fig. 6. Spatial distribution of the first mode.

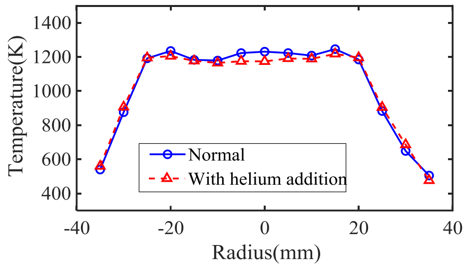
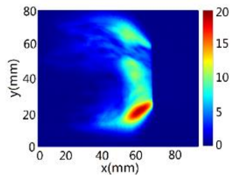


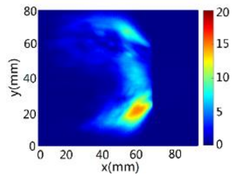
Fig. 7. Radial temperature distribution (Helium volume content: 1).

4.2 Changes in Flame Pulsation Response (External exited)

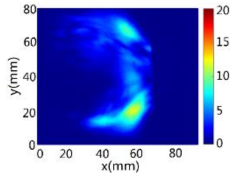
To study the effects of helium addition on the flame sensitivity to acoustic disturbance, in the external-excited combustion instability experiments, the disturbance wave was applied in the bypass pipe. Then, the flame showed periodic pulsating characteristics and was sampled by a high-speed camera. The DMD method was employed to process flame brightness (luminous intensity of flame) to obtain the periodic pulsation-dominant frequency, initial phase and amplitudes. Under the condition of a 200 Hz acoustic disturbance, the pulsation amplitude distribution of the flame fluctuation with different levels of added helium is shown in Fig. 8. The unit of color bar appearing in pulsation amplitude distribution is gray value. The span of acoustic disturbance frequency is 100~700Hz. The effects of helium dilution on flame pulsation is similar when the disturbance frequency is lower than 300Hz. The flame pulsation amplitudes can be similarly and significantly reduced by adding helium when the frequency does not exceed 300 Hz. There are random soot in the flame, in addition, the velocity pattern in the combustor is asymmetry due to the manufacturing and installation errors of components, so the flame oscillation pattern shows asymmetry. It indicates that helium dilution can greatly reduce the sensitivity of flame to acoustic disturbance. Especially when the amount of helium is equal to the volume flow of fuel, the flame pulsation amplitude is reduced by more than half. The flame is affected by the acoustic disturbance and mainly shows periodic pulsation characteristics in the swirling jets at the outlet of the cyclone. While the sound speed is relatively large, the flame pulsates under the fluctuation of airflow velocity with relatively smaller amplitudes and lags behind the airflow pulsation. Fig. 9 shows that the above-mentioned phase delay can be discovered by the initial phase from DMD, the color bar is in radians. The wavelength of flame pulsation can be determined according to the pulsation period. When the pulsation phase difference reaches one period (the phase difference is 2), it can be considered that a pulsation wavelength is reached. When helium is added, the phase of flame pulsation changes greatly. It has more pulsation period distribution in the entire flame region when no helium is added to the fuel, while only two pulsation period exist after adding helium with the equivalent volume flow rate with the fuel. The results show that when enough helium is added, the pulsation region of the flame becomes smaller, indicating that the flame is more inert.



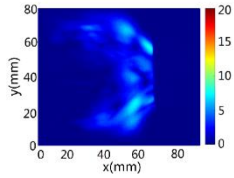
Helium volume content: 0



Helium volume content: 0.3

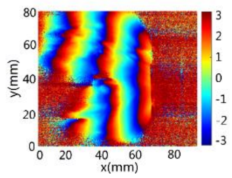


Helium volume content: 0.6

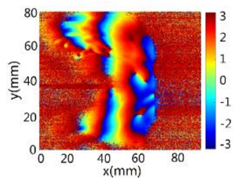


Helium volume content: 1

Fig. 8. Flame pulsation amplitude distribution with 200 Hz of acoustic disturbance.



