

## Postprint: Experimental Study on the Effect of Mixing Time on Combustion Stability

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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 regimes of combustion oscillation and stability are mapped by varying the equivalence ratio. Experimental results reveal that mixing time exerts a significant influence on combustion stability; combustion oscillations only occur when the mixing time falls within a specific interval, and the equivalence ratio range over which combustion oscillations occur is also dependent on mixing time. Additionally, this work examines the relationships between combustion oscillation frequency and amplitude with respect to equivalence ratio and air flow velocity.

### Full Text

#### Preamble

With increasingly prominent atmospheric environmental issues, countries worldwide have implemented increasingly stringent emission standards for gas turbine power plants. In gas turbines fueled by natural gas, nitrogen oxides (NO<sub>x</sub>) and carbon monoxide (CO) represent the two primary pollutants, with NO<sub>x</sub> emissions being particularly challenging to control. During high-temperature combustion of natural gas, NO<sub>x</sub> formation is dominated by the thermal mechanism, generated through oxidation of atmospheric nitrogen (N<sub>2</sub>). This process becomes significant above 1800 K and increases exponentially with temperature. Earlier gas turbines typically employed diffusion combustion, which offered good

stability but produced substantial thermal NO<sub>x</sub> due to high combustion temperatures, failing to meet current emission standards. To reduce NO<sub>x</sub> emissions from gas turbines, numerous advanced combustion technologies have been proposed, with lean premixed combustion being the most widely adopted.

In lean premixed combustion, fuel mixes with excess air in a premixing device before entering the combustion chamber together. This approach effectively reduces combustion temperature, making it possible to control NO<sub>x</sub> through combustion process management. However, a common issue with this combustion mode is its susceptibility to combustion oscillation. Also known as “thermoacoustic oscillation” or “combustion instability,” this phenomenon arises from the interaction between heat release rate fluctuations and pressure oscillations and their propagation and reflection within the combustor, forming a periodic cycle. During combustion oscillation, both heat release rate and combustor 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 oscillations may also damage combustor structures.

In 1878, Rayleigh [1] first provided a qualitative explanation of combustion oscillation mechanisms, known as the “Rayleigh Criterion,” which has been widely used for diagnosing and analyzing combustion oscillations. The criterion states that when heat release rate fluctuations ( $q'$ ) and pressure fluctuations ( $p'$ ) coexist in a combustor, and their phase difference in the combustion zone is less than 90°, the energy from unsteady combustion transfers to pressure oscillations. If this energy exceeds the total energy dissipated at all boundaries, pressure oscillations are continuously amplified until reaching equilibrium, resulting in combustion oscillation. Conversely, when the phase difference exceeds 90°, combustion oscillation cannot occur. While the Rayleigh Criterion describes the conditions for combustion oscillation, it does not specify when the phase difference between  $p'$  and  $q'$  will be less than 90°, making it unsuitable for predicting whether 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 elements do not act in isolation but often interact collectively, and the key factors affecting combustion stability may differ across combustor geometries, making prediction of combustion oscillation occurrence highly challenging. A fundamental explanation for combustion oscillation suggests that fluctuations in equivalence ratio or combustor flow velocity cause flame front and heat release rate pulsations. These heat release fluctuations induce pressure oscillations in the combustor, which propagate and reflect, further promoting flow velocity or equivalence ratio fluctuations, thereby forming a positive feedback loop until limit-cycle oscillation is achieved [2].

Studies by Lieuwen [3] and Auer [4] have demonstrated that equivalence ratio fluctuations in the fuel-air mixture significantly affect the dynamic characteristics of premixed flames and constitute an important factor leading to combustion

