Study on Stability of Aero-Engine Combustion Chamber

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Abstract. Through a comprehensive investigation into the stability of the combustion chamber in aircraft engines, this study aims to enhance its operational efficiency and safety under variable and complex conditions. By constructing and validating models for flame stability, acoustic coupling effects, and reaction kinetics, the research delves into the specific impacts of the interactions between the flow field, thermal field, and acoustic field on flame stability within the combustion chamber. The findings indicate that a finely optimized combustion chamber design and control parameters significantly improve flame stability, while also reducing the adverse effects of turbulence and acoustic waves on combustion efficiency. These insights provide valuable theoretical and practical guidance for the design and optimization of aircraft engine combustion chambers.

Keywords: aero-engine; Combustion chamber; flame stability

1 Introduction

The combustion chamber of an aero-engine is the core component that produces thrust in flight, and its performance directly affects the thrust output, combustion efficiency, emission, and flight safety of the engine. Under complex working conditions such as high altitude, low temperature, and high pressure, the combustion chamber is easily disturbed by turbulence, sound waves, and airflow fluctuation, which leads to the decline of flame stability and thus affects the overall performance of the engine. The engine used is a Gao Han turbofan engine of CFM56 -5B, with a maximum thrust of 133 kN, a working temperature range of 300-1600 degrees Celsius, and a maximum fuel injection pressure of 8 MPa. As flight altitude and environmental conditions change, the fluid dynamics within the combustion chamber become increasingly complex, directly affecting combustion efficiency and thrust stability. To better understand the mechanisms behind these factors, flame stability models, acoustic coupling models, and reaction kinetics models were developed to analyze the interactions between the flow field, thermal field, and acoustic field in the combustion chamber from multiple perspectives. Through numerical simulations and experimental validation, the combustion chamber design and control parameters were optimized to ensure stable flame performance under various complex operating conditions. This also reduces the disruptive effects of turbulence and acoustic waves on the combustion process, further enhancing overall combustion efficiency and flight safety.

2 The Importance of Combustion Chamber in Aero-Engine

In the aero-engine, the combustion chamber is the place where fuel and air are mixed and burned at high temperatures. Its design and operation directly affect the thermal efficiency and thrust output of the engine [1]. The stability of the combustion chamber is very important to ensure the stable operation of the engine under complex working conditions such as high altitude, low temperature, and high pressure, which are directly related to combustion efficiency and pollutant emission levels. In this paper, the CFM56 - 5B Gao Han turbofan engine is used in the test, with a maximum thrust of 133 kN, a working temperature range from 300℃ to 1600℃, and a maximum fuel injection pressure of 8 MPa. During the experiment, the combustion chamber realizes the uniform distribution of fuel through the high-pressure injection system, and accurately controls the air-fuel ratio (ranging from 0.8 to 1.5) by using the adjustable premixing system to simulate the operating environment of the combustion chamber under complex flight conditions. Key equipment such as the fuel injection system, air preheating device, and high-precision temperature and pressure sensors ensure the accurate operation of the combustion chamber and the accuracy of data in the experiment. Under such strict experimental conditions, the running stability of the combustion chamber plays a decisive role in the overall performance, reliability, and flight safety of the engine. The design, material selection, cooling technology, and fuel injection control of the combustion chamber are all key factors that determine its stability. Any deficiency in design and operation will lead to a decrease in combustion efficiency, incomplete combustion, flameout, or excessive vibration, and even lead to engine failure and even safety accidents in serious cases [2].

3 Aeroengine Combustion Chamber Stability Model Design

3.1 Basic Flame Stability Performance Model

In the design of aircraft engine combustion chambers, the flame stability model provides theoretical support for combustion chamber stability by accurately describing key parameters such as fuel-air mixture ratio, pressure, temperature, and flow velocity. By analyzing the behavior of these variables under extreme conditions like high altitude and low temperature, the model ensures the continuity and stability of the combustion process. Numerical simulations using Computational Fluid Dynamics (CFD) software are conducted, with selected turbulence models capturing the dynamic characteristics of complex flows within the combustion chamber. The reaction kinetics model reveals the chemical reaction mechanisms between fuel and oxidizer under high-temperature and high-pressure conditions, ensuring precise simulation of the combustion process.

