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Numerical Analysis of Dual-Swirl Effects on NOx Emissions in Hydrogen Combustion

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ABSTRACT

Hydrogen combustion offers a promising pathway toward carbon-free energy conversion, especially for gas turbines and aviation applications. However, its high flame temperature can lead to nitrogen oxide (NOx) formation. This study numerically investigates the effect of dual-air swirling on flame behavior, temperature distribution, and NOx emissions in a hydrogen-fueled bluff-body combustor. A modified combustor geometry with two co-flow air inlets was simulated using ANSYS Fluent. The flow was modeled using the Reynolds-Averaged Navier–Stokes approach with the RNG k–ε turbulence model, a non-premixed combustion model using probability density function treatment, and the discrete radiation model. Nine dual-swirl angle combinations of 30°, 45°, and 55° were examined and compared with a non-swirling baseline case. The results show that swirl angle strongly influences air–fuel mixing, recirculation strength, peak temperature, and NOx formation. Higher swirl angles generally enhanced mixing and flame compactness but increased peak temperature and thermal NOx emissions. Among the swirling cases, the 30°–30° configuration provided the best compromise, producing a stable flame with relatively uniform temperature distribution and the lowest NOx level among the dual-swirl configurations. The 30°–55° configuration produced the highest local NOx concentration, reaching 1699.40 ppm due to the increased peak flame temperature and stronger recirculation intensity. In contrast, reversing the swirl arrangement to 55°–30° significantly reduced the outlet-averaged NOx concentration to 3.84 ppm, demonstrating the strong sensitivity of dual-swirl systems to inlet configuration. Overall, the findings demonstrate that careful selection of dual-swirl angles can improve hydrogen flame stability while controlling NOx emissions, supporting cleaner hydrogen combustion systems.

Keywords: CFD Simulation, hydrogen Combustion, dual-swirl combustor, NOx Emissions, swirl angle, flame stabilization

1. INTRODUCTION

The need for sustainable, carbon-free, and efficient fuels has been increasing, owing to growing health and environmental concerns. Investigating various fuel options has demonstrated that using pure H_2 can minimize CO and CO_2 emissions and reduce fuel consumption by 58.81% [1]. However, combusting hydrogen produces water vapor and nitrogen oxides (NOx) that increase ozone concentration, and contribute to greenhouse gases [2]. Consequently, optimizing H_2 combustion to improve its performance as a fuel and reduce emissions has become a key research area.

NOx are common pollutants produced in high-temperature combustion environments. Swirlers are employed in combustion systems to control the temperature distribution. Introducing a swirl into the airflow creates a rotating flow pattern that induces a recirculation zone in the combustion chamber, thereby reducing the temperature gradients within the flame and spreading the heat more evenly, and resulting in lower NOx emissions [3–6].

Research on combustion in swirl-stabilized combustors has either considered single-swirler configurations or focused on gaseous fuels other than pure H_2. Additionally, most research has been limited to theoretical swirl-number adjustments or single air-fuel-stage variations [4,5,7,8], neglecting the interplay between two distinct swirl air inlets and their impact on the combustion stability and NOx reduction. Several studies have investigated swirl-stabilized combustion to improve the flame stability and reduce pollutant emissions. Previous investigations have reported that increasing the swirl intensity enhances the internal recirculation zones, improves fuel-air mixing, and reduces thermal NOx formation through better temperature distribution [3–6]. Other studies have focused on single-swirler combustors operating with conventional gaseous fuels, such as methane [4,5,7,8].

Although these studies have provided important insights into the combustion behavior and emissions, they examined either single-swirler configurations or generalized swirl number variations without considering the interaction between multiple swirling air streams. More recent studies have explored H_2 combustion in dual-swirl combustors [9,10]. However, the combined influence of two independent swirl air inlet angles on the flame stabilization, combustion characteristics, and NOx emissions for pure H_2 has not been investigated. Therefore, a significant research gap exists in terms of optimizing the dual-swirl angle configurations for H_2-fueled combustors.

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The novelty of this study lies in using computational fluid dynamics (CFD) to investigate nine dual-swirl angle combinations operating on pure H_2, and identify the optimal configuration that simultaneously enhances the flame stability and reduces the NOx emissions. Unlike previous studies that focused on single-swirl systems or non-H_2 fuels, this study evaluates the interaction between two swirling airstreams and their influence on the combustion performance within a dual-swirl combustor configuration. The results of this study will contribute to developing more efficient and environmentally friendly H_2 combustion systems for aeronautics, gas turbines, and other industrial applications [14,15].

2. METHODOLOGY

2.1. Computational Domain and Boundary Conditions. The geometry of the combustor in this study was based on the KAUST experimental setup for a non-premixed ammonia–H_2 bluff-body-stabilized flame [16,17]. The original design included a bluff-body burner with a central fuel jet surrounded by co-flow air, which is known to enhance the recirculation and stabilize the flame. The originally used single co-flow air inlet was modified to include two co-flow air inlets, which enabled exploring the impact of dual air inlets with different flow conditions on the flame stability and NOx emissions using H_2.

