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Study on Suppression of Combustion Instability using Quarter Wavelength Tube

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ABSTRACT

The passive suppression of combustion instability by quarter wavelength tube was hereby studied to absorb the oscillation pressure with large amplitudes caused by combustion instability. The suppression effects of quarter wavelength tube on combustion instability were systematically analyzed by combining the acoustic numerical simulation and the experimental research methods. Firstly, the influence of quarter wavelength tube on the acoustic characteristics of the system was analyzed using acoustic numerical simulation; and then, the acoustic absorption characteristics to external acoustic disturbance and the suppression effects on the self-excited combustion instability were experimentally studied. The results show that the quarter wavelength tube can effectively absorb the acoustic pressure when the dominant frequency of acoustic pressure is close to the resonance frequency of the system, and can effectively suppress the combustion instability under acoustic resonance. However, given that the quarter wavelength tube adds adjoint dominant frequencies after eliminating the original resonant frequency of the system, and the combustion instability is stabilized on the adjoint dominant frequencies, combustion instability suppression is different from noise suppression. In addition, the diameter of wavelength tube exercises obvious effects on the above characteristics. All these make it necessary to determine the best parameters and the maximum suppression efficiency by combining numerical simulation and experiments. The research results of this paper provide theoretical and technical supports for the suppression of combustion instability by the quarter wavelength tube.

Keywords: Quarter wavelength tube; Combustion instability; Passive suppression; Acoustic numerical simulation; Acoustic absorption efficiency.

NOMENCLATURE

FFT Fast Fourier Transform

1. INTRODUCTION

Combustion instability is a common problem in combustion systems such as gas turbines, rocket engines and combustion furnaces. In an unstable combustion environment, the pulsation of heat release from a flame is coupled with the oscillation pressure, resulting in a large value of pressure pulsation in the system (Liu *et al.* 2019). At present, the suppression of combustion instability can be divided into passive and active inhibition: in passive inhibition, the pressure oscillation intensity is usually reduced by changing the system geometry; while in active inhibition, the collected input signals are calculated by the controller, and the external energy is input into the system through the actuator. Passive suppression is relatively easy to implement only by changing the structure. For example, combustion instability in a model gas turbine combustor was ever experimentally suppressed with annular air jets (Zhou *et al.* 2020); considering that the acoustic boundary of the combustion system has important impacts on combustion instability, the purpose of passive suppression of combustion instability with acoustic absorption structure is to change the acoustic characteristics of the combustion system (Han *et al.* 2021; Dubey *et al.* 2021; Yoon 2020); in addition, attempts have also been made to use heat source for passively suppressing combustion instability (Li and Morgans 2015; Surendran *et al.* 2017). For the cases of changing the system structure, the wall of the flame tube in the main combustor of an aircraft engine or the insulation screen of an afterburner are furnished with porous structure, reasonable design of its diameter and other dimensions can achieve the effects of absorbing a certain frequency acoustic pressure. In terms of sound absorption metal materials, Duan *et al*. (2020) studied a new type of micro-perforated compressed metal plate, the acoustic absorption characteristics of which were verified by finite element simulation and standing wave tube test; in addition, placing a porous material in the combustion chamber was also proven capable of absorbing the acoustic pressure of combustion instability (Meadows and Agrawal 2015; Kim *et al.* 2018). The acoustic absorption structure installed on the wall of the equipment is an easy method to achieve passive suppression. The structure such as Helmholtz resonator or quarter wavelength tube is commonly used to absorb the pressure pulsation. The wavelength tube makes it convenient to change the absorption dominant frequency by adjusting its length, while the absorption frequency of Helmholtz resonator is always difficult to adjust. To solve the problem of the narrow frequency band of the controller in passive control, Zhang *et al*. (2015) studied the suppression of combustion instability by adjusting the neck area of the Helmholtz resonator; in the acoustic theoretical study of Helmholtz resonators, Koval'Aková *et al*. (2020) fitted the theoretical relationship between the forced vibration displacement amplitude and the change of frequency to the corrected curve of the acoustic pressure amplitude and the change of frequency, providing the natural frequency and damping constant of the resonant cavity; and Jena *et al*. (2019) and Sachedina *et al*. (2020) evaluated the acoustic absorption performance of the resonator by analyzing the reflection coefficient and transmission coefficient using experimental and numerical simulation methods. The quarter wavelength tube is frequently applied to the noise elimination system and is also a common acoustic absorption component in automobiles, which can eliminate the fixed frequency acoustic pressure in the intake and exhaust systems. For example, it has been proven to work effectively in the indoor noise reduction of automobiles (Sun *et al.* 2019); Han *et al.* (2017) detailed how to design a Helmholtz silencer and a quarter wavelength tube; Howard and Craig (2014b) introduced an adaptive quarter wavelength tube for reducing exhaust noise of large diesel engines with the sliding Goertzel algorithm adopted for calculating the phase angle of the transfer function between the adaptive quarter wavelength tube microphone and the microphone in the main exhaust channel, which was proven to effectively reduce the production machine scheduling noise; and Nie *et al.* (2001) applied an acoustic cavity structure similar to the quarter wavelength tube to suppress combustion instability in rocket engines. It is also worth noting that the efficiency of the quarter wavelength tube will be reduced under the action of high velocity airflow. Anderson (1977) paid early attention to the influence of air flow on the acoustic absorption performance of a quarter wavelength tube; Lambert (1956) theoretically analyzed the effects of average flow on the acoustic absorption of the sound absorption damping tube, which was proven especially significant for an Mach number greater than 0.1; subsequently, Howard and Craig (2014a) studied the effects of air flow on acoustic characteristics of the anechoic unit, and the side branch with the trumpet structure was found to exercise the best noise reduction effects after adopting the adaptive quarter wavelength tube. In summary, the quarter wavelength tube has a wide range of applications in the noise suppression field, but relatively few studies on passive suppression of combustion instability have been reported.