The acoustic coupling effect model quantifies the interaction between the acoustic field and the combustion field, explaining the flame instability caused by acoustic waves during combustion. These models are chosen because they address the complex coupling between the flow field, thermal field, and acoustic field within the combustion chamber. The numerical simulation methods based on these models offer high flexibility, allowing accurate prediction of combustion chamber performance under different flight conditions, while providing reliable reference points for subsequent experimental validation. The experimental setup integrates high-precision sensors and complex combustion simulation equipment to ensure data accuracy and reproducibility, faithfully replicating actual operating conditions [3]. In the model setup, boundary conditions include a pre-mixed fuel-air ratio of 1.0 at the combustion chamber inlet, an inlet pressure of 8 MPa, an inlet temperature of 300°C, adiabatic boundary conditions for the wall, and ambient pressure at the outlet, set to 1 atmosphere. The initial conditions are shown in Table 1.

Table 1. Initial condition settings of numerical simulation.

Parameter	Value	Unit
Initial pressure	8	MPa
Initial temperature	300	℃
Oil-gas mixing ratio	one	Non-dimensional
Turbulence intensity	5%	Non-dimensional
Combustion chamber inlet velocity	60	m/s
Reaction rate constant	2.5 × 10^9	$m^3/(mol·s)$
Activation energy	150	kJ/mol
Stefan-Boltzmann constant	5.67 × 10^-8	$W/(m^2·K^4)$

A well-designed flame stability model integrates reaction rate and turbulence intensity to predict the flame behavior under different operating conditions, thus ensuring the efficient operation of the combustion chamber. The following are two core models.

1) Reaction rate equation:

$$r = k \cdot [Fuel]^{\alpha} \cdot [O_2]^{\beta} \cdot e^{-\frac{E_a}{RT}} \tag{1}$$

In the reaction rate equation, the reaction rate is represented by the reaction rate constant, which respectively represents the concentration of fuel and oxygen, the activation energy, the gas constant, the temperature, and the reaction order. r represents the reaction rate, k is the reaction rate constant, $[Fuel]$ and $[O_2]$ represent the concentrations of fuel and oxygen, respectively, E_a is the activation energy, R is the gas constant, T is the temperature, and β denotes the reaction order.

2) Flame Stability Equation: α

$$S = \frac{\dot{m} \cdot C_p \cdot T}{\sigma \cdot A \cdot \Delta T_{ad}} \tag{2}$$

Here, it represents the flame stability index, is the mass flow rate, is the constant pressure-specific heat, is the temperature, is the Stefan-Boltzmann constant, is the combustion area, is the adiabatic combustion temperature difference. Using the above model, the combustor designer can predict the flame behavior under different flight altitudes and environmental conditions. These equations not only emphasize the importance of precisely controlling the fuel-oxygen mixing ratio and supply rate, but also illustrate the important effects of temperature and pressure on combustion stability. S represents the flame stability index, $\dot{m}$ is the mass flow rate, C_p is the specific heat at constant pressure, T is the temperature, σ is the Stefan-Boltzmann constant, A is the combustion area, and ΔT_{ad} is the adiabatic combustion temperature difference. Using the above model, combustion chamber designers can predict flame behavior under varying flight altitudes and environmental conditions [4].

3.2 Acoustic Coupling EffectModel

The interaction between turbulent airflow and flame in a combustion chamber, especially under high temperature and high-pressure conditions, can easily lead to acoustic instability. This leads to the coupling of sound waves and combustion waves, forming self-excited oscillation called thermoacoustic instability. The acoustic coupling effect amplifies the pressure fluctuation in the combustion chamber, increases the instability of the flame, intensifies the structural vibration, shortens the life of the combustion chamber, and may even lead to failure [5]. The model quantifies the coupling between sound field and combustion field through an acoustic wave equation, and describes the complex interaction between pressure disturbance and heat release. The equation is as follows:

$$\frac{\partial^2 p(x,t)}{\partial t^2} - c^2 \nabla^2 p(x,t) = \gamma(\dot{q}(x,t) = \rho \frac{\partial u(x,t)}{\partial x}) \tag{3}$$

