Experimental Study on the Effect of Mixing Time on Combustion Stability (Postprint)

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Abstract

Combustion oscillation is a phenomenon arising from the coupling between unstable combustion processes and acoustic waves within a combustion chamber, commonly observed in lean premixed combustors of gas turbines, whose occurrence can readily damage combustor structures and reduce operational lifespan. This study conducts a series of experiments using a model combustor to investigate the influence of fuel-air mixing time on the stability characteristics of swirl premixed combustion. The mixing time is varied by adjusting the premixing length and air flow velocity, while the equivalence ratio is varied to delineate the regimes of combustion oscillation and stable operation. Experimental results reveal that mixing time exerts a significant effect on combustion stability; combustion oscillation can only occur when the mixing time falls within a specific interval, and the equivalence ratio range over which combustion oscillation occurs is also dependent on mixing time. Additionally, this work examines the relationships between combustion oscillation frequency, amplitude, and both equivalence ratio and air flow velocity.

Full Text

Preamble

Title: Experimental Investigation of the Effect of Mixing Time on Combustion Stability

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Abstract: Combustion oscillation is a coupling phenomenon of unsteady combustion and acoustic waves in combustors, which is common in lean premixed combustors of gas turbines. The occurrence of combustion oscillation can damage combustor structures and shorten their operation lifetime. In this paper, the effect of fuel-air mixing time on the stabilization of swirling premixed combustion was investigated through a series of experiments conducted in a model combustor. In the experiments, mixing time was changed by varying premixing lengths and airflow velocities. Experiments with different equivalence ratios were conducted to obtain the ranges of combustion oscillation and stable combustion. Experimental results indicate that fuel-air mixing time has a significant effect on combustion stabilization. Combustion oscillation can only occur when mixing time is within certain ranges. The range of equivalence ratio in which combustion oscillation can occur is also related to mixing time. The influence of equivalence ratio and airflow velocity on the frequency and amplitude of combustion oscillation was also studied in this paper.

Keywords: Mixing time; Equivalence ratio; Swirling premixed combustion; Combustion oscillation

Introduction

With increasingly prominent atmospheric environmental issues, countries worldwide have imposed stricter requirements on pollutant emissions from gas turbine power plants. In gas turbines fueled by natural gas, nitrogen oxides (NOx) and carbon monoxide (CO) are the two primary pollutants, with NOx emissions being more difficult to control. During high-temperature combustion of natural gas, NOx is generated mainly through the thermal mechanism, formed by the oxidation of nitrogen (N) in air. This becomes significant at temperatures above 1800 K and increases exponentially with temperature. Earlier gas turbines typically employed diffusion combustion, which offers good stability but produces large amounts of thermal NOx due to high combustion temperatures, failing to meet current emission standards. To reduce NOx emissions from gas turbines, various novel combustion technologies have been proposed, among which lean premixed combustion is the most widely adopted.

In lean premixed combustion, fuel mixes with excess air in a premixing device before entering the combustion chamber together for combustion. This approach effectively reduces combustion temperature, making it possible to reduce NOx through combustion process design. However, a common problem with this combustion mode is the tendency for combustion oscillation. Also known as "thermoacoustic oscillation" or "combustion instability," combustion oscillation is a periodic phenomenon formed by the interaction between heat release rate fluctuations and pressure pulsations and their propagation and reflection in the combustion chamber. When combustion oscillation occurs, the heat release rate and combustion chamber pressure vary periodically, accompanied by high-intensity combustion noise at specific frequencies. These heat release fluctuations can lead to local high temperatures and incomplete combustion, increasing pollutant emissions, while high-intensity pressure pulsations may also damage combustor structures.