oscillation. In swirl-stabilized dump combustors, flow expansion at the dump plane generates corner vortices, while swirl effects create a central recirculation zone. Kashan et al. [5] and Rogers et al. [6] respectively proposed theories that turbulent vortex shedding also drives combustion oscillation, which has been confirmed by numerous researchers. The premixing process of fuel and air before combustion determines equivalence ratio fluctuations, and mixing time influences the phase of these fluctuations, thereby affecting the phase of heat release rate pulsations. Consequently, mixing time may be a critical factor determining whether combustion oscillation occurs. In this paper, “mixing time” refers to the time required for fuel to travel from the injection port to the flame front. Research by Cho and Lieuwen [7] found that the response time of heat release rate fluctuations 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 identifying the mixing time intervals for combustion oscillation and stable combustion, with specific interval values depending on combustor geometry and boundary conditions at the fuel injection port. Lee et al. [9], when studying active control of combustion oscillation through secondary fuel injection, discovered that the time delay of secondary fuel injection relative to combustor pressure fluctuations significantly affected control effectiveness, and that this relationship was non-monotonic. Richards and Janus [10] and Steele et al. [11] experimentally investigated the influence of mixing time on combustion stability, finding that combustion became unstable when mixing time fell within a certain range and stable outside this range, though the identified interval ranges differed substantially. Existing studies on mixing time effects exhibit considerable discrepancies and have yet to establish universally applicable principles. This paper investigates the influence of mixing time ( $\tau$ ) on combustion stability through multiple experiments with different premixing lengths ( $L_p$ ), equivalence ratios ( $\phi$ ), and airflow velocities ( $v$ ). The first part of the paper introduces the experimental system and methodology, while the second part presents and discusses the experimental results.

## 1 Experimental and Measurement System

The experimental system used in this study is shown in [Figure 1: see original paper]. The main component 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], where fuel and air mix in the premixing section before entering the combustion chamber, with combustion products discharged through a converging 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 measurements. To cover a wide range of mixing times, two premixing sections with different lengths ( $L_p = 2.5$  cm and  $L_p = 10$  cm) were designed. Except

for their mixing lengths, both sections were structurally identical. The shorter premixing device is shown in [Figure 3: see original paper]. The premixing length  $L_p$  was defined as the distance from the fuel nozzle exit to the premixing section exit. In the premixing device, air passes through swirl vanes before merging with natural gas injected from the fuel nozzle, entering the combustion chamber in a swirling flow. The axial swirler employs three-dimensional twisted blades with a swirl number of approximately 0.9. The nozzle features a 5-tube  $\times$  6-hole design, with natural gas injected co-flow into the airstream. The five tubes are circumferentially uniformly distributed, with hole density increasing from inner to outer tubes to achieve as uniform a natural gas distribution across the cross-section as possible, thereby improving mixing quality.

Pressure fluctuation measurements employed the semi-infinite tube method to eliminate resonance effects from wall cavities and improve measurement accuracy. Since direct placement of pressure sensors on combustor walls was impossible due to high temperatures, pressure was first extracted through pressure transmission tubes vertically installed at measurement points. Cooling jackets surrounding these tubes reduced internal temperatures to within the sensor's operating range. The upper end of each transmission tube connected to a T-junction, 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-junction connected to a flexible hose. Heat release rate fluctuations were measured using chemiluminescence, implemented through a grating spectrometer and photomultiplier tubes. Natural gas combustion produces various radicals, among which OH radical concentration is suitable for characterizing heat release rate magnitude. Therefore, this experiment measured OH radical chemiluminescence intensity signals (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 the two premixing sections with different lengths, covering multiple air velocity conditions (represented by average air velocity). At each air velocity, natural gas flow rate was adjusted to obtain different equivalence ratios, and pressure and heat release rate fluctuations were measured to analyze combustion stability. The results ultimately reveal the influence of mixing time ( $\tau$ ) on combustion stability.

## 2.1 Combustion Mode Analysis

Tables 1 and 2 present the experimental conditions for the short and long premixing sections, respectively. Here,  $f_c$  represents the frequency of pressure fluctuations in the combustor, and  $\tau f_c$  is a dimensionless number that reflects mixing time effects while being independent of specific mixing times and oscillation frequencies, thus offering broader applicability. The characteristic frequency of pressure fluctuations in this combustor is approximately 500 Hz, so  $f_c = 500$  Hz was used in the calculation of  $\tau f_c$  for experimental design purposes.