Helium volume content: 0



Helium volume content: 1

Fig. 9. Initial phase distribution with 200 Hz of acoustic disturbance.

However, when the disturbance acoustic frequency exceeds 300Hz, the effects of mixing helium in fuel becomes worse. The flame itself has strong anti-interference ability and has relatively small pulsating amplitudes under high frequency acoustic disturbance. Fig.10 shows the effects of helium on flame pulsating amplitudes with 400 Hz acoustic disturbance. Compared to the above results, the flame pulsation caused by high frequency is relatively smaller. At this moment, the helium effects are relatively weak. Gradually increasing the added helium does not significantly reduce the flame's pulsating intensity. The above-discussed results show that the helium dilution to the fuel can significantly affect the flame fluctuation amplitude. These effects are especially prominent in low frequency disturbance environments. This is primarily because the flame has a large pulsating surface in a low-frequency disturbance environment, while the added helium has less effect on reducing the flame pulsation in a high-frequency disturbance environment.

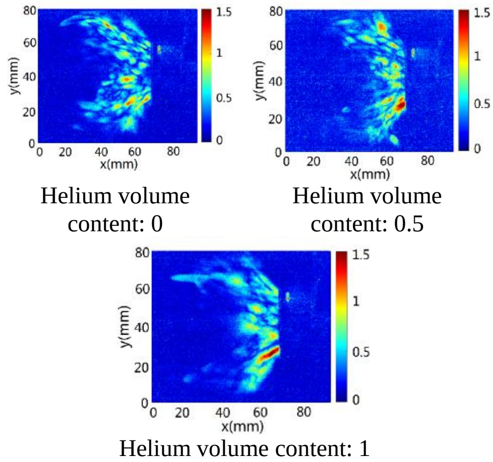


Fig. 10. Flame pulsating amplitude with 400 Hz of acoustic disturbance.

4.3 Suppression of Oscillating Pressure (Self Exited)

For the test system shown in Fig. 1, the model combustor has thermoacoustic combustion instability boundaries, which are related to inlet Reynolds number, fuel supply and geometry, as shown in Fig. 11. This is similar to some studies of combustion instability. Combustion instability will occur when the fuel-air-ratio is lower than the critical value. According to the acoustic characteristics of the system, combustion instability has two unstable modes, which are excited under different inlet parameters. For example, Fig. 12 shows the oscillating pressure in Case A. Under the self-excited combustion instability, the pressure presents a strong fluctuation.

The combustion instability investigated in this paper mainly has two dominant frequencies, namely 160Hz and 240Hz, which respectively correspond to the acoustic resonance frequencies of the system. These

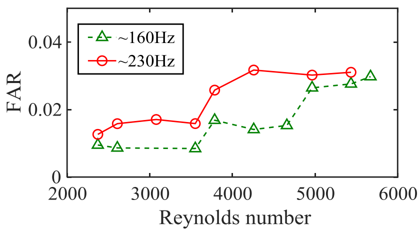


Fig. 11. Combustion instability boundary.

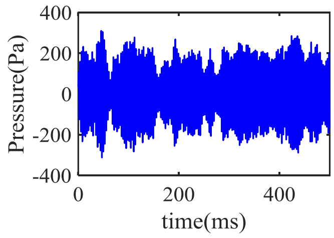


Fig. 12. Dynamic pressure under self-excited combustion instability.

