

# Combustion of $\text{NH}_3\text{-CH}_4$ blend in a Coaxial Swirl Burner

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**Abstract.** Ammonia is a promising carbon-free fuel for decarbonizing the energy sectors. However, implementing it in combustion systems is limited by difficulties in maintaining flame stability and controlling nitrogen oxide ( $\text{NO}_x$ ) emissions. This study investigates the turbulent non-premixed combustion of  $\text{NH}_3\text{-CH}_4$  blend in a coaxial swirl burner under atmospheric pressure, using experimental diagnostics. Two configurations are examined: (i) high swirl number ( $\text{Sn} = 1.4$ ) and (ii) low swirl number ( $\text{Sn} = 0.8$ ). Flame structure and stability was analysed via  $\text{OH}^*$  and  $\text{NH}_2^*$  chemiluminescence imaging of four blend cases. Results show that high swirl enhances mixing of fuel and oxidizer resulting in a compact flame anchored to the burner. In contrast, low swirl shows better flame stability, the flame is more diffused toward radial and axial direction. However, it indicates higher  $\text{NO}_x$  emissions.

## 1 Introduction

The need to decarbonize energy sectors is increasing by environmental stringent laws, therefore the need for carbon-free fuels has intensified research into the subject. Ammonia ( $\text{NH}_3$ ) has emerged as a promising option due to its zero-carbon emission during combustion, established global infrastructure of production and transport, and high energy density (7.1–2.9 MJ/L) [1]. However,  $\text{NH}_3$  exhibits a low laminar flame speed (~6 cm/s vs. ~34 cm/s for  $\text{CH}_4$ ), narrow flammability limits, and high auto-ignition temperature (650°C), posing significant challenges for flame stabilization in practical burners [2].

Recent studies have explored  $\text{NH}_3$  combustion primarily in premixed swirl configurations [3], whereas non-premixed systems are more representative of industrial furnaces and gas turbines they remain less understood. Blending  $\text{NH}_3$  with  $\text{CH}_4$  provides a promising transitional pathway, combining methane's favorable combustion characteristic (higher laminar flame speed) with reduced  $\text{CO}_2$  emissions [4]. The influence of burner design, including coaxial configuration and swirl, is a critical factor in controlling flame stability, temperature distribution, and pollutant formation. Swirl-induced recirculation zones have been shown to reduce peak temperatures and pollutant emissions by enhancing fuel-air

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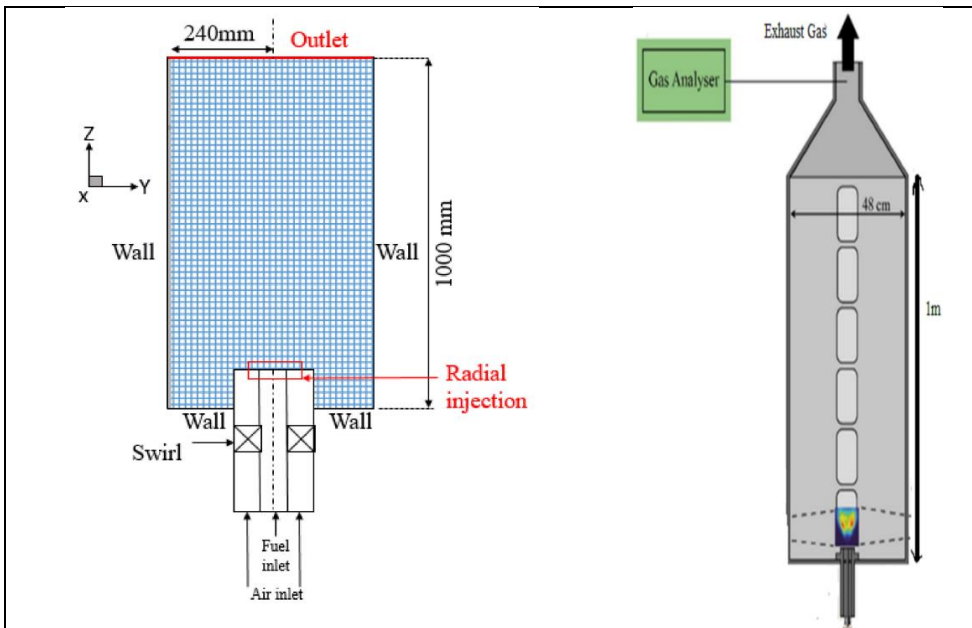
mixing [5]. On the other hand, swirl number have impact on flame structure, intermediate radical ( $\text{OH}^*$ ,  $\text{NH}_2^*$ ) distributions, and pollutant formation [6]. However, despite growing interest in  $\text{NH}_3$  flames, a systematic comparison between high and low swirl regimes in non-premixed, turbulent flames of  $\text{NH}_3\text{-CH}_4$  mixture with air as an oxidizer covering flame structure and stability limits has not yet been established. Addressing these points are essential for developing robust burner designs capable of operating with ammonia with low  $\text{NO}_x$  formation.

