# Experimental investigation of oxygen concentration effect on spherical turbulent flame propagation limits of ammonia–oxygen–nitrogen premixed flames

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## 1 Introduction

Ammonia ($NH_3$) is emerging as a promising carbon-free energy carrier and fuel due to its high hydrogen content, ease of storage and transport, and existing production infrastructure. As global decarbonization efforts accelerate, ammonia is gaining attention for use in power generation, transportation, and industrial applications. Recent studies have demonstrated effective power generation with low $NO_x$ emissions using rich-lean two-stage combustion in swirl combustors (Kobayashi et al., 2021[1]). To further optimize ammonia combustion, flame enhancement techniques are essential. Oxygen-enriched combustion has shown potential to improve flame stability, increase burning velocity, and raise flame temperature without altering combustion chemistry. This is particularly beneficial in high-temperature industrial applications such as turbulent jet diffusion flame combustors. Xia et al. (2024) [2] demonstrated that oxygen-enriched, rich-lean staged combustion can achieve low NOx emissions. However, fundamental understanding of turbulent ammonia combustion under oxygen-enriched conditions remains limited, highlighting the need for further research in this area.

The study of turbulent flame propagation and burning characteristics of ammonia is essential for understanding the safety, stability, and performance of combustion systems that utilize this fuel. Ichimura et al. [3] demonstrated that fuel-lean ammonia–air premixtures are capable of sustaining flames at higher turbulent Karlovitz numbers compared to fuel-rich mixtures, primarily due to diffusional-thermal instability. Similarly, Xia et al. [4] emphasized the role of diffusional-thermal instability in the turbulent flame propagation of ammonia under oxygen-enriched conditions. Hashimoto et al. [5] investigated the turbulent flame propagation and extinction of ammonia–methane–air premixtures, reporting that fuel-lean mixtures exhibit enhanced flame stability at high Karlovitz numbers, which can be attributed to diffusional-thermal effects. Furthermore, Dai et al. [6] explored the impact of the Lewis number on both laminar and turbulent expanding flames in ammonia–hydrogen–air mixtures at elevated pressures. Their results suggest that turbulent flames in these mixtures exhibit self-similar propagation, with flames characterized by a Lewis number (*Le*) less than 1 propagating more rapidly.

One critical aspect of this investigation is determining the turbulent flame propagation limits, which define the conditions under which a premixed flame can stably propagate in turbulent flow. These limits are influenced by several factors, including fuel composition, equivalence ratio, temperature, pressure,

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and turbulence intensity. While previous studies have provided valuable insights into the laminar and turbulent flame characteristics of ammonia–air mixtures [3], the effects of oxygen enrichment and nitrogen dilution on turbulent flame extinction behavior remain inadequately explored.

This study aims to investigate the turbulent flame propagation limits of ammonia–oxygen–nitrogen premixtures under oxygen-enriched conditions. By systematically varying the equivalence ratio and turbulence intensity, we seek to elucidate the complex interactions between flame and turbulence eddies. The findings of this research will contribute valuable insights into the fundamental combustion characteristics of ammonia, thereby supporting the development of advanced combustion systems for ammonia-based energy applications.

## 2 Experimental methods

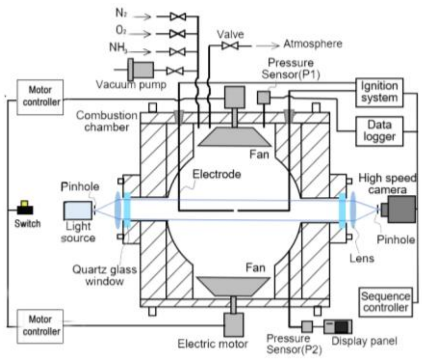



Fig. 1 Schematic figure of experimental apparatus.

The schematic diagram of the experimental setup is shown in Figure 1. The combustion experiments were conducted in a constant-volume spherical combustion chamber with an inner diameter of 200 mm and a height of 280 mm.

The mixture was ignited by an electric spark, providing an energy of 2.8 J at the center of the chamber. To generate near-homogeneous and near-isotropic turbulence, two identical counter-rotating seven-bladed fans were mounted at the top and bottom of the chamber. Turbulence parameters were measured using particle image velocimetry (PIV). The PIV measurements indicated that the turbulence intensity was nearly proportional to the fan rotational speed. The longitudinal integral length scale, $L_f$, was found to be 20.9 mm, irrespective of the turbulence intensity. In all experiments, the initial pressure and temperature were set to 1 atm and 298 K, respectively. The equivalence ratio, $\phi$, was varied from 0.9 to 1.2, while the turbulence intensity, ranged from 0 m/s to 4.0 m/s. $\Omega$ of 0.23 was used for current research to obtain the $O_2$-enriched condition. At least six combustion experiments were performed on each condition to obtain repeatability results.

$\Omega$ was defined as follows:

$$\Omega = \frac{X_{O_2}}{X_{O_2} + X_{N_2}} \tag{1}$$

$X$ means mole fraction. The detailed experimental conditions can be found in Table 1.