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 at the flame front, accompanied by no significant combustion noise and low  $p'$  amplitude. The dominant frequencies of pressure and heat release rate fluctuations differed (typically, heat release rate fluctuations showed no clear dominant frequency), with pressure fluctuation frequencies being either high (around 500 Hz) or low (100 Hz and below). During combustion oscillation, both the flame zone and flame front position exhibited large-amplitude periodic fluctuations with intense noise, and  $p'$  amplitude was substantial. Pressure and heat release rate fluctuations shared the same dominant frequency, which was approximately 500 Hz in these experiments.

Taking several cases at  $v = 40$  m/s with the long premixing section as examples, both combustion oscillation and stable combustion modes existed at different equivalence ratios. At  $\phi = 0.92$ , combustion oscillation occurred. As shown in [Figure 4: see original paper], the measured  $p'$  and  $q'$  signals maintained a constant phase difference, with total pressure fluctuation amplitude of approximately 6000 Pa (6% of mean pressure), indicating coupling between heat and acoustics. Due to different measurement locations for pressure and heat release rate signals, and different response times between the dynamic pressure sensor and spectrometer, [Figure 4: see original paper] cannot provide the exact 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 primary frequency of 510 Hz, confirming their coupling and demonstrating combustion oscillation. Since  $q'$  measurement employed photoelectric conversion and intermediate amplification, its values only represent relative heat release rate fluctuation magnitude, whereas  $p'$  values represent actual pressure fluctuations measured by the dynamic pressure sensor and possess physical significance. [Figure 5: see original paper] shows that in this high-frequency oscillation, the 510 Hz pressure fluctuation amplitude is approximately 4500 Pa. With a mean combustor pressure of about 1 atm (101 kPa), the  $p'$  amplitude exceeds 4% of the mean pressure.

High-speed camera images of flame shapes during one period of high-frequency oscillation are shown in [Figure 7: see original paper], revealing large-amplitude periodic axial fluctuations in flame shape at the same frequency as  $p'$  and  $q'$  (approximately 2 ms). During one oscillation period, the flame root remained at the premixing section exit, but the flame shape changed significantly, corresponding to variations in the main flame zone. Periodic pressure fluctuations caused flow velocity pulsations in the combustor, continuously altering the relative magnitude between flame propagation speed and gas flow velocity, resulting in periodic flame front position changes. These flame position variations in turn caused heat release rate fluctuations, which coupled with pressure fluctuations to sustain the oscillation.

In contrast to the oscillating state described above, when the equivalence ratio decreased below 0.8, high-frequency oscillations disappeared and combustion became stable. The characteristics of  $p'$  and  $q'$  at  $\phi = 0.73$  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 fluctuations without a definite phase difference, with instantaneous  $p'$  maxima of only about 500 Pa (less than 1% of mean combustor pressure). FFT results ([Figure 9: see original paper] and [Figure 10: see original paper]) reveal that under stable combustion, heat release rate fluctuations showed no clear dominant frequency, while pressure fluctuations 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 thus no combustion oscillation. [Figure 9: see original paper] shows that under stable combustion, pressure fluctuations contain more low-frequency components but still exhibit a high-frequency peak near 500 Hz. This distribution pattern appears in other stable combustion cases, indicating that 500 Hz is a characteristic frequency of this combustor.

Flame shape images captured by high-speed camera during one characteristic period (2 ms) under stable combustion are shown in [Figure 11: see original paper]. Compared with high-frequency oscillation cases, these images appear darker overall, partly because lower equivalence ratios produce lower flame temperatures and brightness, and partly because minimal flame shape variation results in small perceived brightness changes by the high-speed camera. [Figure 11: see original paper] shows that during stable combustion, the flame front position exhibits only small, non-periodic fluctuations with a relatively fixed flame zone. Under these conditions, small pressure fluctuations propagate, reflect, and attenuate within the combustor, creating an initial pressure distribution. However, since  $p'$  and  $q'$  are not coupled, pressure fluctuations are not amplified, and flame shape variations show small random fluctuations with minimal influence from pressure pulsations.