This study combined experimental investigation of  $\text{NH}_3\text{-CH}_4\text{-air}$  flames at 10 kW in a coaxial swirl burner, comparing  $\text{Sn} = 1.4$  (high swirl) and  $\text{Sn} = 0.8$  (low swirl) across 0–30%  $\text{NH}_3\text{-CH}_4$  blend. Flame morphology is characterized via  $\text{OH}^*$  and  $\text{NH}_2^*$  chemiluminescence along the experience.

## 2 Experimental Setup and Methods

### 2.1 Combustion Chamber Configuration

Experiments were conducted in a combustion chamber (1000 mm height, 480mm diameter) at atmospheric pressure and 10 kW thermal input. A coaxial swirl burner injected  $\text{CH}_4/\text{NH}_3$  radially through eight 3-mm holes, while air flowed co-axially through an annular passage ( $D = 38$  mm). Two swirlers were used ( $\text{Sn} = 1.4$  and  $\text{Sn} = 0.8$ ), positioned 60 mm upstream of the burner exit as represented in the Fig.1. The equivalence ratio in the conducted experiment was  $\phi = 1$ .



**Fig. 1.** Combustion chamber geometry

### 2.2 Diagnostics

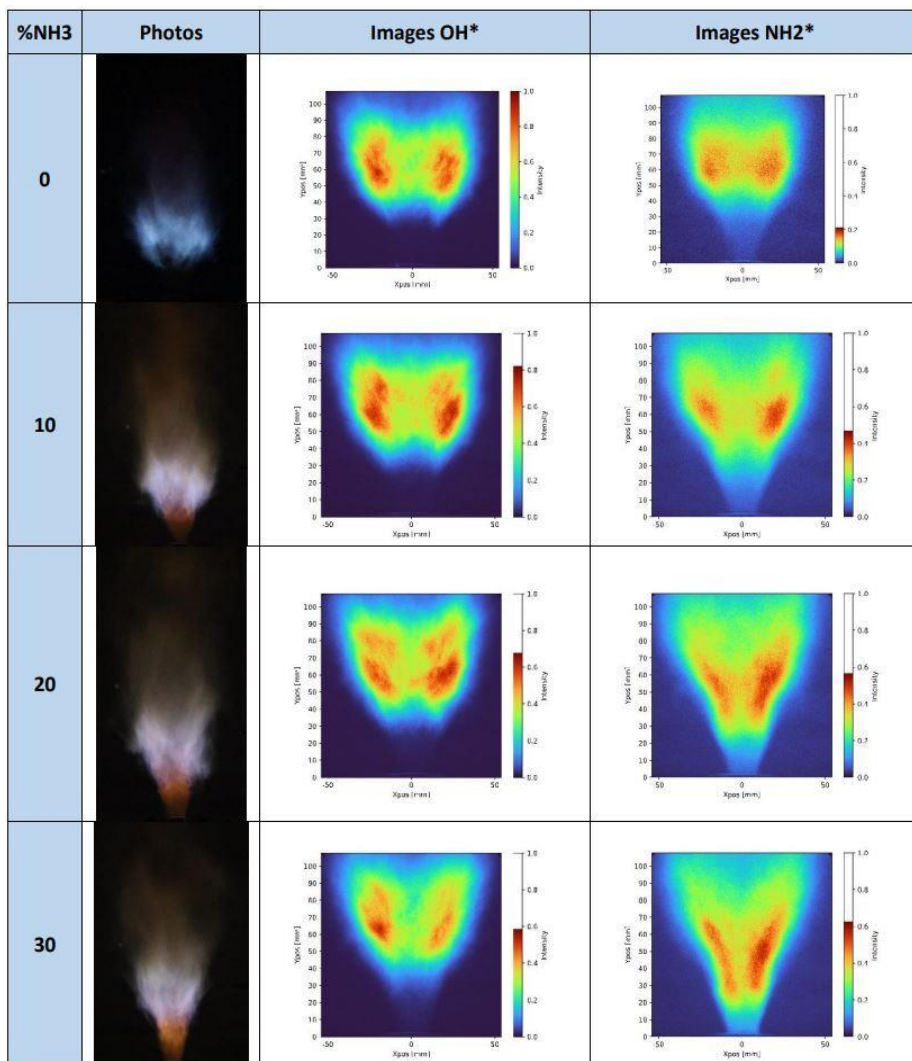
The chemiluminescence technique was used to get  $\text{OH}^*$  ( $310 \pm 5$  nm) and  $\text{NH}_2^*$  ( $632 \pm 5$  nm) radical emissions were captured using an intensified CCD camera (PI-MAX4) to assess flame structure and anchoring.