two dominant frequencies are excited under different operating parameters. The dominant oscillation frequency in Case A is 240Hz, while the dominant oscillation frequencies in Case B and Case C include 240Hz and 160Hz. Fig. 13 shows the pressure signal in time domain in case A, and Fig. 14 shows the corresponding spectrum analysis of pressure signal. Different amounts of helium have different effects on pressure suppression. When the inlet Reynolds number is relatively low, the oscillating frequency is around 240 Hz when the FAR is 0.0158. The experimental results show that the dominant frequency is slightly different at different ambient temperatures, which is mainly caused by the average temperature of the air flow. In addition, the shape and temperature gradient of the flame affect the acoustic impedance of the system, which will also change its resonance frequency. When helium is added to the fuel supplement, the combustion instability intensity of self-excited oscillation decreases. Amplitudes of oscillating pressure are significantly reduced when a 20% volume ratio of helium is added. In particular, when the volume ratio reaches up to 40%, the oscillating pressure amplitude drops below 20 Pa. At this point, the combustion instability is extremely weak, and the ability to further reduce the amplitude is limited. In addition, the dominant frequency of combustion instability did not change significantly after adding helium. The added helium flow is very small, which is not enough to have a significant impact on the gas density in the combustor.

In cases B and C, the oscillating pressure caused by the combustion instability shows relatively complex spectral characteristics, and there are two pulsating dominant frequencies (~160Hz and ~240Hz) in the spectrum analysis without having added the helium. In general, the dominant hydrodynamic frequency of swirling jets is less than 130Hz, which is inconsistent to the dominant frequencies of combustion instability. At a low inlet Reynolds number, ~160Hz dominant frequency oscillation is not easily excited. After increasing the inlet Reynolds number, the oscillating pressure tends to present the above two

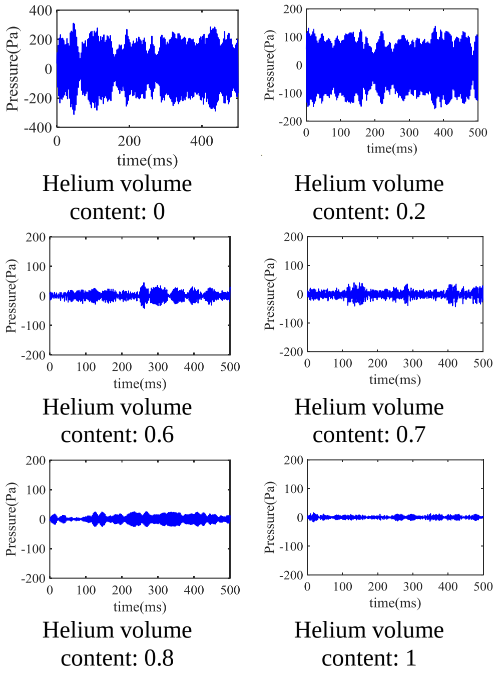


Fig.13. Oscillating pressure in time domain in case A.

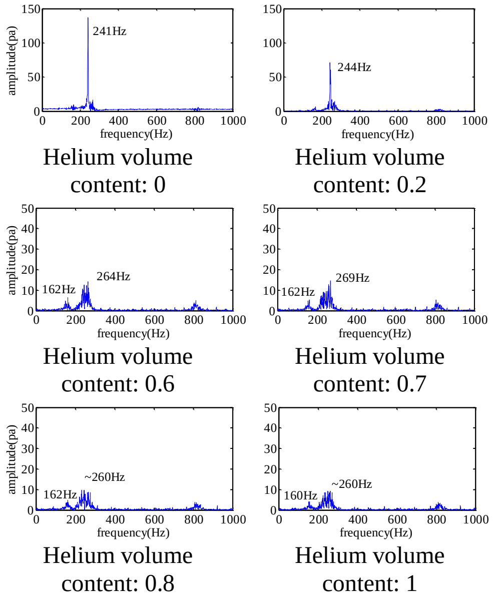


Fig. 14. Spectrum analysis of oscillating pressure with different added helium contents in case A.

dominant frequencies. Especially when the inlet Reynolds number increases to 6500, the amplitude of low-frequency (~160Hz) oscillation is relatively large in case C, which is fairly unfavorable to the stability of flame and easily leads to the flameout of the combustion. Fig. 15 and Fig. 16 show the effects of helium's addition to combustion instability in cases B and C. The oscillation frequency of ~240Hz is relatively easy to suppress. After adding a small amount of helium (less than 20%) to the fuel, the amplitude can be reduced to less than 50 Pa. However, the amplitude corresponding to ~160Hz