In this paper, a quarter wavelength tube was installed on the wall of model combustor to absorb the oscillating pressure caused by self-excited combustion instability, and based on the acoustic characteristics of the combustion system, the feasibility and effects of the quarter wavelength tube on the suppression of combustion instability were studied systematically by combining the acoustic numerical simulation and experimental research methods.

2. EXPERIMENTAL SYSTEM

The combustion instability test system is composed of the air supply and measurement system, the fuel supply and measurement system, the swirling-stabilized combustor, the dynamic pressure measurement system, etc. The fuel used in the test is butane fuel, and the combination mode of swirler and porous nozzle is adopted to make the combustion close to the partial premixed combustion state, as shown in Fig. 1.

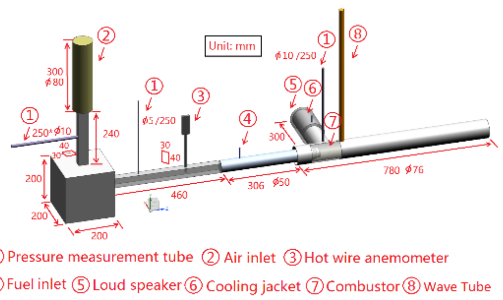


Fig. 1. System setup.

Figure 2 shows the structure of the swirler and nozzle. The two stage swirlers in opposite directions have a large shear stress in the shear layer, and can promote the mixing of fuel and air. The swirling intensity in swirler is large, and the flame is extremely susceptible to various disturbances. As a result, the coupling of acoustic wave and heat release leads to combustion instability and pressure pulsation with large amplitude.

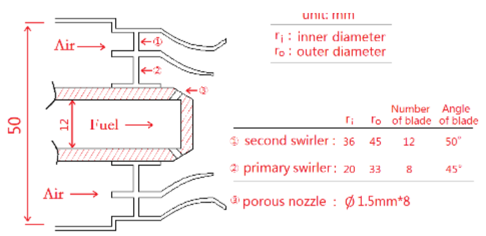


Fig. 2. Head structure of combustor.

In the test, the air flow was measured by hot-wire anemometer, the hot-wire anemometer was firstly calibrated by a thermal air mass flowmeter with 0.5% accuracy, and the butane fuel was measured by a calibrated rotameter. A proper size square tank was designed in this test system for absorbing the dominant frequency pulsation of the fan and producing a steady air flow. The side pipe, 300mm long, was installed on the side of the combustor, and the end of the pipe was installed with a loudspeaker, which could be used as an acoustic source to generate acoustic waves with different amplitudes and frequencies. In order to avoid thermal damage caused by high flame temperature to the pressure sensor, a dynamic pressure measuring tube with a length of 250mm and an inner diameter of 10mm was designed in the test to isolate the pressure sensor from high temperature gas. Fig.3 shows the correction data of the pressure measurement tube. The gain G is defined as $G = P_2/P_1$. P_2 represents the pressure amplitude measured through the pressure measurement tube, P_1 represents the actual pressure amplitude.

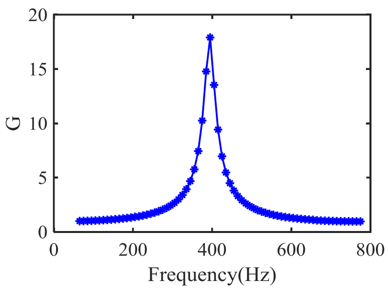


Fig. 3. Correction of pressure measurement tube.

The oscillation pressure pulsation amplitude was evaluated using the Fast Fourier Transform (FFT) method. The pressure signal sampled within 2 seconds was subjected to FFT with a frequency resolution of 0.5 Hz for obtaining the amplitudes corresponding to dominant frequencies, and the sampling frequency was 4096 Hz. The oscillating pressure amplitudes presented pulsating characteristics, and thus, the average amplitude of oscillating pressure within 20 seconds was calculated. The AE-H sensor with a measuring range of -3~3 KPa of Aire Sensor Technology Co., Ltd was adopted as the high frequency pressure sensor, the comprehensive accuracy and the measuring frequency response range of which were 0.5% and 0~20 KHz, respectively.