### 3 Results and Discussion

#### 3.1 Flame structure

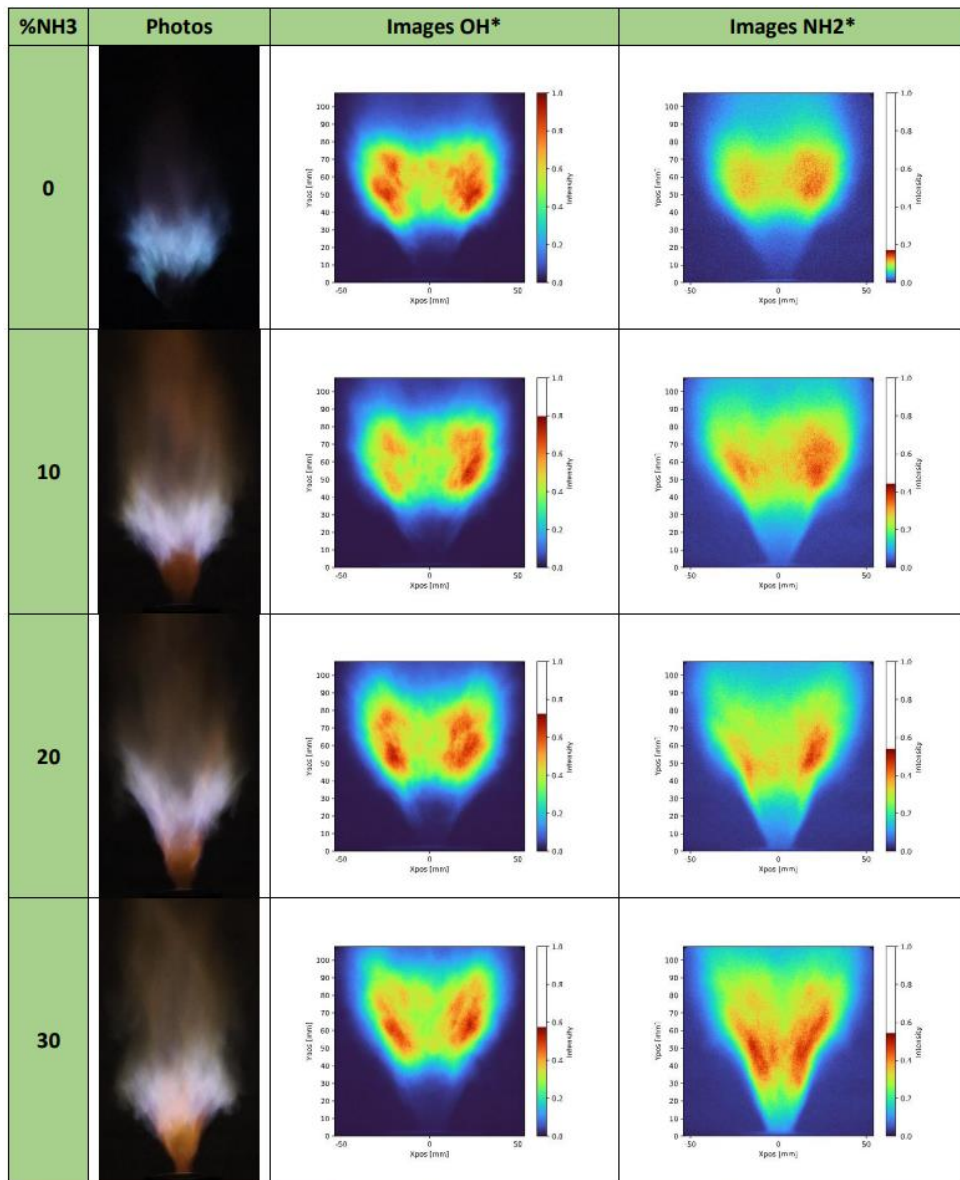
Figures 2 and 3 present OH\* and NH<sub>2</sub>\* chemiluminescence images of NH<sub>3</sub>-CH<sub>4</sub> flames for swirl numbers Sn = 1.4 (high swirl) and Sn = 0.8 (low swirl), respectively, across ammonia blending ratios ranging from 0% to 30%.

Under high swirl conditions (Sn = 1.4) and for 0% NH<sub>3</sub>, a lifted methane flame is observed. It is characterized by strong OH\* intensity, indicating high reaction rates associated with methane oxidation. As the NH<sub>3</sub> fraction increases to 10% and 20%, the flame becomes progressively closer to the burner exit. At 30% NH<sub>3</sub>, a stable Y-shaped flame structure emerges. This can be caused by vortex breakdown and formation of a strong inner recirculation zone (IRZ). This can be verified with numerical simulation in future work.



**Fig. 2.** Flame behaviour across different NH<sub>3</sub> fractions from 0 to 30% for high swirl (Sn = 1.4)

In contrast, under low swirl conditions ( $Sn = 0.8$ ), the flame structure is significantly more extended in both axial and radial directions. The reaction zone appears broader and less confined, indicating weaker recirculation and