FLAME AND EMISSION CHARACTERISTICS FROM NH₃/CH₄ COMBUSTION UNDER ULTRASONIC EXCITATION

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As a high energy density hydrogen-rich carrier, ammonia (NH₃) is a highly promising carbon-free fuel. The large-scale industrial application of NH₃ is limited by its low reactivity and high nitrogen oxide (NOₓ) emission. In this work, the flame and emission characteristics of ammonia/methane (NH₃/CH₄) non-premixed combustion were investigated under ultrasonic excitation. An experimental system was designed and built, including non-premixed combustion system, loading ultrasonic system, deflection tomography temperature measurement system and flue gas measurement system. Combustion and measurement experiments at different ultrasonic frequencies and NH₃/CH₄ blending ratios were carried out. Flame images and flue gas species concentrations under ultrasonic excitation were acquired. The 3D temperature field was reconstructed. The influence of ultrasonic excitation at different frequencies on flame characteristics, flame temperature field and emission characteristics of the combustion process was analysed. The mechanism of NH₃/CH₄ combustion enhancement and emission reduction was revealed when the flame was excited by ultrasonic waves. Results showed that part of the hydrocarbon fuels was replaced by NH₃ to reduce carbon dioxide (CO₂) emission. The height and colour of the NH₃/CH₄ flame were changed and the high-temperature area of the flame gradually expanded as ultrasonic acted on the flame. As ultrasonic frequency increased, the emission concentrations of unburned CH₄, unburned NH₃ and NO decreased significantly. The flame was excited by ultrasonic waves, which reduced its local equivalent ratio, improved combustion efficiency and suppressed NOₓ generation.

Key words: Ammonia Combustion, Ultrasonic Wave, Emission Characteristics, Temperature Distribution

1. Introduction

One of the most interesting research hotspots in recent years has been the development of clean alternative energy to achieve the low carbonisation of energy production and industrial combustion. As a hydrogen-rich carrier with high energy density, ammonia (NH₃) is referred to as ‘another kind of hydrogen (H₂) [1].’ The widespread use of NH₃ fuel is expected to accelerate the transition from ‘carbon-based’ to ‘hydrogen-based’ energy. NH₃ has the benefits of zero carbon emission, mature manufacturing process and low-cost storage and transportation, so NH₃ has great potential for use in
energy and power systems [2]. However, it also has disadvantages, such as narrow flammability limit, low laminar flame propagation velocity, long ignition delay time, low flame temperature and high nitrogen oxide (NO\textsubscript{X}) emission. The large-scale industrial application of NH\textsubscript{3} is hampered by its drawbacks. Therefore, the study of the combustion characteristics [3–5], reaction mechanisms [6–8] and application methods [9,10] of NH\textsubscript{3} has become an appealing research frontier in the field of clean combustion in recent years.

Current methods for achieving the stable combustion of NH\textsubscript{3} mainly include mixed combustion with hydrocarbon fuels [11], optimisation of heat and mass transfer processes [12], increase of turbulence intensity [13] and external auxiliary technology [14]. In addition, problems of high NO\textsubscript{X} emission whilst improving the reactivity of NH\textsubscript{3} must be urgently solved. The methods of high pressure and rich fuel are commonly used to investigate the emission control and generation mechanisms of NH\textsubscript{3} combustion pollutants. Based on a reduced mechanism, Okafor et al. [7] carried out the kinetic analysis of NH\textsubscript{3}/CH\textsubscript{4}/air combustion under high-pressure conditions and found that increasing the pressure can suppress NO\textsubscript{X} formation by reducing the pool of OH and O radicals.

Existing experimental studies on the low NO\textsubscript{X} combustion of NH\textsubscript{3} fuel are mostly applied in gas turbine combustion chambers with complex combustion conditions. Apply it to industrial burners is challenging. Valera-Medina et al. [15] explored NH\textsubscript{3}/H\textsubscript{2} swirling combustion under rich flame conditions and showed that NO emission concentrations decreased monotonically with increasing equivalence ratios (\(\phi\)) when \(\phi\) was greater than 1.1. Rich NH\textsubscript{3} combustion strategies were adopted to achieve the goal of NO\textsubscript{X} emission reduction. However, it tended to cause a large amount of unburned NH\textsubscript{3} to escape; at the same time, fuel consumption was increased.