3. Acoustic Numerical Simulation of Combustion System

In the process of acoustic wave propagation, only the continuity equation, momentum equation (motion equation) and the equation of state of acoustic wave were considered, except the energy equation. In fluid mechanics, it was considered that the net outflow of the fluid mass in the fluid element was equal to the change of the mass in the element. Acoustic source could produce a unit volume velocity in the element. The continuity equation of the acoustic wave is:

$$\frac{\partial(\rho_0+\rho')}{\partial t}+(\rho_0+\rho')\nabla\bar{v}=(\rho_0+\rho')q' \tag{1}$$

where ρ represents the density, and the density and volume velocity are represented by the sum of average quantity and pulsation quantity, that is, $\rho=\rho_0+\rho'$, $q=q_0+q'$. However, the mass force acting on the fluid element was not considered in the motion equation of acoustic wave, so the motion equation of acoustic wave can be expressed as:

$$(\rho_0+\rho')\left(\frac{\partial}{\partial t}+\bar{v}\cdot\nabla\right)\bar{v}=-\nabla(p_0+p') \tag{2}$$

In addition, the propagation speed of acoustic wave was considered much faster than that of heat, and the propagation process of acoustic wave was considered adiabatic. The pressure, velocity, and density in that adiabatic environment satisfy the following state equation:

$$\frac{p}{p_0}=\left(\frac{V_0}{V}\right)^n=\left(\frac{\rho_0}{\rho}\right)^n \tag{3}$$

where, n represents the adiabatic exponent, and for an ideal gas, the adiabatic exponent is equal to the specific heat ratio γ . After linearizing Eqs. (1-3) and removing small quantities of higher order, the linear acoustic wave equation of fluid in non-viscous and adiabatic equation can be obtained:

$$\nabla^2 p'-\frac{1}{c^2}\frac{\partial^2 p'}{\partial t^2}=-\rho_0\frac{\partial\rho'}{\partial t} \tag{4}$$

where, $c=\sqrt{\gamma p_0/\rho_0}$ represents the propagation velocity of acoustic wave in fluid media. Any fluctuation can be regarded as a plurality of harmonic motion superposition, so the acoustic wave equation is often solved in the frequency domain. The acoustic pressure and volume velocity of the acoustic source can be described as:

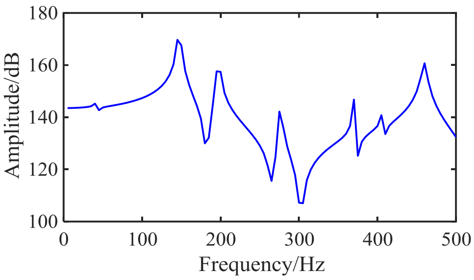
$$p'=p(x,y,z)e^{j\omega t},q'=q(x,y,z)e^{j\omega t} \tag{5}$$

Substitute Eq. (5) into Eq. (4) to obtain the Helmholtz equation:

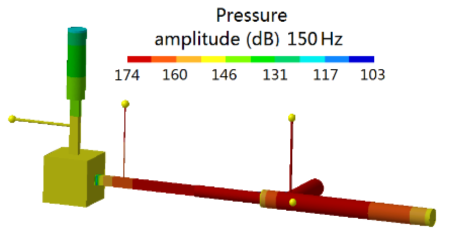
$$\nabla^2 p(x,y,z)-k^2 p(x,y,z)=-j\rho_0\omega q(x,y,z) \tag{6}$$

Equation (6) represents the acoustic wave equation in frequency domain, where $\omega=2\pi f$ represents angular frequency; and $k=\omega/c$, the wave number. For the Helmholtz equation expressed in Eq. (6), numerical solutions satisfying the boundary conditions can be obtained using numerical calculation methods, i.e., the acoustic finite element method or the acoustic boundary element method.

In the LMS Virtual.Lab Acoustic, the acoustic finite element method is used for calculating the acoustic pressure response at the flame position under different frequencies of acoustic source disturbance. The inlet and outlet of the system are set as open infinite element boundary conditions. The acoustic source is a monopole with an amplitude of 1kg/s^2, which is equivalent to a pressure of 1 Pa at a radius of 1 meter. The environment pressure is 101300Pa, the temperature is 25℃, and the calculated acoustic velocity is 346.6m/s and the air density is 1.196kg/m^3. The total number of grid nodes is about 600 thousand, and the maximum computational frequency satisfied the grid size is 3900Hz. The dynamic pressure below 500Hz was mainly concerned for the combustion instability problem studied in this paper, so the grid size was reasonable. The acoustic pressure response amplitude at flame position in cold environment is shown in Fig.4 (a). The results show that there are multiple acoustic resonant frequencies in the combustion system, that the acoustic pressure feedback at the dominant frequency point has an extreme value, and that the purpose of installing a quarter wavelength tube is to eliminate or reduce the dominant frequency peak. Fig.4 (b) shows the acoustic amplitude distribution corresponding to the first dominant frequency, indicating a distinguishable acoustic intensity distribution at different positions, and a slight change of the amplitude of acoustic pressure near the flame in the combustion chamber.