In 1878, Rayleigh [1] first provided a qualitative explanation of the combustion oscillation mechanism, known as the "Rayleigh Criterion," which is widely used for combustion oscillation prediction and analysis. The Rayleigh Criterion states that when heat release rate fluctuation (q') and pressure fluctuation (p') coexist in a combustion chamber, and the phase difference between q' and p' in the combustion zone is less than 90°, the heat released by unstable combustion will be transferred to the pressure pulsation. If this energy exceeds the total energy dissipated by the pressure pulsation at various boundaries, the pressure pulsation will be continuously amplified until equilibrium is reached, causing combustion oscillation. Conversely, when the phase difference between q' and p' in the combustion zone exceeds 90°, combustion oscillation cannot occur. While the Rayleigh Criterion describes the conditions for combustion oscillation, it does not specify under what circumstances the phase difference between p' and q' will be less than 90°, and therefore cannot be used to predict whether combustion oscillation will occur in specific situations.

The mechanism of combustion oscillation is extremely complex, involving flow pulsations, acoustic wave propagation, flame front fluctuations, equivalence ratio pulsations, and other factors. These factors often act together rather than independently, and the key factors affecting combustion stability may differ in combustors with different structures, making prediction of combustion oscillation very difficult. A fundamental explanation for combustion oscillation is that when the equivalence ratio or flow velocity in the combustion chamber fluctuates, the flame front and heat release rate will pulsate. The heat release rate fluctuations cause pressure fluctuations in the combustion chamber, which propagate and reflect, further promoting flow velocity or equivalence ratio fluctuations, forming a positive feedback loop until limit cycle oscillation is reached [2].

Studies by Lieuwen [3] and Auer [4] have shown that equivalence ratio fluctuations in the fuel-air mixture significantly affect the dynamic characteristics of premixed flames and are important factors leading to combustion oscillation. In swirl-stabilized dump combustors, flow separation creates corner vortices due to the sudden expansion, while a central recirculation zone forms under the swirl effect. Kashan et al. [5] and Rogers et al. [6] respectively proposed theories that turbulent vortex shedding is also a driving factor for combustion oscillation, which has been confirmed by many researchers. The premixing process of fuel and air before combustion determines equivalence ratio fluctuations, and mixing time affects the phase of equivalence ratio pulsations, thereby influencing the phase of heat release rate pulsations. Therefore, mixing time may be a crucial factor in determining whether combustion oscillation can occur. In this paper, mixing time refers to the time required for fuel to travel from the injection nozzle to the flame front. Cho and Lieuwen [7] found that the response time of heat release rate pulsations to velocity and equivalence ratio fluctuations is closely related to mixing time. Lieuwen et al. [8] proposed a simple model for the effect of mixing time on combustion stability, qualitatively determining the ranges of mixing time for combustion oscillation and stable combustion, with specific values depending on combustor structure and boundary conditions at the fuel injection location. Lee et al. [9], when studying active control of combustion oscillation through secondary fuel injection, found that the time delay of secondary fuel injection relative to combustion chamber pressure pulsation significantly affects control effectiveness, and that this effect is non-monotonic. Richards and Janus [10] and Steele et al. [11] experimentally studied the effect of mixing time on combustion stability, finding that combustion becomes unstable when mixing time falls within a certain range and stable outside this range, though the ranges obtained differed significantly. Existing studies on the effect of mixing time on combustion stability show considerable discrepancies and have not yet established universally applicable 规律. This paper investigates the effect of mixing time ( ) on combustion stability through multiple experiments with different mixing lengths (Lp), equivalence ratios ( ), and airflow velocities (v). The first part of the paper introduces the experimental system and methods, while the second part presents the experimental results.