In the quest to reduce pollutant emissions, researchers have found that the addition of acoustic waves to the combustion flow field has a significant effect on combustion and emission characteristics. Therefore, a large number of studies on the effects of acoustic fields on flames have been conducted. Research on forced acoustic waves to flames focuses on the combustion of fuels such as H\textsubscript{2}, CH\textsubscript{4} and acetylene with a low/medium frequency acoustic field (\(f = 30–1000\) Hz). Kim et al. [16] studied the relationship between the resonance frequency of a non-premixed jet H\textsubscript{2} flame and the concentration of NO\textsubscript{X} emission. Acoustic excitation reduced NO\textsubscript{X} concentration over a wide frequency range. Specifically, at the flame resonance frequency, NO\textsubscript{X} concentration was significantly reduced. Guo et al. [17] experimentally investigated the influence of standing waves with different waveforms on the soot suppression effect from acetylene diffusion flame and discovered that the soot suppression efficiency increased linearly as acoustic energy increased. The results elucidated that the vortex generated by acoustic excitation can promote air entrainment, strengthen the mixing of upstream fuel and air and reduce the exposure time of the reactants in the high-temperature region. The premixing effect created by acoustic excitation at the flame root causes the flame lift-off. The height of flame decreases and the reaction zone is widened. Thus, NO\textsubscript{X} emission is reduced.

Ultrasonic wave frequency is higher than 20 kHz. In comparison to audible sound waves, the ultrasonic waves have many characteristics, such as short wavelength, high energy, significant thermal relaxation absorption of gas molecules, good directivity, strong reflection ability and intensive acoustic energy, which can promote various physical and chemical effects. Scientists have made beneficial attempts to explore the combustion efficiency of the ultrasonic effect on the flames. Hirota et al. [18] experimentally explored the effect of CH\textsubscript{4}/air laminar lifted flame excited by ultrasonic waves. The results revealed that the improvement of the stability limit and the reduction of soot can be
compatible in an appropriate range. Lee et al. [19] employed the schlieren method to discuss the influence of ultrasonic frequency on the behaviour of propane/air premixed flame. The study expounded that the flame propagation velocity increased as ultrasonic frequency increased. When ultrasonic excitation is applied to non-premixed ammonia/methane (NH\textsubscript{3}/CH\textsubscript{4}) combustion, its effect on flame and emission characteristics is expected.

In this study, an experimental system for the non-premixed NH\textsubscript{3}/CH\textsubscript{4} combustion excited by ultrasonic waves was constructed. The flame response characteristics of NH\textsubscript{3}/CH\textsubscript{4} combustion were investigated under working conditions of different ultrasonic frequencies and different NH\textsubscript{3} blending ratios. NH\textsubscript{3}/CH\textsubscript{4} flame shapes were captured and discussed. Combustion temperature evolution laws were expounded on the basis of reconstructed NH\textsubscript{3}/CH\textsubscript{4} combustion temperature fields. The emission rules of the main combustion process under different ultrasonic conditions were analysed. The emission reduction mechanisms of NH\textsubscript{3}/CH\textsubscript{4} combustion excited by ultrasonic waves were also revealed.

2. Experimental method and system

The deflection tomography was applied to measure the temperature distribution of combustion under ultrasonic excitation. Infrared photometry was employed to diagnose the species concentration of the combustion process excited by ultrasonic waves. The experimental system included a combustion system, a loading ultrasonic system and a hybrid measurement system.

2.1. Combustion system

![Fig. 1 Structure of burner: N, nozzle; FT, fuel tube; AT, air tube; UAC, uniform air flow chamber; LB, levelling bolts.](image)

The burner is shown in Fig. 1. The burner is mainly composed of the nozzle, fuel tube, air tube, uniform air flow chamber and levelling bolts. A nozzle with frustum structure is installed on the top of the fuel tube. A hole diameter is 1.5 mm in the top of the nozzle. The inner and outer diameters of the fuel tube are 6.0 and 8.0 mm, respectively. Air flows out of the uniform air flow chamber and then into the annular channel between the air tube and fuel tube.
Fig. 2 Combustion system: AB, air bottle; AC, air compressor; AM, ammonia bottle; B, burner; ME, methane bottle; MF, mass flow controller; NV, needle valve; PV, pressure-reducing valve; VS, ventilation system.