(a) Acoustic response without quarter wavelength tube

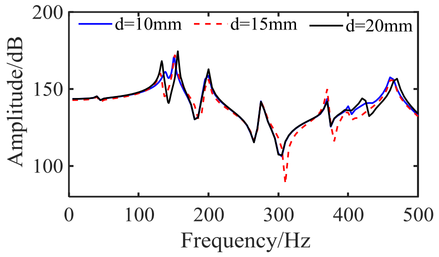


(b) Acoustic intensity distribution

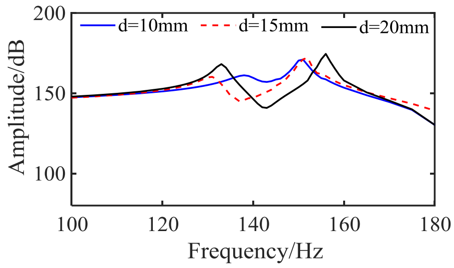
Fig. 4 Acoustic characteristics of system under cold condition.

In order to absorb the dominant frequency peak of 150 Hz, a quarter wavelength tube was installed on the wall of the combustion chamber, the length of which was one quarter of the wavelength of the sound wave, and room temperature was used for calculating the parameters of acoustic wave. In the experiment, the root of the wavelength tube was cooled using high-speed air jet, and the single test time was strictly controlled to ensure that the air inside the wavelength tube maintained a room temperature environment. The quarter wavelength tube was installed 90 mm downstream of the pressure measuring tube, after which, the acoustic response of the system was calculated using the numerical simulation method. According to Fig.1 and Fig.4 (b), the installation distance between wavelength tube and flame position was less than 30mm, and the acoustic pressure amplitude difference was less than 5dB. Considering the viscous layer in the wavelength tube, the wavelength tube would present the characteristics of impedance and capacitance. The viscosity effects were significantly different on the wavelength tubes with different inner diameters involved, which would affect their sound absorption efficiency. The influence of three wavelength tubes with different diameters on the acoustic characteristics was hereby analyzed in the presence of viscous action. The viscosity characteristics of the air in the wavelength tube was considered according to its diameter. The surface contacting the wavelength tube and the main part was set as the coupling boundary. The specific heat ratio was 1.4 and the dynamic viscosity was 1.84e-5 N•S/m^2.

Figure 5 depicts the acoustics response at flame position when the quarter wavelength tube was installed. The results show that the wavelength tube had significant influence on the acoustic pressure response near 150 Hz dominant frequency, but exercised little influence in other frequency ranges. After installing the wavelength tube, the original 150 Hz dominant frequency disappeared, and two dominant frequencies were added near 150 Hz. For instance, the adjacent dominant frequencies were 138 Hz and 155 Hz when the diameter was 15 mm, and these two dominant frequencies were the left offset dominant frequency and the right offset dominant frequency, respectively. The amplitude of the offset dominant frequencies was less than that of the 150 Hz dominant frequency of the original structure. As shown in Fig. 5 (b), the diameter of the wavelength tube exerted important effects on the acoustic response: First, when the diameter of the wavelength tube was increased, the offset dominant frequency was further away from the original resonant dominant frequency, that is, the left offset dominant frequency was smaller while the right offset dominant frequency was larger; secondly, the amplitude of the offset dominant frequency was also correlated with the diameter of the wavelength tube, that is, the two offset dominant frequencies possessed larger acoustic pressure amplitudes with the increase of the diameter. In addition, the viscosity in tubes resulted in the asymmetry of the two adjoint frequencies. The adjacent peak values around 150 Hz were almost the same when the viscosity was not taken into account, though it could not be ignored in practice. Then, the amplitude of the left offset dominant frequency was significantly smaller than that of the right dominant frequency, when the symmetry would be more significant for the wavelength tube with a diameter of 10 mm, since the viscosity effect would be more obvious when the diameter was smaller. The corresponding amplitude of the left offset dominant frequency increased with the increase of the diameter, which may be attributed to the fact that the increase of the diameter would weaken the viscous effect of the air inside the tube, thereby leading to the symmetry of the two offset dominant frequencies.



(a) 0~500Hz



(b) 100~180Hz

Fig. 5 Acoustic response with wavelength tube (considering viscous effect).

These results indicate that although the corresponding resonant frequency of the original system can be eliminated after the installation of the quarter wavelength tube, two offset dominant frequencies will be added, bringing about a possibility that combustion instability is stabilized at the offset dominant frequency. The following tests also confirm this view.