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1 Experimental System and Measurement Techniques

The experimental system used in this study is shown in [Figure 1: see original paper]. The main component of the test rig is a model combustor equipped with flame observation windows, supplemented by compressed air systems, fuel gas systems, cooling water circulation systems, exhaust systems, control systems, and data acquisition systems. The model combustor structure is illustrated in [Figure 2: see original paper]. Fuel and air mix in the premixing section before entering the combustion chamber for combustion, with combustion products discharged through a contracted outlet. The combustor features a double-walled structure with circulating water cooling between the walls. A quartz glass observation window at the upstream end enables flame shape observation and heat release rate fluctuation signal measurement. To cover a wide range of mixing times, two premixing sections with different lengths (Lp = 2.5 cm and Lp = 10 cm) were designed. Except for the mixing length, all other structural parameters were identical. The shorter premixing device is shown in [Figure 3: see original paper]. The premixing length Lp is defined as the distance from the fuel nozzle outlet to the premixing section outlet. In the premixing device, air passes through swirl vanes and merges with natural gas injected from the fuel nozzle, entering the combustion chamber in a swirling flow. The axial swirler uses three-dimensional twisted blades with a swirl number of approximately 0.9. The nozzle employs a 5-tube × 6-hole design, with natural gas injected co-flow into the air stream. The five tubes are uniformly distributed circumferentially, with injection holes gradually becoming denser from inner to outer sections to achieve as uniform a natural gas distribution as possible across the cross-section and improve mixing effectiveness.

Pressure fluctuation signals were measured using the semi-infinite tube method to eliminate resonance effects from wall cavities and improve measurement accuracy. Since the high temperature inside the combustion chamber prevents direct placement of pressure sensors on the combustor wall, pressure was first extracted through pressure transmission tubes vertically installed at measurement points. These tubes were equipped with cooling water jackets to reduce the internal temperature to within the sensor' s operating range. The upper end of each transmission tube connected to a T-joint, with a dynamic pressure sensor mounted on one end such that the sensor' s pressure-sensing head was flush with the tube inner wall. The other end of the T-joint connected to a flexible hose. Heat release rate fluctuations were measured using chemiluminescence spectroscopy, implemented with a grating spectrometer and photomultiplier tubes. During natural gas combustion, multiple radicals are produced, among which OH radical concentration is suitable for characterizing heat release rate magnitude. Therefore, this experiment measured the intensity signal of OH radical chemiluminescence (wavelength 309 nm) to represent heat release rate fluctuations. Additionally, a high-speed camera captured flame structure variations during combustion to assist in analyzing combustion oscillation phenomena.

Experiments were designed for two premixing sections with different mixing lengths, covering multiple groups of fuel flow velocities (represented by average air flow velocity). For each air velocity, different equivalence ratios were obtained by adjusting natural gas flow rate, and pressure pulsations and heat release rate pulsations were measured to analyze combustion stability. Finally, the influence 规律 of mixing time ( ) on combustion stability was obtained.

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2 Results and Analysis

2.1 Combustion Mode Analysis

The experimental conditions designed for the short and long premixing sections are shown in and , respectively, where fc represents the pressure pulsation frequency in the combustion chamber and fc is a dimensionless number that reflects the effect of mixing time without being constrained by specific mixing times or oscillation frequencies, thus having broader applicability. The characteristic frequency of pressure pulsation in this combustor is approximately 500 Hz, so fc = 500 Hz was used in calculating fc for the experimental design.

Two distinct combustion modes were observed in the experiments: high-frequency oscillation and stable combustion. During stable combustion, the flame zone remained essentially unchanged with only small random fluctuations of the flame front, accompanied by no significant combustion noise and small p' amplitude. The dominant frequencies of pressure and heat release rate pulsations differed (generally, heat release rate pulsation showed no obvious dominant frequency), with pressure pulsation frequency being either high (around 500 Hz) or low (100 Hz and below). When combustion oscillation occurred, both the flame zone and flame front position exhibited large-amplitude periodic fluctuations with intense noise, large p' amplitude, and identical dominant frequencies for pressure and heat release rate pulsations. In this experiment, the oscillation frequency was around 500 Hz.