Here, the pressure disturbance in the sound field is the sound speed, the specific heat ratio, the heat release rate of combustion, the air density, and the change of sound speed. The equation describes how the sound pressure changes due to the fluctuation of heat release during the propagation of sound waves, and how these changes are coupled with sound waves through heat release in the combustion chamber. In addition, the acoustic damping characteristics of the combustion chamber play an important role in controlling thermoacoustic instability. These damping characteristics are closely related to the structure, material, and flow field distribution of the combustion chamber [6]. In order to ensure acoustic stability under complex working conditions, an accurate damping model must be introduced to represent the energy dissipation under different conditions. Acoustic resistance can be described by the following equation: $p(x,t)$ representatives the pressure disturbance in the acoustic field, c is the speed of sound, γ is the specific heat ratio, $\dot{q}(x,t)$ is the rate of heat release from combustion, ρ is the air density, and $u(x,t)$ is the change in sound speed. This equation describes how sound pressure changes during sound wave propagation due to fluctuations in heat release and how these changes are coupled with acoustic waves through the heat release in the combustion chamber. Additionally, the acoustic damping characteristics of the combustion chamber play a crucial role in controlling thermoacoustic instability. These damping properties are closely related to the structure, materials, and flow field distribution within the combustion chamber [6]. To ensure acoustic stability under complex working conditions, a refined damping model must be introduced to characterize energy dissipation under different conditions. Acoustic damping can be described by the following equation:

$$D = \frac{1}{2}\rho_0 c_0 S \int \left(\frac{\partial p}{\partial t}\right)^2 dt \tag{4}$$

In this equation, the acoustic damping is represented, and the sum is the static density and the static speed, the cross-sectional area of the combustion chamber, and the pressure change rate. The equation reveals the process of energy dissipation in sound waves, especially how the attenuation of sound wave energy through damping can improve the stability of the combustion chamber. Energy dissipation caused by acoustic damping plays a key role in reducing pressure fluctuation and thermoacoustic instability, and ultimately contributes to the overall stability of the combustion chamber during operation. In this equation, D represents the acoustic damping, ρ_0 and c_0 are the static density and static sound speed, respectively, S is the cross-sectional area of the combustion chamber, and $\frac{\partial p}{\partial t}$ is the rate of pressure change. This equation reveals the process of energy dissipation in sound waves, particularly how the attenuation of sound wave energy through damping improves the stability of the combustion chamber. The energy dissipation caused by acoustic damping plays a critical role in reducing pressure fluctuations and mitigating thermoacoustic instability, ultimately contributing to the overall stability of the combustion chamber during operation.

3.3 Reaction Kinetics Model

The reaction kinetic model is the key to studying the stability of aero-engine combustion chambers because it reveals the chemical reaction rate and energy release process of fuel and oxidants under high temperatures and high pressures. This model directly affects the formation, maintenance, and efficiency of flame [7]. The model uses nonlinear equations to describe the relationship among reaction rate, temperature, pressure, and reactant concentration. The dependence of reaction rate on temperature accords with the Arrhenius formula, which ensures the stability analysis of the combustion chamber under complex working conditions. The equation is as follows:

$$k = A \cdot \exp\left(-\frac{E_a}{RT}\right)[Fuel]^m [O_X]^n \tag{5}$$

In this equation, the reaction rate is represented by the reaction rate constant, the activation energy, the gas constant, and the absolute temperature, which represent the concentration of fuel and oxidant and the reaction order, respectively. The equation can accurately predict the combustion reaction rate at different temperatures and pressures, thus determining the conditions required for flame maintenance and evaluating the stability of the combustion process [8]. In addition, the distribution of heat release in the combustion process directly affects the coupling between temperature field and flow field in the combustion chamber, and then has a far-reaching impact on flame stability. The heat release rate can be described by the following equation: k represents the reaction rate, A is the reaction rate constant, e is the activation energy, r is the gas constant, t is the absolute temperature, Fuel and O_x represent the concentrations of fuel and oxidizer, respectively, and m and n are the reaction orders. This equation allows for accurate prediction of the combustion reaction rate under different temperatures and pressures, thereby determining the conditions required for flame maintenance and assessing the stability of the combustion process [8]. Furthermore, the distribution of heat release during combustion directly affects the coupling between the temperature field and flow field within the combustion chamber, which in turn has a profound impact on flame stability. The heat release rate can be described by the following equation:

$$\dot{q} = \frac{\Delta H \cdot \rho \cdot u}{1 + \frac{\gamma - 1}{2} M^2} \tag{6}$$

In this equation, the exothermic rate is the enthalpy change of the reaction, the density, the flow rate, the specific heat ratio, and the Mach number. The equation is helpful to analyze the influence of heat release on the flow field in the combustion process, thus evaluating the thermodynamic stability of the combustion chamber. The establishment of a reaction dynamics model not only helps to deeply explore the micromechanism of the combustion process, but also provides a theoretical basis for optimizing the performance of the combustion chamber under various flight conditions. $\dot{q}$ represents the heat release rate, ΔH is the enthalpy change of the reaction, ρ is the density, u is the flow velocity, γ is the specific heat ratio, and M is the Mach number. This equation helps analyze the impact of heat release on the flow field during the combustion process, allowing for an assessment of the thermodynamic stability of the combustion chamber. The establishment of the reaction kinetics model not only enables a deep er exploration of the microscopic mechanisms of the combustion process but also provides a theoretical foundation for optimizing the performance of the combustion chamber under various flight conditions.