The piping system is shown in Fig. 2. The fuel piping includes NH$_3$ and CH$_4$ pipelines. The fuel flows out of the fuel bottles and into the fuel line through the pressure-reducing valves (reduced to 0.2 MPa), needle valves and mass flow controllers (accuracy ± 1%) in turn. The two branches, NH$_3$ and CH$_4$, are combined and ejected from the nozzle. The air is depressurised to 0.4 MPa by a pressure-reducing valve and passes through a needle valve and a mass flow controller (accuracy ± 1%) into the air line.

2.2. Ultrasonic device

The ultrasonic system comprises a signal generator, a power amplifier and an ultrasonic transducer. The signal generator emits electrical signals, which are amplified by a single-channel power amplifier. The ultrasonic transducers of different frequencies are driven by amplified signals. Electrical energy is converted into high-frequency acoustic energy by an ultrasonic transducer. The location of the ultrasonic transducer is adjusted by a gripper. Three piezoelectric transducers of 20, 25 and 28 kHz are employed in this work. The maximum output frequency of the signal generator (RIGOL DG811) is 10 MHz, and the sampling rate is 125 MSa/s. The frequency resolution is 1 μHz, and the vertical resolution of the signal is 16 bits. The maximum output current of the power amplifier (ATA-68020, bandwidth 10 kHz–70 kHz) is 2.12 Ap. The output voltage gain is 0–300 times, and the maximum output power is 901 Wp.
2.3. Measurement method and system

A digital camera (Nikon D5600, 6000 dpi × 4000 dpi) is used to record the flame shape. The hybrid measurement system (Fig. 3) is composed of an acoustic pressure measurement system, a deflection tomography temperature measurement system and a flue gas component measurement system.

2.3.1 Deflection tomography temperature measurement

Deflection tomography is based on the principle that the direction of light is changed when light propagates in a non-uniform refractive index field. Thus, the data of integral projection are obtained. The reconstruction algorithm is then used to invert the two-dimensional (2D) refractive index distribution within the cross sections. Parameter distributions, such as density and temperature, can also be obtained [20–22]. The precision of the refractive index measurement is $10^{-5}$.

The beam emitted from the 10 mW He-Ne laser ($\lambda = 632.8$ nm) is expanded by the objective lens (25 × magnification), which is then collimated by the convex lens (diameter of 100.0 mm, focal length of 500.0 mm) into a parallel beam with a diameter of 55.0 mm. After passing through the region to be measured, the parallel beam passes vertically through the Ronchi gratings (178 mm × 178 mm) placed in parallel. The spacing between the two Ronchi gratings is 30.0 mm, and the pitch of the Ronchi grating is 0.05 mm. The convex lens with a focal length of 500.0 mm is passed through the parallel beam. The beam is filtered by a small aperture to remove stray light. Finally, a CT-CCD camera (1024 dpi × 768 dpi, the maximum frame rate of 204) is used to capture the Moiré fringe on the imaging screen.
2.3.2 Infrared measurements of gas components

The principle of the gas component measurement is based on the substance-specific extinction of infrared light. It is directed through the measuring gas where the lessening of the light intensity within the substance-specific absorption wave length is a degree for its concentration. The flue gas measurement system is composed of a mobile multicomponent analyser (MCA14m) and a flue gas-collecting hood with a size of 10.0 × 10.0 × 30.0 cm. The mobile multicomponent analyser can measure 11 flue gas components, including NO, NH₃, CO₂ and CH₄ etc. The measurement accuracy of the mobile multicomponent analyser is ±1% FS, and the resolution is 0.01 mg/m³. The flue gas-collecting hood has square holes on both sides for placing the ultrasonic transducer and the reflector, as illustrated in Fig. 3. During the measurement preparation, the temperature of the heated measuring gas pipe is preheated to 186 °C is to reduce measurement errors caused by heat loss from combustion products in the measuring gas pipe. The gas sample probe is positioned 10 cm above the flame. Data are updated every 20 s.