Table 1 Physical properties of the mixtures in current experiments

| Ω | $\phi$ | $Le$ [-] | $T_{ad}$ [K] |
|---|---|---|---|
| | 0.8 | 0.938 | 1859.640 |
| | 0.9 | 0.930 | 1976.990 |
| 0.21 | 1.0 | - | 2071.390 |
| | 1.1 | 1.097 | 2022.120 |
| | 1.2 | 1.096 | 1950.800 |
| | 0.8 | 0.930 | 1946.64 |
| | 0.9 | 0.922 | 2063.52 |
| 0.23 | 1.0 | - | 2151.60 |
| | 1.1 | 1.101 | 2107.71 |
| | 1.2 | 1.100 | 2032.36 |

## 3 Laminar burning characteristics

For the discussion of turbulent flame extinction characteristics of ammonia flames under oxygen-enriched conditions, the laminar burning velocity is a crucial parameter for quantifying both turbulent burning and extinction behaviors. Therefore, the laminar burning velocity of ammonia combustion under oxygen-enriched conditions was calculated using CHEMKIN Pro[7]. Three chemical kinetic mechanisms were employed for the calculation of laminar burning velocity: those developed by Nakamura et al. [8], Okafor et al.[9], and Shrestha et al. [10]. To validate the chemical kinetic mechanism, published experimental data were utilized. The experimental results for Ω = 0.21 were obtained from our previous research [3] and Hayakawa et al. [11], while those for Ω = 0.23 were sourced from Shrestha et al. [10].

As shown in Figure 2, the predictions of laminar burning velocity using Okafor's mechanism exhibit good agreement with the experimental data for Ω = 0.21 and 0.23. Consequently, the laminar burning velocity results predicted by Okafor's mechanism were adopted for the subsequent discussion on turbulent flame propagation limits.

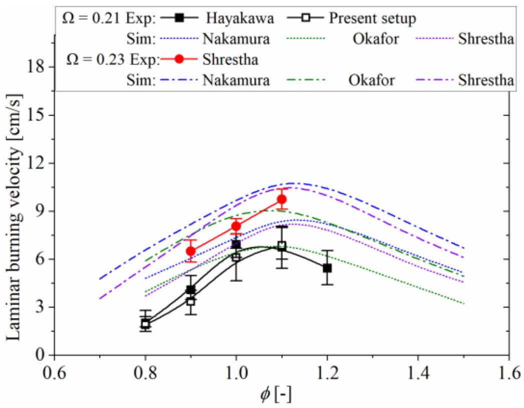



Fig. 2 The comparison of experimental and simulation results of laminar burning velocity

## 4 Turbulent flame propagation limits of ammonia under oxygen enriched conditions

Figure 3 presents the turbulent flame propagation probability map for ammonia–oxygen–nitrogen flames under Ω = 0.23, across varying turbulence intensities and ammonia equivalence ratios. For each condition, at least six experiments on turbulent flame extinction were conducted. However, consistent flame propagation or extinction outcomes were not always observed under identical conditions. Moreover, the turbulent flame propagation probabilities (*p*) were classified into four categories: blue squares represent 100% propagation, green circles indicate 50%–99% propagation, purple triangles denote 1%–49% propagation, and black crosses correspond to 0% propagation. The turbulent flame propagation limits were defined as the boundary between the propagation region ($p > 0\%$) and the non-propagation region ($p = 0\%$).

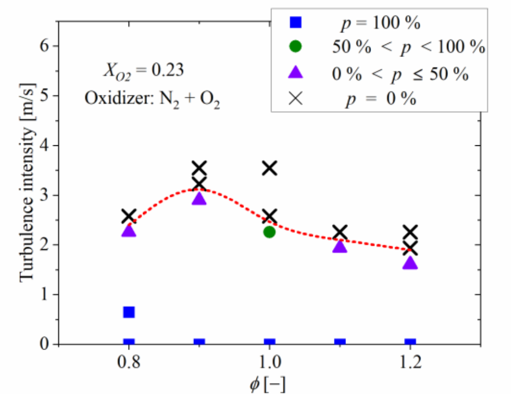


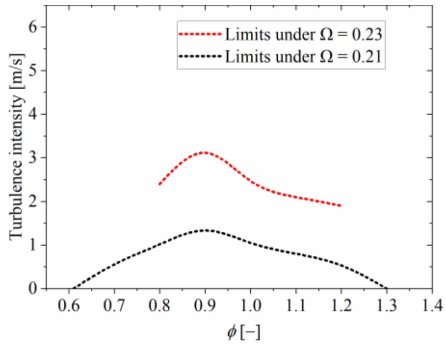

Fig. 3 Turbulent flame propagation probability map for ammonia–oxygen–nitrogen premixtures under Ω = 0.23.

As shown in Fig. 3, the turbulence intensity required to achieve turbulent flame propagation limits initially increases with the equivalence ratio of the premixed mixtures, from 0.8 to 0.9. However, as the equivalence ratio increases from 0.9 to 1.2, the required turbulence intensity decreases. At an equivalence ratio of 0.9, ammonia–oxygen–nitrogen flames exhibit the highest turbulence intensity for sustained propagation. Notably, the maximum laminar burning velocity of ammonia–oxygen–nitrogen flames under $\Omega = 0.23$ occurs at an equivalence ratio of 1.1.