3.4 Numerical Simulation Method

Numerical simulation, through precise modeling of complex physical and chemical processes, accurately captures the dynamic evolution of multiple factors such as airflow, heat transfer, and chemical reactions within the combustion chamber [9]. Using CFD technology, the Navier-Stokes equations are discretely solved, combined with reaction kinetics and acoustic models to describe in detail the turbulent field, pressure distribution, and flame propagation path within the combustion chamber. This method can also couple turbulent reactions with heat release effects, analyzing flame stability under different operating conditions and flexibly adjusting parameters for multi-dimensional analysis, such as the synergistic effects of fuel flow rate, temperature, and chemical reaction rates, providing in-depth understanding and prediction of the combustion process.

4 Experimental Results and Analysis

4.1 Experimental Settings and Methods

The experiment was carried out using a highly accurate simulated combustion chamber, which accurately reproduced the high temperature and high-pressure conditions encountered in real-world scenes to ensure the accuracy of experimental data. The core components of the combustion chamber include THE fuel injection system, air preheating device, and high-precision temperature and pressure sensors, which can accurately control and monitor the fuel-air mixing ratio, combustion temperature, and airflow speed [10]. During the experiment, the fuel is evenly distributed in the combustion chamber through the high-pressure injection system, and the air-fuel ratio is finely controlled through the adjustable premixing system. Combined with the CFD numerical simulation model, the system realizes dynamic parameter adjustment and ensures the consistency between experimental and real flight conditions (see Table 2).

Table 2. Key parameters of the experimental device.

Parameter	Equipment function	Adjustment range
Injection pressure	Uniform fuel distribution and flame formation	0-10 MPa
Temperature sensor	Real-time monitoring of combustion temperature	300-2000 degrees Celsius
Air-fuel ratio control	Control of fuel and air mixing ratio	0.8-1.5

4.2 Experimental Results of Flame Stability

The results of flame stability experiments show significant differences in flame behavior under different conditions. Firstly, the flame stability under different injection pressures and air-fuel ratios was tested. Table 3 shows that the flame stability index increases significantly with the increase in injection pressure. At low pressure, the flame is more susceptible to turbulence and shows instability, while at high pressure, the flame is more concentrated and stable. The change of air-fuel ratio also has a profound influence on flame stability. When the air-fuel ratio is close to the ideal value of 1.0, the combustion efficiency is the highest, and the flame stability is the best. However, an air-fuel ratio that is too high or too low will lead to increased flame oscillation and decreased stability.

Table 3. Influence of Injection Pressure on Flame Stability and Combustion Efficiency.

Injection pressure (MPa)	Flame stability index	Combustion efficiency (%)
2	0.65	seventy-eight
five	0.83	eighty-five
eight	0.91	eighty-nine

Table 3 shows the changes in the flame stability index under different injection pressures, indicating that high-pressure injection is helpful in improving flame stability and combustion efficiency. Based on these experimental results, the influence of temperature on flame stability is further analyzed, as shown in Table 4. With the increase in combustion temperature, the flame stability is also improved. However, excessive temperature will lead to incomplete combustion and increase pollutant discharge.

Table 4. Influence of combustion temperature on flame stability andcombustion efficiency.

Temperature (°C)	Flame stability index	Combustion efficiency (%)
1000	0.78	82
1500	0.85	88
2000	0.92	90

4.3 Experimental Results of the Acoustic Coupling Effect

When exposed to sound waves with different frequencies and amplitudes, changes in flame stability are observed, especially at certain frequencies where resonance occurs between sound waves and heat release in the combustion chamber. This resonance intensifies the flame oscillation. Fig. 1 shows the change in flame stability index at different sound wave frequencies. With the increase in frequency, the flame stability index decreases nonlinearly, and the most significant acoustic coupling effect occurs at 600 Hz. At this frequency, the oscillation amplitude of the flame increases significantly, and the combustion efficiency decreases accordingly.