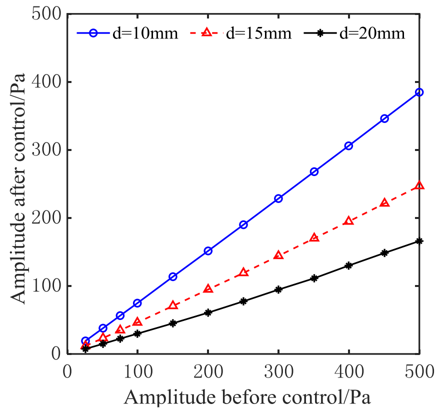
4. Suppression of Combustion Instability Using Quarter Wavelength Tube (Test)

4.1 Acoustic Absorption Efficiency of Quarter Wavelength Tube

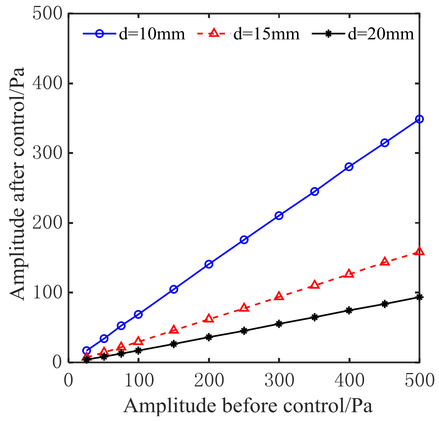
The absorption efficiency of the quarter wavelength tube on acoustic waves was studied for exploring the suppression effects of the quarter wavelength tube on oscillating pressure of combustion instability. The test system is shown in Fig. 1. The external excitation source (loudspeaker) produced acoustic waves with different frequencies and amplitudes. The absorption efficiency of the wavelength tube on disturbed acoustic waves in the frequency range of 100~500 Hz was studied. Fig .6. shows the visual results of the sound pressure amplitude before and after installing the quarter wavelength tube, reflecting the reduction of pressure amplitude.

Within the parameter range in this study, the sound wave absorption curve with the increase of amplitude was close to linear, which visually reflects the absorption ratio of the quarter wavelength tube to the sound wave. Therefore, the absorption effects of the wavelength tube can be expressed by the slope of the acoustic pressure absorption curve. The absorption efficiency of the wavelength tube can be defined in Eq. (7) as:

$$\eta = 1 - k \tag{7}$$



(a) 164Hz



(b) 225Hz

Fig. 6. Absorption effects of quarter wavelength tubes.

where, k represents the slope of the acoustic pressure absorption curve. A smaller slope means a better acoustic absorption efficiency. When the slope is 1, the wavelength tube has no acoustic absorption, that is, the acoustic pressure amplitude does not change after the installation of the wavelength tube. Given that the length of the wavelength tube is always adjusted to absorb the acoustic waves, the slope of the absorption curve is generally less than 1. It is worth noting that the slope of absorption curve can be greater than 1 for an unreasonable length of the wavelength tube.

The absorption effects of the quarter wavelength tubes with different diameters were quite different. For different disturbance frequencies, the wavelength tube should be adjusted to a reasonable length to ensure that its resonance frequency was consistent with the frequency of the acoustic wave. In this way, it had a minimum acoustic impedance at the inlet of the wavelength tube. Ideally, the acoustic wave with resonance frequency is completely absorbed with the viscous effect of the wavelength tube ignored, but, in reality, wavelength tubes with different diameters do have different viscous effects and thus, different absorption characteristics. The acoustic absorption efficiency of wavelength tubes with three diameters is shown in Fig. 7. When the frequency was greater than 250Hz, the acoustic absorption efficiency of the three wavelength tubes was relatively low, less than 0.1. This was because the high frequency acoustic wave in a small diameter

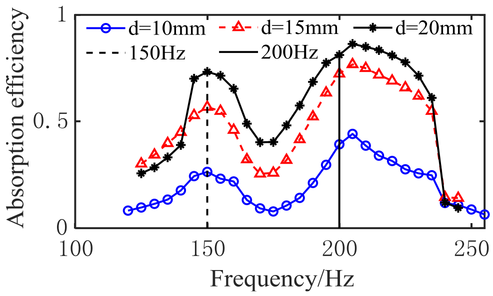


Fig. 7. Acoustic absorption efficiency of wavelength tubes with different diameters.

wavelength tube had a large viscous loss, which led to the large acoustic impedance of the wavelength tube. In addition, it is noteworthy that the acoustic absorption efficiency of the quarter wavelength tube varied greatly in different frequency ranges. As can be seen from Fig. 4 (a), the resonant frequencies of the system include 150Hz and 200Hz. Then, the acoustic absorption efficiency of the wavelength tube was relatively higher near the resonant frequencies, since the sound absorption coefficient reached its maximum as the sound absorption structure was installed at the maximal value point of the standing wave. However, the absorption efficiency was greatly reduced when the disturbance frequency deviated from the resonant frequency. The diameter of the wavelength tube was closely related to its acoustic absorption efficiency. For example, the absorption efficiency increased with the increase of the diameter, which would reach more than 0.85 especially when the frequency was near 210Hz. The acoustic absorption efficiency was always below 0.5 for a diameter of 10mm.The results show that in a certain frequency range, the wavelength tube with a larger diameter is provided with a better acoustic absorption efficiency, which, however, will be lower at a higher frequency.