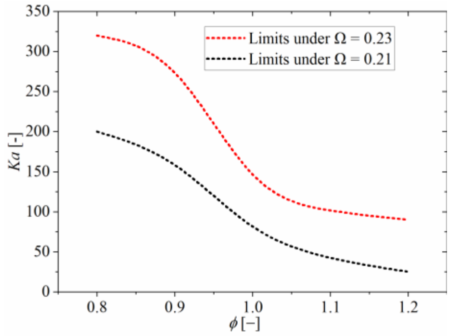
The black line in Fig. 4(a) shows the turbulent flame propagation limits for ammonia–air premixtures [3], while the red line represents the limits obtained under $\Omega = 0.23$. As demonstrated in Fig. 4(a), the turbulent flame propagation limits expand with increasing oxygen concentration in the oxidizer. Despite variations in oxygen concentration, the premixed mixtures sustain the highest turbulence intensity at an equivalence ratio of 0.9.

Figure 4(b) demonstrated the turbulence Karlovitz number (*Ka*) at turbulent flame propagation limits. As shown in Fig. 4(b), the turbulence *Ka* at turbulent flame propagation limits decreases with the increase of equivalence ratio. This phenomenon may corelated to the sensitivity of the flame to stretch caused by the turbulence. Under fuel lean case, the flame can be sustained under high turbulence level (quantified by the turbulence *Ka* number). It is thus plausible that diffusional-thermal instability influences the turbulent flame extinction phenomena in the combustion of ammonia–oxygen–nitrogen mixtures under oxygen-enriched conditions. As shown in Table 1, for ammonia-lean mixtures, the Lewis number is less than unity, indicating that mass diffusion dominates over thermal diffusion. When the flame surface is distorted by turbulent eddies, creating concave and convex shapes, the local burning velocity is influenced by diffusional-thermal instability. In concave flame regions, where the Lewis number is less than unity, the mass diffusion of reactants from the unburned to the burned area exceeds the thermal diffusion from the burned to the unburned area. Consequently, the local temperature and burning velocity in convex regions increase, promoting the development of a convex shape, while those in concave regions decrease, enhancing the concave structure. This effect ultimately leads to an overall increase in burning velocity due to the expanded flame surface area, driven by diffusional-thermal effects associated with a Lewis number less than unity. However, when the Lewis number exceeds unity, the convex and concave structures tend to be suppressed due to the opposite effect. Consequently, ammonia–oxygen–nitrogen flames can sustain a flame at the highest turbulence intensity for an equivalence ratio of 0.9, despite the fact that the maximum laminar burning velocity for ammonia–oxygen–nitrogen flames occurs at an equivalence ratio of 1.1.

According to Faghih et al.[12], ammonia flames with low burning velocities may experience significant radiation heat loss, particularly for very lean and rich mixtures, leading to a reduction in laminar burning velocity. Additionally, Shy et al. [13] found that lean $CH_4$–diluent–air flames with radiation heat loss are more difficult to quench compared to richer mixtures under the same laminar burning velocity conditions. In the present study, where all mixtures have a laminar burning velocity less than or equal to 9 cm/s, both flames investigated are likely influenced by radiation heat loss, especially under lean ($\phi$ = 0.8) and rich ($\phi$ = 1.2) conditions. However, in the lean case ($\phi$ = 0.8), despite higher radiation heat loss, the turbulent Karlovitz number (*Ka*) at the turbulent flame propagation limit is the highest among the cases. In contrast, under rich conditions ($\phi$ = 1.2), where radiation heat loss is also significant, the turbulent *Ka* at the turbulent flame propagation limit is the lowest. These observations highlight the critical role of diffusional-thermal instability in determining the turbulent flame propagation limits, reinforcing the main conclusion of the current research.




(a) effect of oxygen concentration on turbulent flame propagation limits of ammonia–oxygen–nitrogen premixtures




(b) The turbulence Karlovitz number, *Ka*, at turbulent flame propagation limits as function of equivalence ratio.

Fig. 4 Effect of oxygen concentration on turbulent flame propagation limits of ammonia–oxygen–nitrogen premixtures

## 5 Turbulent flame propagation limits of ammonia under oxygen enriched conditions

In this study, turbulent flame propagation and extinction experiments of ammonia flames were conducted under oxygen-enriched conditions with an oxygen concentration of 0.23 and compared with previously published data on ammonia–air flames. The findings indicate that the turbulent flame propagation limits expand with an increase in the oxygen concentration in the oxidizer. Moreover, the premixed mixture with an equivalence ratio of 0.9 can sustain the highest turbulence intensity. It is hypothesized that diffusional-thermal instability may play a important role in the turbulent flame propagation and extinction behavior of ammonia–oxygen–nitrogen premixtures under oxygen-enriched conditions. Further experiments will be conducted to consolidate the conclusions of this research.

## Acknowledgements

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