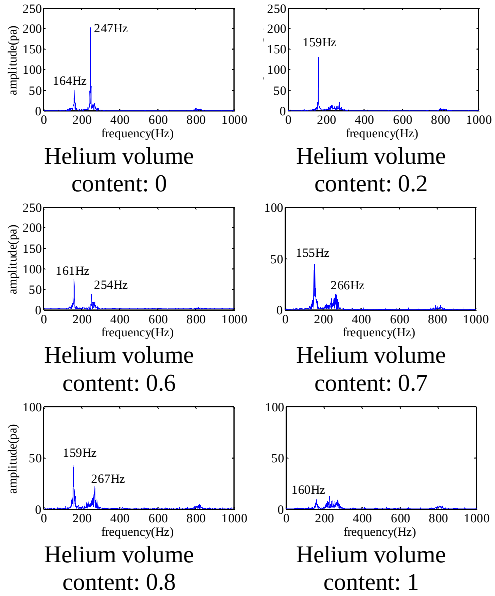


Fig. 15. Spectrum analysis of oscillating pressure with added helium in case B.

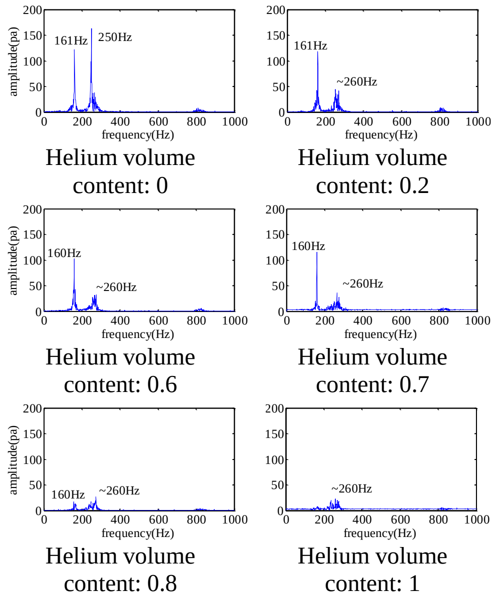
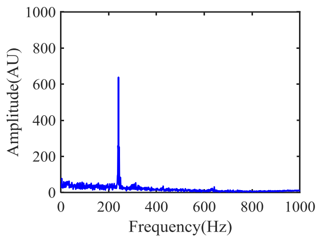


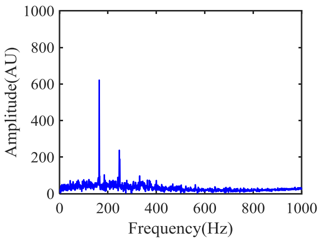
Fig. 16. Spectrum analysis of oscillating pressure with added helium in case C.

frequency decreases slowly and even increases when the amount of added helium is less than 20%. Only when the added helium reaches 80% does it drop below 50 Pa. Even though there are large differences in inhibition effects for different dominant frequencies, enough helium can reduce the sensitivity of the flame to acoustic disturbance, destroy the combustion instability feedback and cut down the oscillating amplitudes of flame and pressure. The above-mentioned results show that the helium dilution of fuel can greatly reduce the oscillating intensity of combustion instability and even suppress the self-excited oscillation to stable combustion. Moreover, when the helium content reaches 100%, the oscillating pressure amplitudes can be reduced to less than 20 Pa under various working conditions.