reduced mixing intensity compared to the  $Sn = 1.4$ . The  $OH^*$  chemiluminescence intensity decreases progressively with increasing  $NH_3$  fraction for both swirl number. Simultaneously,  $NH_2^*$  emission increases when increasing  $NH_3$  proportion in the blend. This highlights the enhanced ammonia decomposition pathways.



**Fig. 3.** Flame behaviour across different  $NH_3$  fractions from 0 to 30% for high swirl ( $Sn = 0.8$ )

### 3.2 Pollutant emissions

Figure 4 presents the evolution of  $\text{NO}_x$  and  $\text{CO}_2$  emissions as a function of ammonia fraction for both swirl numbers. For  $\text{Sn} = 1.4$ ,  $\text{NO}_x$  emissions reach a maximum of 1272 ppm at 20%  $\text{NH}_3$ . In contrast, under low swirl conditions ( $\text{Sn} = 0.8$ ),  $\text{NO}_x$  emissions increase significantly and reach 1850 ppm at the same ammonia fraction. This increase in  $\text{NO}_x$  emissions under low swirl conditions can be attributed to weaker mixing, resulting in localized high-temperature zones and enhanced thermal  $\text{NO}_x$  formation. In contrast, the stronger recirculation under high swirl may promote temperature homogenization and reduce peak flame temperature, thereby limiting  $\text{NO}_x$  formation.