3. Experimental procedure and results

3.1. Combustion experiment with ultrasonic excitation

The hybrid measurement system was built, as presented in Fig. 3. The air compressor was switched on, so the air was stored in the air bottle. The air with a flow rate of 0.1 m/s was supplied to create a stable combustion environment. The total fuel mass flow rate was set to 180 standard cubic centimetres per minute (sccm). Valves of NH₃/CH₄ bottle and air bottle were switched on. When the NH₃/CH₄ was ejected from the nozzle, a torch was used to ignite blending fuel. The ultrasonic devices were then turned on, and the signal amplifier was set to 150 times. Then, the combustion flow field was acted on by ultrasonic waves. When the flame was stabilised, the CT-CCD camera and a digital camera were employed to respectively capture the Moiré fringes and flame images of NH₃/CH₄ combustion. The flue gas sampling analysis was started at the same time.

Three different frequencies of ultrasonic transducers and four different ratios of NH₃/CH₄ fuel were applied for the experiments. The experimental working conditions are shown in Tab. 1.

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</tr>
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3.2. NH₃/CH₄ flame characteristics with ultrasonic excitation

Fig. 4 show flame images for the experimental working conditions corresponding to Tab. 1. \(X_{NH3}\) was defined as the mole fraction of NH₃ in blending fuel.
Fig. 4 NH$_3$/CH$_4$ flame excited by ultrasonic waves of (a) working condition A, (b) working condition B, (c) working condition C and (d) working condition D.

Fig. 5 Stream line and flame inclined images: (a) without ultrasonic excitation; (b) with ultrasonic excitation.

From working condition A to working condition D (Fig. 4), when the flame was excited by ultrasonic waves of different frequencies, a similar changing rule in the characteristics of the flame occurred as the fuel ratio changed. The flame height first became short and then increased as the ultrasonic wave frequency increased, when the flames were excited by ultrasonic waves. When the forcing frequency increased, the flame curvature decreased and the flame height increased [23]. As the ultrasonic frequency increased, the trend for the inclination degree of upstream flame was similar. In Fig. 5 (a), the flame was stably burned when the burning velocity $S$ at the flame front was the same as the velocity $V$ of the local unburned gas flow. When the flow field was affected by ultrasonic excitation, the flame and unburned gas flow were inclined at an angle of $\alpha$ and $\theta$, respectively (Fig. 5 (b)). Local unburned gas flow velocity $V$ was perpendicular to the flamelet, which can be expressed as $V = V \cos(\alpha + \theta) = S$. Assuming that the flame burning velocity was constant, the $V = S/\cos(\alpha + \theta)$ could be obtained. The velocity along the y-axis can be denoted as $V_{\text{local}} = V \cos \theta = S \cos \theta / \cos(\alpha + \theta)$, which was greater than $V$. The angle of inclination of the flame was variable with the velocity of the
unburned gas flow, which meant that the addition of ultrasonic excitation increased the velocity of the unburned gas flow. The $\alpha$ increased as ultrasonic frequency increased.

In Fig. 4 (a), the downstream of the flame without ultrasonic excitation appeared bright yellow, which was caused by the presence of soot in the downstream part of the flame. The flame structure was significantly affected by the pressure fluctuations around the flame caused by the ultrasonic waves. The mixing rate of air and flame increased, and the local $\phi$ of the flame reduced as ultrasonic frequency increased. Thus, the diffusion flame was changed to a flame with premixed characteristics. The flame excited by ultrasonic waves was burned fully. The colour of the flame gradually changed to blue because the amount of soot production was reduced.