Taking several cases at v = 40 m/s on the long premixing section as examples, both combustion oscillation and stable combustion modes existed at different equivalence ratios. At = 0.92, combustion oscillation occurred. As shown in [Figure 4: see original paper], the measured p' and q' signals had a constant phase difference, with a total pressure pulsation amplitude of approximately 6000 Pa (6% of mean pressure), indicating coupling between heat and sound and confirming combustion oscillation. Since the pressure measurement location differed from the heat release rate measurement location, and the response times of the dynamic pressure sensor and spectrometer were different, [Figure 4: see original paper] cannot provide the accurate phase difference between p' and q' at a specific location. To further analyze the spectral characteristics of p' and q' , Fast Fourier Transform (FFT) was applied to obtain their frequency domain distributions, shown in [Figure 5: see original paper] and [Figure 6: see original paper]. Both p' and q' exhibit a dominant frequency of 510 Hz, confirming their coupling and proving combustion oscillation occurrence. Since q' measurement involved photoelectric conversion and intermediate amplification, its values only represent relative magnitude of heat release rate fluctuations, whereas p' values represent actual pressure pulsations at the dynamic pressure sensor location with physical significance. [Figure 5: see original paper] shows that in this high-frequency oscillation, the 510 Hz pressure pulsation amplitude is approximately 4500 Pa. With a mean combustion chamber pressure of about 1 atm (101 kPa), the p' amplitude exceeds 4% of the mean pressure.

High-speed camera images of flame shapes during high-frequency oscillation over one period are shown in [Figure 7: see original paper]. The images reveal large-amplitude periodic axial fluctuations of flame shape during high-frequency combustion oscillation, with a pulsation frequency identical to p' and q' at approximately 2 ms. During one pulsation period, the flame root remained at the premixing section outlet position, but the flame shape changed significantly, corresponding to variations in the main flame zone. Periodic pressure pulsations caused flow velocity fluctuations in the combustion chamber, continuously changing the relative magnitude between flame propagation speed and gas flow velocity, leading to periodic flame front position variations. These flame position changes caused heat release rate pulsations, which coupled with pressure pulsations to sustain the oscillation.

In contrast to the combustion oscillation state, when the equivalence ratio decreased below 0.8, high-frequency oscillation disappeared and combustion became stable. The characteristics of p' and q' at = 0.73 are shown in [Figure 8: see original paper] through [Figure 10: see original paper]. [Figure 8: see original paper] shows that both p' and q' exhibited random fluctuation characteristics without a definite phase difference, with instantaneous p' maximum values of only about 500 Pa (less than 1% of mean pressure). FFT results ([Figure 9: see original paper] and [Figure 10: see original paper]) reveal that under stable combustion, heat release rate pulsation showed no obvious dominant frequency, while pressure pulsation exhibited both a low-frequency (21 Hz) peak and a high-frequency (497 Hz) peak in the frequency domain, both with small amplitudes below 100 Pa. This indicates no coupling between p' and q' and no combustion oscillation. [Figure 9: see original paper] shows that under stable combustion, pressure pulsation contained more low-frequency components but still exhibited a high-frequency peak near 500 Hz. This distribution appeared in all stable combustion cases, indicating that 500 Hz is a characteristic frequency of this combustor.

High-speed camera images of flame shapes during one characteristic period (2 ms) under stable combustion are shown in [Figure 11: see original paper]. Compared with images from high-frequency oscillation cases, these images appear overall darker, partly because lower equivalence ratios produce lower flame temperatures and overall brightness, and partly because minimal flame shape variation results in small brightness changes detectable by the high-speed camera. [Figure 11: see original paper] shows that during stable combustion, the flame front position exhibited only small, non-periodic fluctuations with a basically fixed flame zone. Under these conditions, small-amplitude pressure pulsations propagated, reflected, and attenuated in the combustion chamber, creating an initial pressure pulsation distribution. However, since p' and q' were not coupled, pressure pulsations were not amplified and flame shape changes were less affected by pressure pulsations, showing small random fluctuation characteristics.