The peaks of acoustic absorption efficiency were near the resonant frequencies of the system, but lagged behind the resonant frequencies. For example, when the frequency appropriately exceeded 150Hz and 200Hz, the quarter wavelength tube presented the best acoustic absorption efficiency. When the combustion instability was stable at an acoustic resonant state, it was appropriate to install a wavelength tube to absorb the oscillating pressure. In this circumstance, the wavelength tube possessed a larger acoustic absorption efficiency. If the combustion instability was caused by flow and other factors, the oscillation frequency was dominated by other reasons except acoustic resonance, and the absorption efficiency of the wavelength tubes was low.

4.2 Passive suppression of combustion instability using quarter wavelength tube

The results of acoustic numerical simulation show that the installation of quarter wave tubes changes the acoustic characteristics of the system: the original peak is absorbed, but the offset dominant frequencies appear near the original peak, and the occurrence of the offset dominant frequency has important effects on the passive suppression of combustion instability. The resonant frequencies of the system in the combustion state include ~150Hz and ~235Hz, which are excited under different inlet conditions, and different ambient temperatures will lead to the slight change in the oscillation frequency. Fig. 8 shows the combustion instability boundaries, which are excited under different working conditions respectively. These two dominant frequencies are consistent with the acoustic resonance frequencies of the combustion system. Generally, the oscillation of ~150Hz is more difficult to be excited than that of ~235Hz, that is, the oscillation with dominant frequency of ~235Hz is excited first in the process of reducing the fuel supplement. When the fuel-air ratio is further reduced, the oscillation frequency turns to ~150Hz. In some special working conditions, the two dominant frequencies exist at the same time. In the test, the wavelength tube was cooled to keep the air in the wavelength tube at room temperature.

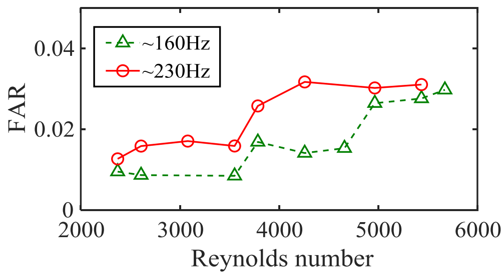


Fig. 8. Combustion instability boundary.

Firstly, the suppression effects of the quarter wavelength tube on ~150Hz oscillation was studied. For the wavelength tube with a diameter of 10mm, the variation of oscillation pressure amplitude is shown in Fig. 9. After installing the wavelength tube at 50s, the amplitude corresponding to dominant frequency decreased, the suppression effects were limited, and the suppression efficiency was only 26.7%. The suppression efficiency was defined as the amplitude reduction ratio. The oscillating pressure of self-excited combustion instability was unstable, so the pressure amplitude calculated by FFT presented fluctuation characteristics.

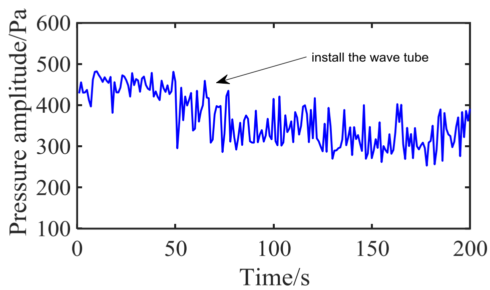
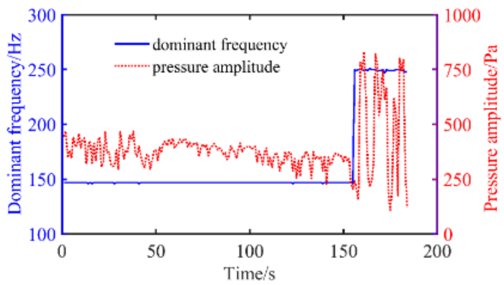
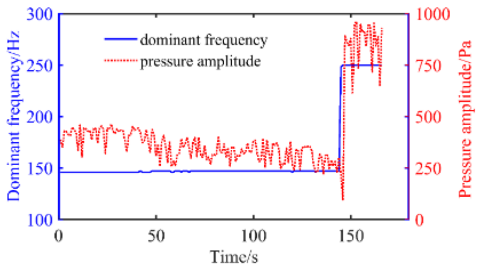


Fig. 9. Dominant amplitude of oscillation pressure (wavelength tube diameter: 10mm).