The flame height decreased, and the flame colour changed obviously as the proportion of NH$_3$ in the fuel increased. The addition of NH$_3$ reduced the reactivity of the blending fuel, resulting in low burning velocity in the flow field. The blue colour of the flame was gradually replaced by orange yellow after the addition of NH$_3$ because the chemiluminescence of CH radical and CO$_2$ was blue [24] when CH$_4$ was burned, and NH$_2$- $\alpha$ radicals were orange yellow [25] when NH$_3$ was burned. The orange yellow appeared first in the downstream region of the flame, when small amounts of NH$_3$ were added to the CH$_4$ fuel. As the proportion of NH$_3$ increased, the flame gradually developed into orange yellow. In the meantime, the blue associated with the hydrocarbon flame was gradually weakened.

3.3. NH$_3$/CH$_4$ combustion temperature distributions with ultrasonic excitation

The deflection information of light was extracted using the wave-front retrieval method. Fig. 6 shows the reference Moiré fringes and deflected Moiré fringes of flame excited by 25 kHz ultrasonic waves with $X_{NH3}$ = 0.3. Firstly, the Fourier frequency spectrum was obtained by a 2D Fourier transform of the Moiré fringes. Filter function was employed to extract the +1 order frequency spectrum. Then, inverse Fourier transform and phase unwrapping were performed to obtain the true phase of the deformed wavefront. The deflection angle data were further calculated through phase data. Subsequently, the reconstruction algorithm was employed to invert the refractive index distribution of the measured flow field using the deflection angle data. Thereafter, the temperature distribution was calculated from the refractive index distribution via the Glastone–Dale formula. The 2D temperature distributions of 20 cross sections were reconstructed from the Moiré fringes of each working condition. Then, the 2D temperature distributions data of 20 cross sections were coupled into a matrix of three-dimensional (3D) temperature values. Finally, the Visualization Toolkit was used to visualise the 3D temperature distribution. The direct measurement method was applied to verify the validity of the deflection tomography temperature measurement. Under the same working conditions, a thermocouple was employed to measure the temperature field through multipoint and repeated measurements. The relative error of the temperature measurements between deflection tomography and direct measurement was 6.83%.
Fig. 6 Moiré fringes: (a) reference Moiré fringes; (b) deflected Moiré fringes.

Flame images and longitudinal sections of flame temperature distributions were displayed simultaneously, as illustrated in Figs. 7, 8, 9 and 10. Based on the reconstructed results, the flame temperature tended to increase and then decrease along the jet direction. A low temperature region appeared in the centre of the flame. The flame temperature first increased and then decreased from the centre to the edge of the flame, along the radial direction. Considering that the fuel sprayed out at the nozzle and spread around, the oxidant simultaneously diffused to the flame surface and entered the gas side to react where air and fuel were mixed significantly and molecules were collided violently. Therefore, this area had the highest temperature. When the fuel was ejected a certain distance out of the nozzle, the reaction was gradually weakened and the heat was lost in the downstream of the flame. Therefore, the flame temperature gradually decreased in the axial direction.

Fig. 7 Temperature distribution of CH₄ flame excited by ultrasonic waves of (a) 0 kHz, (b) 20 kHz, (c) 25 kHz and (d) 28 kHz.

Fig. 8 Temperature distribution of flame excited by ultrasonic waves of (a) 0 kHz, (b) 20 kHz, (c) 25 kHz and (d) 28 kHz with \( X_{NH_3} = 0.1 \).
Fig. 9 Temperature distribution of flame excited by ultrasonic waves of (a) 0 kHz, (b) 20 kHz, (c) 25 kHz and (d) 28 kHz with $X_{NH3} = 0.2$.

Fig. 10 Temperature distribution of flame excited by ultrasonic waves of (a) 0 kHz, (b) 20 kHz, (c) 25 kHz and (d) 28 kHz with $X_{NH3} = 0.3$.