Experimental results show that both equivalence ratio and airflow velocity significantly affect the frequency and amplitude of p' , with the influence 规律 of airflow velocity differing between premixing sections of different lengths. Based on experimental phenomena and data analysis, a p' amplitude greater than 1000 Pa was adopted as the criterion for combustion oscillation. The distributions of p' dominant frequency and amplitude are shown in [Figure 12: see original paper] and [Figure 13: see original paper].

[Figure 13: see original paper] shows that combustion oscillation only occurs in the region where > 0.8, and the equivalence ratio range for combustion oscillation differs under different airflow velocities and premixing lengths. [FIGURE:13(a)] indicates that on the short premixing section (Lp = 2.5 cm), no combustion oscillation occurred at v = 40 m/s and v = 25 m/s, while at v = 20 m/s, combustion oscillation only occurred at = 1.03. In contrast, on the long premixing section (Lp = 10 cm), no combustion oscillation occurred at v = 20 m/s, only at = 0.92 for v = 25 m/s, while at v = 40 m/s, combustion oscillation occurred at = 0.82, 0.92, and 0.98. These differences indicate that different airflow velocities correspond to combustion oscillation for different premixing lengths, but these differences can be unified using mixing time, as discussed in Section 2.3.

On the long premixing section, besides the cases at v = 20, 25, and 40 m/s, combustion stability was also studied at several other airflow velocities, as shown in [FIGURE:13(b)]. On the long premixing section, combustion oscillation is less likely to occur at low flow velocities. For example, at v = 25 m/s, combustion oscillation only occurred at = 0.92 among five equivalence ratios. When flow velocity was between 30-50 m/s, combustion oscillation occurred for equivalence ratios between 0.82-1.03. At v = 80 m/s, combustion oscillation only occurred at equivalence ratios above 0.9. These trends indicate that with the same premixing length, as airflow velocity increases, the equivalence ratio range for combustion oscillation first gradually expands and then shrinks. Combined with comparison to the short premixing section, this demonstrates that mixing time is an important factor affecting combustion stability.

Comparing [Figure 12: see original paper] and [Figure 13: see original paper] reveals that when combustion oscillation occurs, the dominant frequency of p' is always near 500 Hz. During stable combustion, the dominant frequency of p'may be either high frequency near 500 Hz or low frequency below 100 Hz. However, as described in Section 2.1, even when the maximum p' amplitude appears at low frequency, a pulsation peak still appears at high frequency, indicating that the characteristic frequency of this combustor is around 500 Hz.

2.3 Role of Mixing Time

Comparative analysis of multiple operating conditions demonstrates that fuel-air mixing time before combustion significantly affects combustion stability. Since air flow rate is much larger than natural gas flow rate, the axial average velocity of the air stream was used to calculate mixing time in this study. Mixing time ( ) affects the phase relationship between p' and q' . If the dominant pressure pulsation frequency (fc) differs, the mixing time at which combustion oscillation occurs also differs. To improve applicability, the dimensionless number fc can be used to represent the effect of mixing time on combustion stability. As mentioned, the characteristic frequency of this combustor is around 500 Hz, so the high-frequency peak frequency of p' was used for fc in calculations.

The combustion stability distribution expressed in terms of dimensionless fc and equivalence ratio is shown in [Figure 16: see original paper]. [Figure 16: see original paper] shows that combustion oscillation only occurs in the region where > 0.8 for both long and short premixing sections. Good consistency in combustion stability between the two premixing lengths appears at fc 0.6, where the equivalence ratio range for combustion oscillation tends to narrow compared to cases with fc > 0.6. This indicates that mixing time is a more fundamental influencing factor than flow velocity and mixing length. Overall, combustion oscillation only occurs in the interval 0.5 < fc < 2, and the closer to the boundaries, the smaller the equivalence ratio range for combustion oscillation and the less likely combustion oscillation becomes.