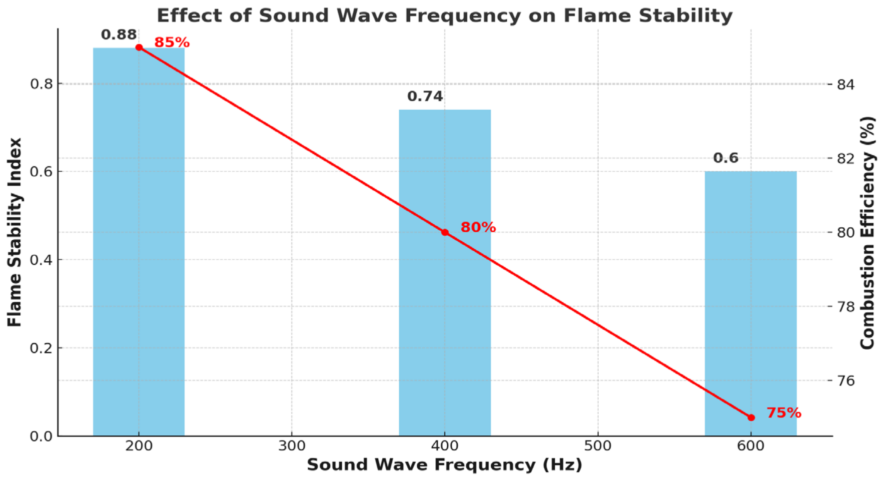

Fig. 1. Influence of different sound wave frequencies on flame stability.

Fig. 1 shows the change in flame stability at different sound wave frequencies. The higher the frequency, the stronger the coupling between sound wave and heat release, which leads to an increase in flame volatility. In order to further analyze the influence of sound wave amplitude, Figure 2 shows the influence of different vibration amplitudes on flame stability at a fixed frequency. It can be seen that with the increase in amplitude, the stability of the flame further deteriorates. At high vibration amplitude, the flame is easily disturbed by sound, which leads to a discontinuous combustion process and reduced efficiency.

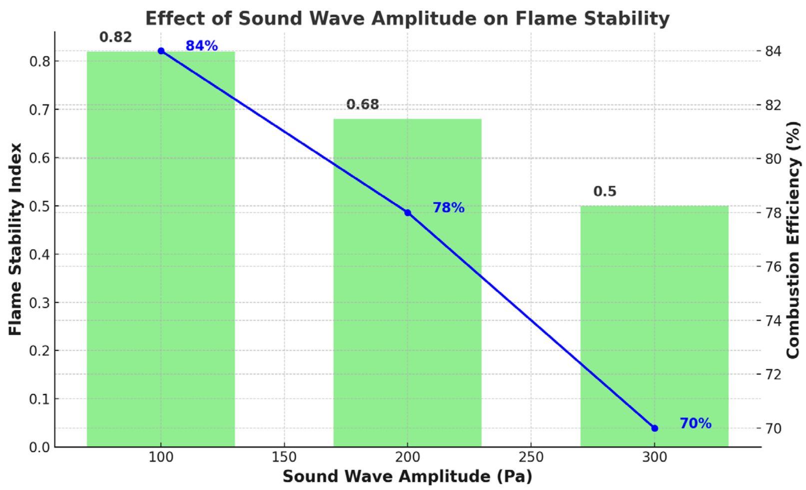

Fig. 2. Influence of different sound wave amplitudes on flame stability.

4.4 Comparative Analysis of Numerical Simulation Results and Experiments

The comparative analysis of numerical simulation and experimental results shows that the predicted flame stability under different working conditions has high consistency, but there are some differences in some extreme working conditions. Numerical simulation uses the CFD model to calculate the distribution of airflow, pressure, and temperature field in the combustion chamber, and accurately capture the dynamic behavior of turbulence and heat release. The difference between the numerical simulation results and the experimental data mainly occurs at low fuel ratio, and the flame stability in the simulation is slightly higher than the actual experimental results, indicating that the model has certain limitations in capturing the influence of turbulence at low fuel ratio (see Figure 3).