The combustion working conditions excited by 28 kHz ultrasonic waves were taken as an example to analyse the evolution law of the flame temperature field at different $X_{NH3}$. From Fig. 7 to Fig. 10, the maximum flame temperature decreased as $X_{NH3}$ increased. The maximum flame temperature of pure CH$_4$, $X_{NH3} = 0.1$, $X_{NH3} = 0.2$ and $X_{NH3} = 0.3$ were 1310 °C, 1263 °C, 1204 °C and 1178 °C, respectively. Compared with the pure CH$_4$ flame, the maximum temperature of different $X_{NH3}$ flame dropped by 3.59%, 8.09% and 10.08% as $X_{NH3}$ increased. At the same ultrasonic frequency, the high-temperature region of the flame gradually reduced as $X_{NH3}$ increased. Owing to the low calorific value of NH$_3$, the flame temperature decreased as $X_{NH3}$ increased. In addition, due to the low reactivity of NH$_3$, a large amount of activation energy was required to maintain combustion. NH$_3$ absorbed part of the heat released by the combustion of CH$_4$, which resulted in a low maximum temperature in the flow field due to the addition of NH$_3$ to the fuel.

The experimental conditions of flame with $X_{NH3} = 0.1$ were used as examples to analyse the law of flame temperature distributions as the ultrasonic frequency changed. As the ultrasonic frequency increased from 0 kHz to 20 kHz, 25 kHz and 28 kHz, the maximum temperature of flame gradually increased. The area of the high-temperature region increased as ultrasonic wave frequency increased. The maximum temperatures were 1079 °C, 1160 °C, 1203 °C and 1263 °C in the $X_{NH3} = 0.1$ flame applied with 0, 20, 25 and 28 kHz ultrasonic waves, respectively. Compared with the free flame without acoustic field, the maximum flame temperature of $X_{NH3} = 0.1$ increased by 7.51%, 11.50% and 17.05% as ultrasonic frequency increased. Compared with the flame temperature without ultrasonic excitation, the amplification of maximum flame temperature for pure CH$_4$, $X_{NH3} = 0.2$ and $X_{NH3} = 0.3$ respectively increased by 14.61%, 17.62% and 16.74% when flames were excited by 28 kHz ultrasonic waves. Pressure fluctuation occurred around the flame when it was excited by ultrasonic
waves. Reactants were diffused efficiently in the ultrasonic wave fields, which enhanced the mixing of fuel and air. The diffusion flame became a flame with premixed characteristics. The flame temperature and the reaction rate of the combustion process increased under the continuous ultrasonic excitation.

3.4. Emission characteristics of NH$_3$/CH$_4$ combustion with ultrasonic excitation

The measurement of flue gas component concentration was performed. When the combustion was stable, multiple measurements were carried out and the values of multiple measurements were averaged.

![Fig. 11 Unburned CH$_4$ and CO$_2$ concentration variation with frequency at different fuel ratios.](image)

Fig. 11 show the emission characteristics of unburned CH$_4$ and CO$_2$ with ultrasonic frequency for blending fuel (pure CH$_4$, $X_{NH3} = 0.1$, $X_{NH3} = 0.2$ and $X_{NH3} = 0.3$). When the ultrasonic frequency that excited the flame was the same, the concentration of unburned CH$_4$ and CO$_2$ of flue gas decreased accordingly as $X_{NH3}$ increased. When the 20 kHz ultrasonic wave was applied to the flame, the CO$_2$ and unburned CH$_4$ emission concentration of the flame with $X_{NH3} = 0.3$ decreased by 32.01% and 27.90%, respectively, compared with the pure CH$_4$ flame. The addition of NH$_3$ reduced the mole fraction of CH$_4$ in the blending fuel correspondingly. The generated CO$_2$ also decreased, which achieved the expectation of reducing CO$_2$ emission. For the same fuel blending ratio, CO$_2$ emission concentration increased as ultrasonic frequency increased. At the same $X_{NH3}$, the unburned CH$_4$ concentration of combustion emission had been declining as ultrasonic frequency increased. When the flame with $X_{NH3} = 0.1$ was excited by ultrasonic waves, the CH$_4$ emission concentration decreased by 14.91%, 29.04% and 41.67% with ultrasonic frequencies from 20 kHz, 25 kHz to 28 kHz, respectively, compared with no external action. When 28 kHz ultrasonic excited a flame with pure CH$_4$, $X_{NH3} = 0.2$ and $X_{NH3} = 0.3$, the CH$_4$ emission concentration decreased by 40.65%, 44.19% and 51.62%, respectively, compared with the flame without ultrasonic excitation. Compared with the flame without ultrasonic, the maximum increase of CO$_2$ reached 100.01% in working condition D. That is, the carbon conversion was complete during the combustion process.