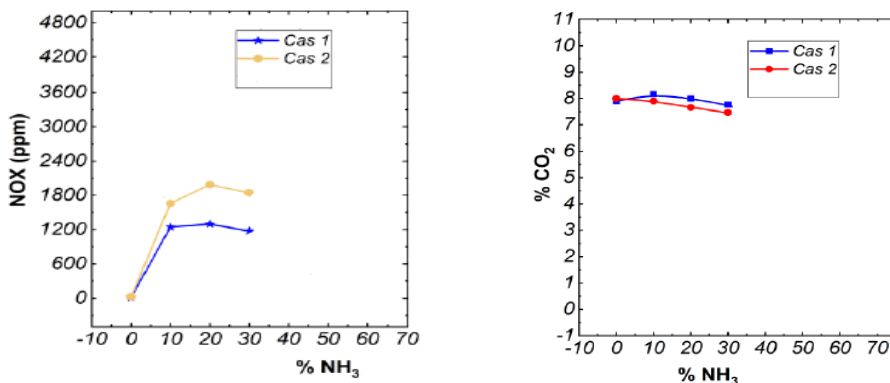


Fig. 4.  $\text{NO}_x$  and  $\text{CO}_2$  emissions

A consistent decrease in  $\text{CO}_2$  emissions is observed with increasing  $\text{NH}_3$  fraction for both swirl numbers. This trend is primarily attributed to the progressive replacement of carbon-containing methane with carbon-free ammonia, resulting in a reduced overall carbon input to the combustion process. Under high swirl conditions ( $\text{Sn} = 1.4$ ), the lowest  $\text{CO}_2$  emission level is recorded at 30%  $\text{NH}_3$ , corresponding to approximately 7.8% of the total measured emissions. In contrast, under low swirl conditions ( $\text{Sn} = 0.8$ ),  $\text{CO}_2$  emissions decrease further to approximately 7.4% under the same ammonia fraction. This represents a relative reduction of about 0.4 percentage points compared to the high swirl configuration. The overall decrease in  $\text{CO}_2$  emissions confirms the effectiveness of ammonia blending as a viable decarbonization strategy. These findings demonstrate that increasing ammonia content significantly reduces carbon emissions while maintaining stable combustion conditions, highlighting the potential of  $\text{NH}_3\text{-CH}_4$  blends for low-carbon energy applications.

The optimal operating condition was determined based on flame stability, emissions performance, and flame structure. Among the investigated configurations, the high swirl condition ( $\text{Sn} = 1.4$ ) combined with  $\text{NH}_3$  blending ratios 30% provided the best performance. Under this condition, the flame exhibited good anchoring (distance to the burner exit 20mm), enhanced compactness (35mm). Additionally,  $\text{NO}_x$  emissions were significantly the lowest (1050ppm) compared to the other experiences. The  $\text{CO}_2$  emissions were in order of 7.8% of the total pollutant emission. Although this value is slightly higher compared to the lower swirl number ( $\text{Sn}=0.8$ ) condition, it still improved structure and compactness and reduced pollutant formation of  $\text{NO}_x$  and  $\text{CO}_2$ .

Table 1 compares the present work with previous studies to contextualize the present work contributions. While prior investigations have established the fundamental combustion

properties of NH<sub>3</sub>-CH<sub>4</sub> blends [2], these studies were largely limited to laminar or simplified combustion configurations. Similarly, other investigations [7-8] reported global emission characteristics but did not resolve flame structure or radical distribution. More recent work [9] focuses on ignition delay, combustion duration, and spatial NO<sub>x</sub> distribution in internal combustion engine or on clarifying synergistic effects of CO<sub>2</sub> and H<sub>2</sub> on flame instability, SL, and NO emissions [10].