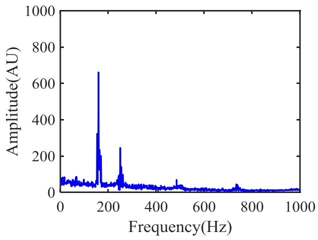
To study the effects of helium dilution on flame dynamics in an oscillation environment, the flame pulsating characteristics under different working conditions are studied using the DMD method. Firstly, the spectral characteristics of flame pulsation under different conditions without added helium are shown in Fig. 17. DMD method decomposes the flame pulsation process to get different modes, each mode has a corresponding frequency and amplitude. The amplitude is the eigenvalue of the flame pulsation matrix and represents the energy of the flame pulsation. The frequencies are derived by analyzing the phase angle of the eigenvalues. It indicates that the flame and oscillating pressure have consistent dominant frequencies. Each mode has its specific spatial distribution, initial phase, frequency and amplitude. In case A, the dominant frequency is 241 Hz; in case B, the dominant frequencies are 164 Hz and 247 Hz, respectively; in case C, the dominant frequencies are 161 Hz and 250 Hz, respectively.



(1) Case A



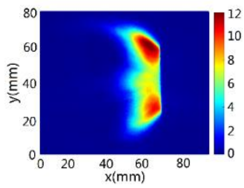
(2) Case B



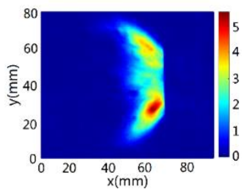
(3) Case C

Fig. 17. Spectrum of flame pulsation without added helium.

The spatial distribution is unitized, and the pulsating intensity is reflected by the amplitudes. In cases B and C, while the oscillating amplitudes corresponding to ~240Hz are relatively larger for oscillating pressure, the pulsating amplitude corresponding to ~160Hz is larger for flame pulsation. In case C and in the absence of helium, there are two primary frequencies of flame pulsation, and the spatial distribution of pulsating amplitudes corresponding to the two primary frequencies are shown in Fig. 18. Note that the amplitudes scalars have been taken into account for the pulsating structures. The results show that the pulsating structure of these two primary frequencies is similar, and that the primary pulsation area is concentrated in the head of the combustor that corresponds to the main flame distribution region. The pulsating intensity is relatively strong in the swirling jets where the fuel and air contact, mix and burn. In addition, due to the difference in the feedback of the flame to the acoustic disturbance, the flame pulsation corresponding to ~160Hz has a larger amplitude, even though the amplitude of oscillating pressure is smaller.



(1) 161Hz



(2) 250Hz

Fig. 18. Pulsating amplitude without added helium in case C.

To achieve self-excited combustion instability, the FAR is relatively low, which makes the pulsating structure of flame different to the previous section. The study of external-excited combustion instability shows that adding helium to fuel supplements can reduce flame response to acoustic disturbance. In the self-excited combustion instability environment, oscillating pressure and pulsating flame are coupled, and so added helium can also affect the degree of coupling and cut down the pulsating amplitudes. For example, Fig. 19 shows the flame pulsating amplitude distribution with helium addition in case A. With the increase of added helium, 20% of the helium content can significantly decrease the intensity of the flame pulsation. Similarly, to the oscillating pressure, when the helium content reaches 40%, the flame only has a small pulsation, such that the combustion occurs in extremely weak oscillation and the self-excited oscillation is essentially eliminated. It has a similar flame pulsating structure for combustion instability with and without added helium. The fluctuations of the flame are characterized by surface stretching caused by acoustic disturbance in the longitudinal direction (air flow direction). Similar to the distributed flame, the added helium makes the flame surface no longer mainly concentrate in the swirling jets, and so the sensitivity of heat release fluctuation to the flame surface is weakened. Therefore, both the oscillating pressure and flame pulsating have smaller amplitudes with the addition of helium.