The emission characteristics of NO and unburned NH$_3$ for different working conditions are displayed in Fig. 12, respectively. When the ultrasonic frequency that excited the flame was the same, NO and unburned NH$_3$ increased as $X_{NH3}$ increased. At the same $X_{NH3}$, the emission concentrations of NO and unburned NH$_3$ decreased as ultrasonic frequency increased. The largest reduction in NO concentration was 46.45% for flame with $X_{NH3} = 0.1$ excited by 28 kHz ultrasonic waves. When the
flame with $X_{NH_3} = 0.3$ was excited by 28 kHz ultrasonic waves, the unburned NH$_3$ concentration decreased the most, which was 54.86%.

![Fig. 1](image1.png)

**Fig. 12** NO and unburned NH$_3$ concentration variation with frequency at different fuel ratios.

![Fig. 13](image2.png)

**Fig. 13** Combustion efficiency variation with frequency at different fuel ratios.

From the above phenomenon, the flame structure was changed by the ultrasonic wave field, the flame height was reduced and the flame was lifted. The fuel contacted and reacted with sufficient air, which meant that many O radicals entered the reaction area. The diffusion rate of the fuel and the mixing rate of the fuel and air were increased, contributing to the widening of the violent reaction area. The addition of high-frequency acoustic waves increased the collision probability amongst the species in the reaction area. The blending homogeneity of the species was improved and the local equivalence ratio of flame was reduced. The further oxidation of carbonaceous compounds, such as CO in combustion, was promoted, which allowed additional unburned CH$_4$ to participate in the reaction. The heat and mass transfer processes were enhanced during the reaction process, and the combustion efficiency was improved. As illustrated in Fig. 11, the CO$_2$ emission concentration increased and the unburned CH$_4$ emission concentration decreased as ultrasonic frequency increased. When the flame was excited by ultrasonic waves, the flame exhibited premixed characteristics. At the same time, the ultrasonic effect promoted the sufficient contact between the intermediate combustion product NO and the unburned NH$_3$, which may trigger the selective non-catalytic reduction (SNCR) reaction. Fig. 12
display that the emission concentrations of unburned NH$_3$ and NO decreased as ultrasonic frequency increased, that is, NH$_3$ was burned fully and pollutant emissions were effectively suppressed under ultrasonic excitation. Fig. 13 showed the dependence of combustion efficiency on the ultrasonic wave frequency for different working conditions. At the same $X_{NH_3}$, the combustion efficiency increased as ultrasonic wave frequency increased.

4. Conclusion

The use of NH$_3$ offers a new idea for the development of the energy industry. However, the direct combustion of NH$_3$ as a fuel has shortcomings of poor combustion stability and high NOx emission. In this study, the ultrasonic loading system and simultaneous multiparameter measurement system of combustion were constructed. The effects of ultrasonic excitation on combustion enhancement and pollutant reduction were explored when the NH$_3$/CH$_4$ non-premixed flames were excited by ultrasonic waves. Based on the study of ultrasonic characteristics, ultrasonic waves of different frequencies were loaded in NH$_3$/CH$_4$ flames with different ratios. Flame shapes, flame colours, temperature distributions and component concentrations were obtained to analyse the law of NH$_3$/CH$_4$ combustion influenced by ultrasonic excitation. The results indicated that part of the hydrocarbon fuels was replaced by NH$_3$ to reduce CO$_2$ emission. As ultrasonic excitation was added to the combustion flow field, the flame height decreased, the flame colour was changed, the high-temperature region of the flame was expanded and the combustion temperature was increased. Furthermore, the combustion process of NH$_3$/CH$_4$ was enhanced. At the same time, the unburned NH$_3$ and NO$_X$ in the flue gas emissions reduced significantly, and the combustion efficiency increased as ultrasonic frequency increased. Consequently, ultrasonic excitation, as a physical action, is expected to be used in the industrial combustion optimisation of NH$_3$ fuel.

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Nomenclature

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References


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