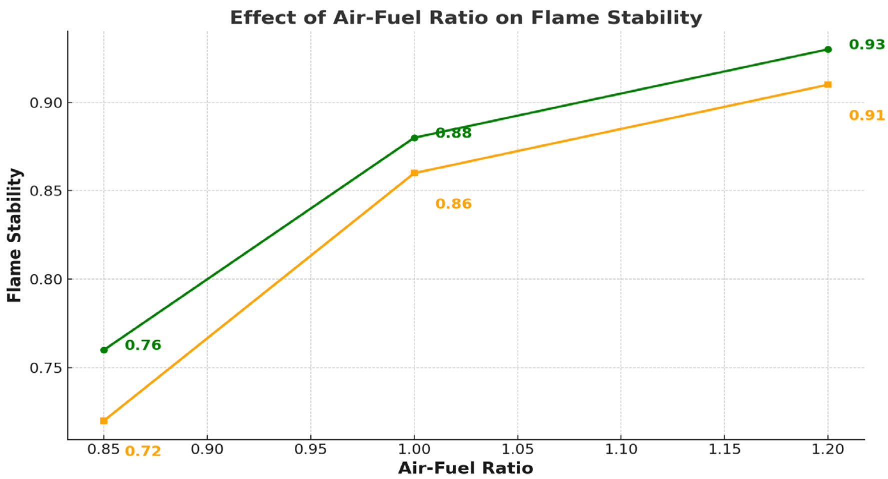

Fig. 3. Influence of air-fuel ratio on flame stability.

In order to further verify the influence of the acoustic coupling effect, the simulation results and experimental results are compared and analyzed at acoustic frequency. It can be seen that numerical simulation can better capture the coupling trend of sound wave and flame, but the simulation accuracy decreases at high frequency, as shown in Figure 4.

Numerical simulation methods demonstrate high accuracy in predicting flame stability and acoustic coupling effects in aircraft engine combustion chambers, particularly under conventional operating conditions where experimental and simulation results show strong consistency, validating their effectiveness. However, under extreme conditions, discrepancies between the two reveal the limitations of existing models in handling complex turbulence and high-frequency acoustic coupling. Future improvements to these models are necessary to enhance their predictive capabilities across a broader range of operating conditions.

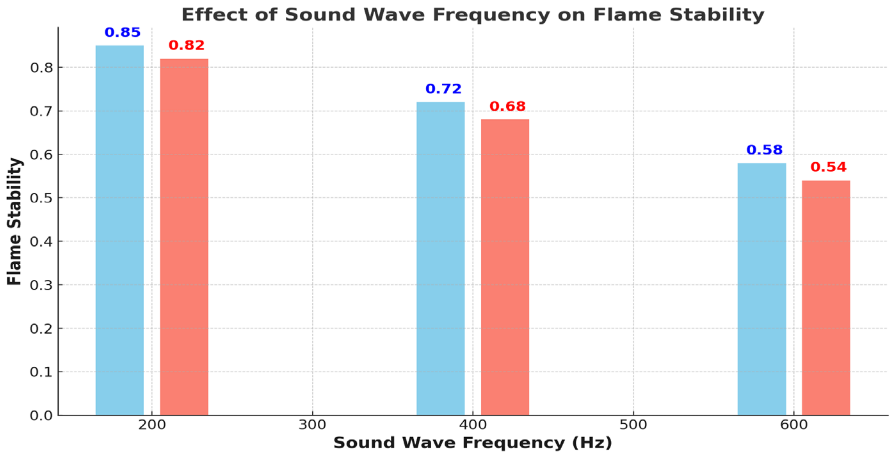

Fig. 4. Influence of sound wave frequency on flame stability.

5 Conclusion

Under complex operating conditions such as high altitude and low temperature, the stability of the combustion chamber directly impacts the performance of aircraft engines and flight safety. By establishing flame stability, acoustic coupling, and reaction kinetics models, combined with numerical simulations and experimental analysis, this study reveals the critical role of the coupled flow, thermal, and acoustic fields in maintaining flame stability within the combustion chamber. These analyses provide essential theoretical support for optimizing combustion chamber design and improving combustion efficiency. However, under extreme conditions, accurately capturing the coupling of turbulence and acoustic waves presents certain technical challenges, particularly in simulating high-frequency turbulence and its interaction with acoustic waves.

To overcome these limitations, future research should focus on developing more precise turbulence-acoustic coupling algorithms and utilizing higher-resolution experimental equipment to conduct in-depth testing of high-frequency acoustic phenomena. Additionally, employing more advanced multi-scale simulation techniques, such as Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS), could further enhance the accuracy of simulations involving turbulence and acoustic interactions, ensuring the efficient and stable operation of combustion chambers under a wide range of extreme conditions.

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