## 2.2 Influence of Equivalence Ratio and Flow Velocity

Experimental results demonstrate that both equivalence ratio and airflow velocity significantly affect the frequency and amplitude of  $p'$ . The influence patterns differ between premixing sections of different lengths. Based on experimental observations 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 at equivalence ratios greater than 0.8, with the specific range varying with airflow velocity and premixing length. [FIGURE:13(a)] indicates that with the short premixing section ( $L_p = 2.5$  cm), no combustion oscillation occurs at  $v = 40$  m/s or  $v = 25$  m/s, while at  $v = 20$  m/s, oscillation only appears at  $\phi = 1.03$ .

In contrast, with the long premixing section ( $L_p = 10$  cm), no oscillation occurs at  $v = 20$  m/s, oscillation only appears at  $\phi = 0.92$  at  $v = 25$  m/s, but at  $v = 40$  m/s, oscillation occurs at  $\phi = 0.82, 0.92,$  and  $0.98$ . These differences indicate that different premixing lengths correspond to different airflow velocities for combustion oscillation, and these differences can be unified through mixing time, as discussed in Section 2.3.

Additional airflow velocities were studied with the long premixing section, as shown in [FIGURE:13(b)]. At low velocities ( $v = 25$  m/s), combustion oscillation only occurs at  $\phi = 0.92$  among the five equivalence ratios tested. When velocity increases to 30-50 m/s, oscillation occurs across equivalence ratios from 0.82 to 1.03. At  $v = 80$  m/s, oscillation only appears 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 expands and then contracts. Combined with comparisons to the short premixing section, this demonstrates that mixing time is a crucial factor affecting combustion stability.

Comparison between [Figure 12: see original paper] and [Figure 13: see original paper] reveals that during combustion oscillation, the dominant frequency of  $p'$  always remains near 500 Hz. During stable combustion, the dominant frequency may be either the high frequency near 500 Hz or low frequencies below 100 Hz. However, as described in Section 2.1, even when the maximum  $p'$  amplitude appears at low frequencies, a high-frequency peak still emerges, confirming that the characteristic frequency of this combustor is approximately 500 Hz.

With the long premixing section, numerous oscillation cases were observed, revealing differences among various oscillation conditions. [Figure 14: see original paper] and [Figure 15: see original paper] show the variation of  $p'$  dominant frequency and amplitude with equivalence ratio under oscillating conditions. [Figure 14: see original paper] indicates that at constant airflow velocity, oscillation frequency increases with equivalence ratio. For velocities between 30-50 m/s, frequency increases with velocity, but shows a decreasing trend before reaching 80 m/s. [Figure 15: see original paper] shows that the equivalence ratio at which maximum oscillation amplitude occurs varies with airflow velocity, appearing at  $\phi = 0.82, 0.95,$  or  $1.02$ . However, comparing maximum values along each constant-velocity line reveals that higher airflow velocities produce larger possible maximum oscillation amplitudes, because higher flow rates correspond to greater thermal power, providing more energy to amplify pressure fluctuations.

## 2.3 Role of Mixing Time

Multi-condition comparative analysis demonstrates that fuel-air mixing time before combustion significantly affects combustion stability. Since air flow rate far exceeds natural gas flow rate, the axial average velocity of the airflow was used to calculate mixing time in this study. Mixing time ( $\tau$ ) influences the

phase relationship between  $p'$  and  $q'$ . If the dominant pressure fluctuation frequency ( $f_c$ ) differs, the mixing time at which combustion oscillation occurs also differs. To enhance applicability, the dimensionless number  $\tau f_c$  can be used to represent mixing time effects on combustion stability. As previously mentioned, the characteristic frequency of this combustor is the high frequency around 500 Hz, so the high-frequency peak frequency of  $p'$  was used to calculate  $f_c$ . The combustion stability distribution expressed in terms of the dimensionless number  $\tau f_c$  and equivalence ratio  $\phi$  is shown in [Figure 16: see original paper].