[Figure 17: see original paper] shows the combustion stability distribution with p' amplitude as the vertical axis and fc as the horizontal axis. The circles represent experimental operating points. With 1000 Pa as the boundary, the fc interval for combustion oscillation can be clearly identified as (0.5, 2). Moreover, smaller fc values correspond to larger possible oscillation amplitudes because higher flow rates mean greater thermal power and more energy available to amplify pressure pulsations.

The experiments identified the fc interval for combustion oscillation as (0.5, 2), with stable combustion maintained outside this interval. However, due to experimental limitations, the position of the next oscillation interval could not be determined. Since mixing time affects the phase of heat release rate, and combustion oscillation occurrence depends on the phase difference between p' and q' , and because fc reflects the period of p' , the fc intervals for combustion oscillation should appear periodically. If we assume (+) represents the phase of q' (where   is chemical reaction time), theoretically the period should be 1, which contradicts experimental results.

The experimentally observed single oscillation interval length of approximately 1.5 exceeds the theoretical repetition period. This discrepancy arises partly from simplified treatment and partly from the complexity of combustion oscillation mechanisms. First, in time-delay models, the time delay of heat release rate pulsation response to pressure pulsation includes: pressure pulsation propagation time upstream to the fuel nozzle, response time for pressure pulsation to cause equivalence ratio pulsation at the nozzle, convection mixing time for equivalence ratio pulsation to travel from nozzle to flame front, and chemical reaction time. Only mixing time was considered here, neglecting possible variations in other time delays. Second, the true meaning of mixing time is the time required for fuel to travel from the nozzle to the flame front. This experiment involved two simplifications: (1) using the average axial velocity of the air stream to approximate fuel velocity, and (2) since the flame front position relative to the premixing section outlet continuously varied and was inconvenient for data processing, the premixing distance was simplified as the distance from fuel nozzle to premixing section outlet, neglecting the distance from premixing section outlet to flame front, affecting mixing time calculation accuracy. Finally, time-delay models are based on pressure pulsation effects on equivalence ratio pulsation, which then affects heat release rate pulsation, causing combustion oscillation. In actual combustion processes, the mechanism of combustion oscillation is extremely complex and not yet fully understood. Therefore, combustion oscillation observed in experiments may result from the combined action of this mechanism and other mechanisms, such as vortex shedding affecting combustion within vortices to excite combustion oscillation.

Although the experimentally obtained combustion oscillation interval deviates from simplified time-delay model predictions, the results still reflect the important influence of mixing time on combustion stability. The fact that combustion oscillation only occurs within a certain mixing time range suggests that reducing or avoiding combustion oscillation through combustor structural design modifications is possible. On the other hand, differences between experimental results and theoretical predictions also reflect that current understanding of combustion oscillation mechanisms remains immature and requires continued efforts from the academic community.

Conclusions

This study experimentally investigated the relationship between mixing time and swirling premixed combustion stability by varying premixing length, airflow velocity, and equivalence ratio. The following conclusions were obtained:

(1) Mixing time significantly affects whether combustion oscillation occurs. Combustion oscillation can only occur when mixing time is within a certain range, and the closer to the interval boundaries, the smaller the equivalence ratio range for combustion oscillation.

(2) When combustion oscillation occurs, the oscillation dominant frequency increases with equivalence ratio at the same flow velocity because higher equivalence ratios increase combustion temperature and sound speed.

(3) If combustion oscillation can occur, larger airflow velocities correspond to greater overall thermal power, resulting in larger maximum oscillation amplitudes when varying equivalence ratio.

(4) In this combustor, combustion oscillation only occurs when > 0.8. At low equivalence ratios, the energy transferred from pulsating combustion to pressure pulsations is lower than the energy dissipated at boundaries, insufficient to excite combustion oscillation.

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Note: Figure translations are in progress. See original paper for figures.