Fig. 10 shows the variation of pressure amplitude corresponding to dominant frequency for the



(a) Diameter=15mm

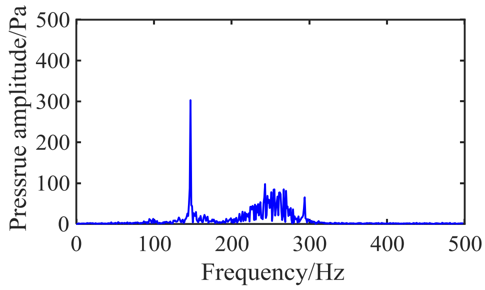


(b) Diameter=20mm

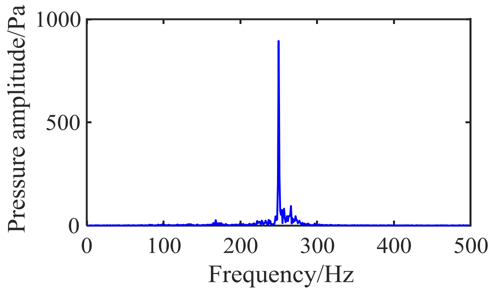
Fig. 10 Effects of wavelength tube on amplitude and frequency of oscillation pressure.

wavelength tubes with diameters of 15mm and 20 mm. The wavelength tubes were installed at 50s, and then, the piston at the end of the wavelength tube was gradually moved to make its dominant frequency close to the dominant frequency of the oscillating pressure. The pressure amplitude decreased until the acoustic suppression efficiency exceeded 20% at 150 s, and then mode transition occurred, that is, the original ~ 150Hz dominant frequency was changed to ~ 250Hz, which corresponded to the dominant frequency of ~235Hz discussed previously. Besides, the increase of the frequency resulted from changes in temperature distribution. When the diameter of the wavelength tube was 20mm, the dominant frequency of combustion instability was completely converted and the amplitude was stable at a high level; when the diameter was 15mm, the dominant frequency of combustion instability still exhibited a switching state, and the amplitude of oscillation pressure fluctuated greatly.

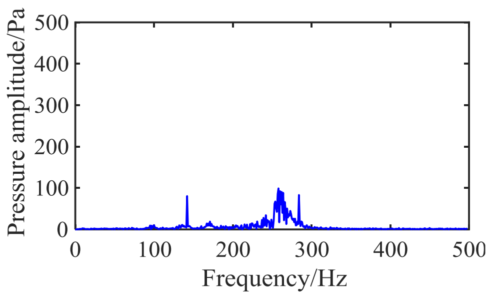
The frequency spectrum analysis of the oscillating pressure without installing the wavelength tube is shown in Fig.11 (a). The oscillation frequency was ~150Hz. Then, the wavelength tube (20mm diameter) was installed and adjusted to a reasonable length, and the ~150Hz oscillation frequency disappeared, when the amplitude corresponding to ~249Hz increased. Fig.11 (b) depicts the spectrum analysis of oscillating pressure. At the same time, another wavelength tube was installed to absorb the oscillation frequency of ~249Hz. The spectrum result of the oscillating pressure is shown in Fig.11 (c), where it can be observed that the two wavelength tubes simultaneously absorbed the oscillating pressure and suppressed the oscillation amplitude below 100Pa. These results show that the wavelength tube is a feasible and efficient passive suppression structure, which can be installed in combination and



(a) Without quarter wavelength tube



(b) With wavelength tube installed to absorb ~ 150Hz dominant frequency

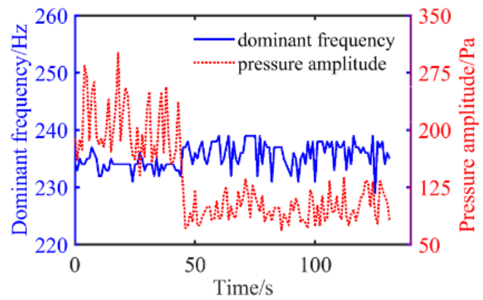


(c) Simultaneously absorb ~ 150Hz and ~ 240Hz dominant frequencies

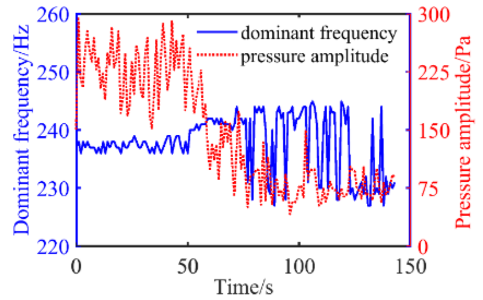
Fig. 11 Amplitude frequency characteristics of oscillating pressure.

can effectively suppress the multi-dominant oscillation frequencies caused by combustion instability.