**Table 1.** Contextualization to literature.

Study	Burner type	Fuel	Swirl Flow /	NH <sub>3</sub> ratio	Diagnostics	Key findings	Limitations
[9]	Laminar burner	NH <sub>3</sub> -CH <sub>4</sub>	No swirl	0-100%	Burning velocity	NH <sub>3</sub> reduces flame speed by up to 50%	No turbulent swirl
[10]	Gas-turbine combustor	NH <sub>3</sub> -CH <sub>4</sub>	Strong swirl	0-50%	Emissions, temperature	Stable combustion up to 40% NH <sub>3</sub>	No flame imaging
[12]	Constant volume combustion chamber	NH <sub>3</sub> with H <sub>2</sub> addition	No swirl, controlled injection	Varied NH <sub>3</sub> /H <sub>2</sub> ratios	High-speed imaging, pressure, species analysis	H <sub>2</sub> improves ignition and stability; NO <sub>x</sub> depends on H <sub>2</sub> fraction; some modes reduce peak NO <sub>x</sub>	Lab-scale chamber, not real burner; limited flow conditions; experimental focus
[13]	Constant volume combustion chamber	NH <sub>3</sub> /CH <sub>4</sub> with CO <sub>2</sub> dilution	No swirl, controlled injection	Varied NH <sub>3</sub> /H <sub>2</sub> ratios	synergistic effects of CO <sub>2</sub> and H <sub>2</sub> on flame instability, SL, and NO emissions	dilution reduces laminar burning velocity	NH <sub>3</sub> /CH <sub>4</sub> with CO <sub>2</sub> dilution (0-30%) and H <sub>2</sub> addition (20-40%)

The present study provides a detailed experimental characterization of turbulent NH<sub>3</sub>-CH<sub>4</sub> swirl combustion using optical diagnostics (chemiluminescence images). Unlike previous studies, the effect of swirl number was quantitatively evaluated based on emissions performance and flame structure, demonstrating that a high-swirl condition (Sn = 1.4) combined with an ammonia blending ratio of 30% yields optimal combustion performance. Under these conditions, the flame exhibited excellent anchoring, with a stabilized distance of 20 mm from the burner exit, and enhanced compactness. Notably, NO<sub>x</sub> emissions were minimized, reaching 1050 ppm, which is significantly lower than in other tested configurations. Furthermore, the study experimentally confirms that ammonia blending reduces CO<sub>2</sub> emissions to as low as 7.8% of total emissions at 30% NH<sub>3</sub>, supporting ammonia's role as a carbon-free energy carrier. Thus, this work provides a combined analysis of swirl intensity, radical chemiluminescence (OH\*, NH<sub>2</sub>\*), flame structure, and emissions for NH<sub>3</sub>-CH<sub>4</sub> combustion in a coaxial swirl burner.

## 4 Conclusions

This study experimentally investigated the turbulent non-premixed combustion characteristics of NH<sub>3</sub>–CH<sub>4</sub> blends in a coaxial swirl burner under atmospheric pressure, with a particular focus on the influence of swirl number and ammonia blending ratio on flame structure and emissions performance. Two swirl configurations (Sn = 0.8 and Sn = 1.4) were examined over ammonia fractions ranging from 0% to 30%, using OH\* and NH<sub>2</sub>\* chemiluminescence imaging and exhaust gas analysis.

Based on the combined analysis of flame structure and emissions performance of NO<sub>x</sub> and CO<sub>2</sub>, the optimal operating condition was identified at high swirl intensity (Sn = 1.4) with 30% NH<sub>3</sub> blending ratio. This condition provides a compromise between good flame anchoring, low NO<sub>x</sub> formation and a reduction in CO<sub>2</sub> emissions.

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