[Figure 16: see original paper] shows that combustion oscillation only occurs in the region where  $\phi > 0.8$  for both premixing sections. Good consistency in combustion stability between the two premixing lengths appears near  $\tau f_c = 0.6$ , where the equivalence ratio range for combustion oscillation tends to narrow compared to cases with  $\tau f_c > 0.6$ . This indicates that mixing time is a more fundamental influencing factor than flow velocity or mixing length. Overall, combustion oscillation only occurs within the interval  $0.5 < \tau f_c < 2$ , and the closer to the boundaries, the smaller the equivalence ratio range for oscillation and the less likely oscillation becomes.

[Figure 17: see original paper] presents combustion stability distribution with  $p'$  amplitude on the vertical axis and  $\tau f_c$  on the horizontal axis. Experimental condition points are marked with circles. Using 1000 Pa as the boundary, the  $\tau f_c$  interval for combustion oscillation is clearly (0.5, 2). Smaller  $\tau f_c$  values correspond to larger possible oscillation amplitudes because higher flow rates produce greater thermal power.

Although the experimentally determined  $\tau f_c$  interval for combustion oscillation is (0.5, 2), with stable combustion maintained outside this range, limited experimental conditions prevented identification of subsequent oscillation intervals. 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  $f_c$  reflects the period of  $p'$ , the  $\tau f_c$  intervals for combustion oscillation should appear periodically. If we assume  $(\tau + \tau_0)$  represents the phase of  $q'$  (where  $\tau_0$  is chemical reaction time), the theoretical period should be 1, which contradicts experimental results.

The experimentally observed single oscillation interval length of approximately 1.5 exceeds the theoretical interval repetition period. This discrepancy arises partly from simplifications and partly from the complex mechanism of combustion oscillation. First, in time-delay models, the response time delay of heat release fluctuations to pressure fluctuations includes: pressure fluctuation propagation time upstream to the fuel injection port, response time for pressure fluctuations to induce equivalence ratio fluctuations at the injection port, convective mixing time for equivalence ratio fluctuations to travel from injection port to flame front, and chemical reaction time. Only mixing time was considered here, neglecting potential variations in other time delays. Second, the true meaning of mixing time is the duration for fuel to travel from injection port to flame front. This experiment employed two simplifications: (1) using the

average axial velocity of airflow to approximate fuel velocity, and (2) defining premixing distance as the distance from fuel injection port to premixing section exit, ignoring the distance from premixing section exit to the flame front (which continuously varies), affecting mixing time calculation accuracy. Finally, time-delay models are based on pressure fluctuations affecting equivalence ratio fluctuations, which in turn affect heat release fluctuations to cause combustion oscillation. However, actual combustion oscillation mechanisms are extremely complex and not yet fully understood, so experimentally observed oscillations may result from combined mechanisms, such as vortex shedding affecting combustion within vortices to excite oscillation.

Despite deviations from simplified time-delay model predictions, experimental results clearly demonstrate the significant influence of mixing time on combustion stability—combustion oscillation only occurs within a specific mixing time range. This suggests that modifying combustor structural design to reduce or avoid combustion oscillation is feasible. On the other hand, differences between experimental results and theoretical predictions also reflect the current immaturity in combustion oscillation mechanism research, requiring continued collaborative efforts from the academic community.

## Conclusions

Through experiments varying premixing length, airflow velocity, and equivalence ratio, this study investigated the relationship between mixing time and swirl premixed combustion stability, yielding the following conclusions:

- (1) Mixing time significantly affects combustion oscillation occurrence. Oscillation only becomes possible when mixing time falls within a specific range, and the equivalence ratio range for oscillation narrows as mixing time approaches interval boundaries.
- (2) During combustion oscillation, at constant flow velocity, the dominant oscillation frequency increases with equivalence ratio because higher equivalence ratios produce higher combustion temperatures and increased sound speed.
- (3) When combustion oscillation can occur, higher airflow velocities correspond to greater overall thermal power and larger possible maximum oscillation amplitudes across varying equivalence ratios.
- (4) In this combustor, combustion oscillation only occurs when  $\phi > 0.8$ . At low equivalence ratios, energy transferred from pulsating combustion to pressure fluctuations is lower than energy dissipated at boundaries, insufficient to excite combustion oscillation.

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