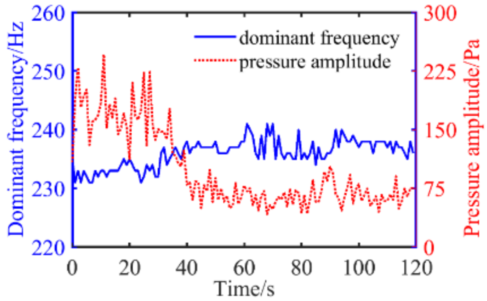
Modal conversion did not occur since the dominant frequency with ~235 Hz was suppressed. The suppression effects on ~235 Hz dominant frequency were also studied in this research. Fig.12 shows the variation of pressure amplitude with different quarter wavelength tubes. The results show that the oscillation amplitude decreases rapidly after the installation of the wavelength tube. It should be noted that the pressure amplitude fluctuation is more obvious after the application of suppression measures, since the installation of quarter wavelength tube affects the acoustic characteristics of the system: the offset dominant frequencies appeared near the original dominant frequency, and the combustion instability switched between the original dominant frequency and the offset dominant frequencies. First, as shown in Fig.12 (a), when the diameter of the wavelength tube was 10 mm, the amplitude decreased rapidly and the dominant frequency fluctuated between 233 Hz and 237 Hz after the installment of the wavelength tube at 50s. 233 Hz is the original dominant frequency, while 237 Hz is the right offset dominant frequency. In the case of the wavelength tube with a diameter of 15mm, the dominant frequency pulsated between the left offset dominant frequency and the right offset dominant frequency, as shown in Fig. 12 (b). With the installment of the wavelength tube with a diameter of 20mm, the dominant frequency of combustion instability stabilized at the right offset dominant frequency, as shown in Fig.12 (c). The diameter of the wavelength tube exerted a significant effect on the frequency pulsation of combustion instability, which was mainly attributed to the influence of wavelength tube on the acoustic resonance frequency of the system. When the diameter of the wavelength tube was small, the acoustic impedance characteristics were obvious, which reduced the suppression efficiency. The suppression efficiency of the wavelength tubes with diameters of 10mm, 15mm and 20mm to the oscillation pressure was 50.6%, 66.4% and 62.2%, respectively. The previous results on acoustic absorption efficiency show that the wavelength tubes with a larger diameter have greater acoustic absorption efficiency, but are not suitable for the suppression of combustion instability. This results from the influence of wavelength tubes on the acoustic characteristics of the system: the combustion instability is stabilized at the right offset dominant frequency after installing the wavelength tube with a diameter of 20mm, while the system still has a large acoustic response, which limits the suppression effects of the wavelength tube on combustion instability. In contrast, the wavelength tube with a diameter of 15mm has a relatively greater suppression efficiency. In conclusion, the diameter selection of wavelength tube needs to be combined with acoustic numerical simulation and combustion instability test for the best suppression effects.



(a) Diameter=10mm



(b) Diameter=15mm



(c) Diameter=20mm

Fig. 12 Effects of wavelength tubes on ~ 237Hz dominant frequency oscillation.

5. Conclusion

The suppression of combustion instability using quarter wavelength tube was studied in detail in this paper using the acoustic numerical simulation and experimental research methods. Firstly, the influence of wavelength tube on the acoustic response of the system was studied using numerical simulation; and then, the acoustic absorption effects of wavelength tube on disturbed acoustic waves was studied, which verified the rationality of suppressing combustion instability under acoustic resonance. The subsequent suppression tests of combustion instability show that wavelength tubes with different diameters can effectively reduce the oscillation intensity, but the oscillation frequency of combustion instability will change after the installment of wavelength tubes, which is mainly attributed to their impacts on the acoustic response of the system. The main conclusions are as follows:

1) The acoustic response of the system changes after the installation of the quarter wavelength tube. The original dominant frequency of the system disappears, but two offset dominant frequencies are added. Compared with the original dominant frequency, the offset dominant frequencies exhibit smaller acoustic response amplitude;

2) The absorption effects of the quarter wavelength tube on disturbed acoustic waves vary greatly: the absorption effects under different amplitudes are relatively stable, and the reduction ratio of acoustic amplitude remains unchanged when the frequency of acoustic waves is fixed. Besides, the acoustic absorption effects of the wavelength tube depend heavily on the acoustic characteristics of the system. In a certain frequency range, it has a large acoustic absorption efficiency near the resonant frequency of the system;

3) The quarter wavelength tube can effectively reduce the oscillation intensity of combustion instability, and the suppression effects are affected by the diameter of the wavelength tube. Given the change of acoustic response of the system after the installment of the wavelength tube, the oscillation frequency of combustion instability fluctuates between the added offset dominant frequencies and the original dominant frequency. When the diameter of the wavelength tube is large, the oscillation frequency of combustion instability can be stabilized at the right offset dominant frequency, thereby

limiting the suppression effects of the wavelength tube on combustion instability. In general, the wavelength tube with smaller or larger diameter fails to work efficiently in the suppression of combustion instability, indicating that the diameter of the wavelength tube should be determined in combination with numerical simulation and experiment to ensure the best suppression effects.

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