As is mentioned above, DMD projects the pulsation on an orthogonal basis. In addition to the spatial vectors representing the pulsation structure, the amplitude scalars represent the intensity of flame

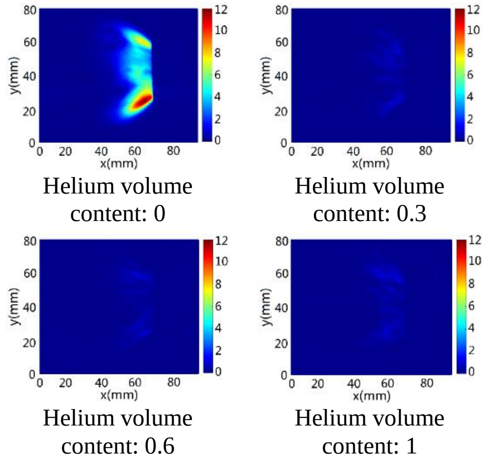


Fig. 19. Pulsating amplitude of flame corresponding to ~240 Hz in case A.

pulsation. Flame has a similar pulsation structure under different working conditions; that is, the flame pulsation is mainly concentrated in the head region of the combustor, but there are significant differences in the pulsation intensity. Thus, the pulsation amplitudes corresponding to the dominant frequencies obtained by the DMD method can be used to characterize the pulsation intensity of the oscillating flame. Fig. 20 shows the pulsation amplitudes in three cases with different amounts of added helium. When considering the amplitude alone, it has no specific physical significance. The amplitudes are more used to compare the relative pulsation intensity of different modes and working conditions. In contrast, the flame pulsation amplitude at ~160Hz is more difficult to eliminate. While the amplitude of ~240Hz is larger without added helium, with the increase of added helium it decreases rapidly. Then, the pulsating energy concentrates at ~160 Hz mode, resulting in an increase in the corresponding amplitude. In particular, it is more difficult to eliminate the amplitude of ~160 Hz mode under a high inlet Reynolds number (in case C), and it does not gradually decrease until the helium content reaches 60% of the fuel volume flow. When the helium content reaches 100%, the flame pulsation amplitude can be reduced to a relatively stable level. In this case, the flame pulsation amplitude is weak, and the oscillation uncouples. In summary, the oscillation with ~160 Hz frequency is more difficult to eliminate than the ~240 Hz one, which requires a larger proportion of helium supplement. However, the oscillation with ~240 Hz can be easily eliminated when the helium content reaches 40%.

5. Conclusion

A The addition of helium to fuel can greatly reduce oscillating pressure amplitudes in combustion instability environments and even convert the instability into a stable combustion process. Meanwhile, Proper Orthogonal Decomposition and Dynamic Mode Decomposition are applied to study the effects of added helium on the flame pulsation

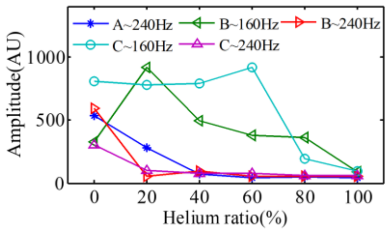


Fig. 20. Pulsating amplitudes of flame under different working conditions and dominant frequencies.

strength. The particular conclusions are described as follows:

1) Added helium can increase the injection speed of fuel jets and enhance their entrainment, which reduces the flame pulsation. In addition, the experimental results show that the addition of helium has no significant influence on the flameout characteristics of combustion.

2) Fuel is diluted by helium and burns in a broader space where flame distributes more uniformly. In external-excited experiments, the results indicate that added helium can decrease flame feedback on acoustic disturbance: both oscillating pressure and flame pulsation are reduced.

3) The self-excited combustion instability experiments are conducted within the unstable boundary; that is, the fluctuation of heat release is coupled with the oscillating pressure without the external acoustic disturbance. This can lead to combustion instability in engineering applications. The suppression results show that after gradually increasing the helium content, the oscillating pressure corresponding to different dominant frequencies are successively suppressed. In contrast, ~160Hz oscillations are more difficult to suppress than ~240Hz and require the addition of more helium.

4) From the self-excited experiments, it was found that the oscillating pressure amplitudes can be reduced to below 20 Pa when enough helium is added to the fuel supplement under various conditions. Meanwhile, the flame pulsation strength is weakened and even the oscillatory combustion is transformed into stable combustion, which proves the feasibility of helium in its application to combustion instability suppression.

Acknowledgements

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