The fuel enters the domain through a long narrow pipe and mixes with the two incoming air flows at the pipe exit. The mixture is then ignited and stabilized using the bluff-body. The inlets are defined as velocity inlets with an ambient temperature of 300 K and velocity magnitudes of 52.95 m/s and 12.84 m/s for the fuel inlet and the two air co-flow inlets, respectively. However, the air co-flow is a swirl with a defined swirling angle. The dual-inlet configuration can enhance the mixing and recirculation zones in the flame, which are critical for stabilizing the combustion process and reducing emissions. The reported NOx values represent the total NOx concentration predicted by the combustion model, including NO and NO_2.

The modified geometry, as shown in Figure 1(a), provided more detailed insights into the impact of the swirl configurations and optimized the balance between the flame stability and NOx reduction in H_2-fueled combustors. Additionally, the geometry was reduced to one-eighth of the original design to improve the computational efficiency, thereby significantly reducing the computational cost without sacrificing the accuracy of the flame structure and mixing processes. The key dimensions of the computational domain are illustrated in Figure 1(b), and their values listed in Table S1.

2.2. Assumptions . In this study, several assumptions were made to simplify the study and reduce the computational cost while ensuring the accuracy of the results.

First, H_2 and air in the combustor were treated as ideal gases, which allowed using the ideal gas law to calculate properties such as the density and specific heat at various temperatures. A Reynolds-averaged Navier–Stokes (RANS) turbulence model was employed to simulate the turbulent flow within the combustor; specifically, the renormalization group (RNG) k–ε turbulence model. RNG models have been proven to efficiently capture the average turbulence effects in industrial combustion systems while maintaining a low computational cost [18–20]. Additionally, a discrete ordinate (DO) radiation model was employed throughout this study [21], because of its proven ability to solve surface-to-surface participation in radiation, and increase the number of rays to improve the accuracy of the results.

A non-premixed model was applied for the combustion process, utilizing the probability density function (PDF) method to account for the turbulence–chemistry interaction and predict the species mass fractions and temperature distributions.

Another assumption was periodicity, implying that the velocity components repeated themselves, and only one-eighth of the original geometry was used in this study. This method has been proven to be efficient in reducing the computational cost while generating accurate results [1].

Finally, the process was assumed to be steady; therefore, the time-dependent flame dynamics were not considered.

These simplifications are valid for this study, which investigates the flame stability and NOx emissions considered to be steady-state combustion characteristics. In this study, the reported NOx emissions represent the total NOx concentrations, including NO, NO_2, and N_2O.

Governing equations, the mesh independence study performed to obtain the final converged mesh for simulations, and a description of the model validation are detailed in the supplementary material.

Table 1. *Angle combinations used in the simulations*

Case number	Angle employed in co-flow 1 (°)	Angle employed in co-flow 2 (°)
Base	0	0
1	30	30
2	30	45
3	30	55
4	45	30
5	45	45
6	45	55
7	55	30
8	55	45
9	55	55

3. RESULTS AND DISCUSSION

Using the methods described in Section 2, a simulation was performed in ANSYS Fluent, and the results were analyzed in terms of the temperature, NOx, vorticity, NOx at the outlet, and temperature at the outlet. Nine simulation cases were studied, each with a different combination of swirl angles. The angles investigated in this study are listed in Table 2.

3.1. Temperature Distribution and Velocity Flow Analysis. Figure 4 illustrates the different temperature distributions for the various cases. In the low-angle configuration (Case 1), the temperature was uniformly distributed with a

moderate gradient. Additionally, the flow exhibited more symmetrical behavior owing to the low mixing intensity, resulting in a stabilized flame with a low peak temperature. For Case 2, a slight increase in the second co-flow angle led to an increased air-fuel mixing, resulting in higher temperatures at the center. The temperature increased notably, but the flame remained stable.

Increasing the second co-flow angle (Case 3) showed a noticeable temperature gradient, with a very high temperature closer to the fuel inlet, owing to the stronger mixing introduced by the higher angle. The highest temperature was observed in this configuration and the flame front was more concentrated, indicating efficient fuel combustion.

The configuration in Case 4 demonstrated a greater stability at high temperatures but was still lower than that for the previous case. Cases 5, 6, and 7 showed higher but more uniform temperatures. The 45° angle improved the mixing and increased the flame stability, leading to higher overall temperatures. Additionally, it indicated efficient combustion in some areas and potential thermal losses in other areas.

Case 8 demonstrated a pattern similar to that of Case 3, with very strong mixing leading to strong combustion near the injector. However, the flame front was the hottest, with a strong decrease downstream, demonstrating a nonuniform distribution. Case 9 surprisingly showed a significantly lower peak temperature but less uniform temperature distribution, with a very high temperature at the start of the flame.

Finally, a base case without swirling was analyzed to facilitate comparing the different angles. As shown in the base case,

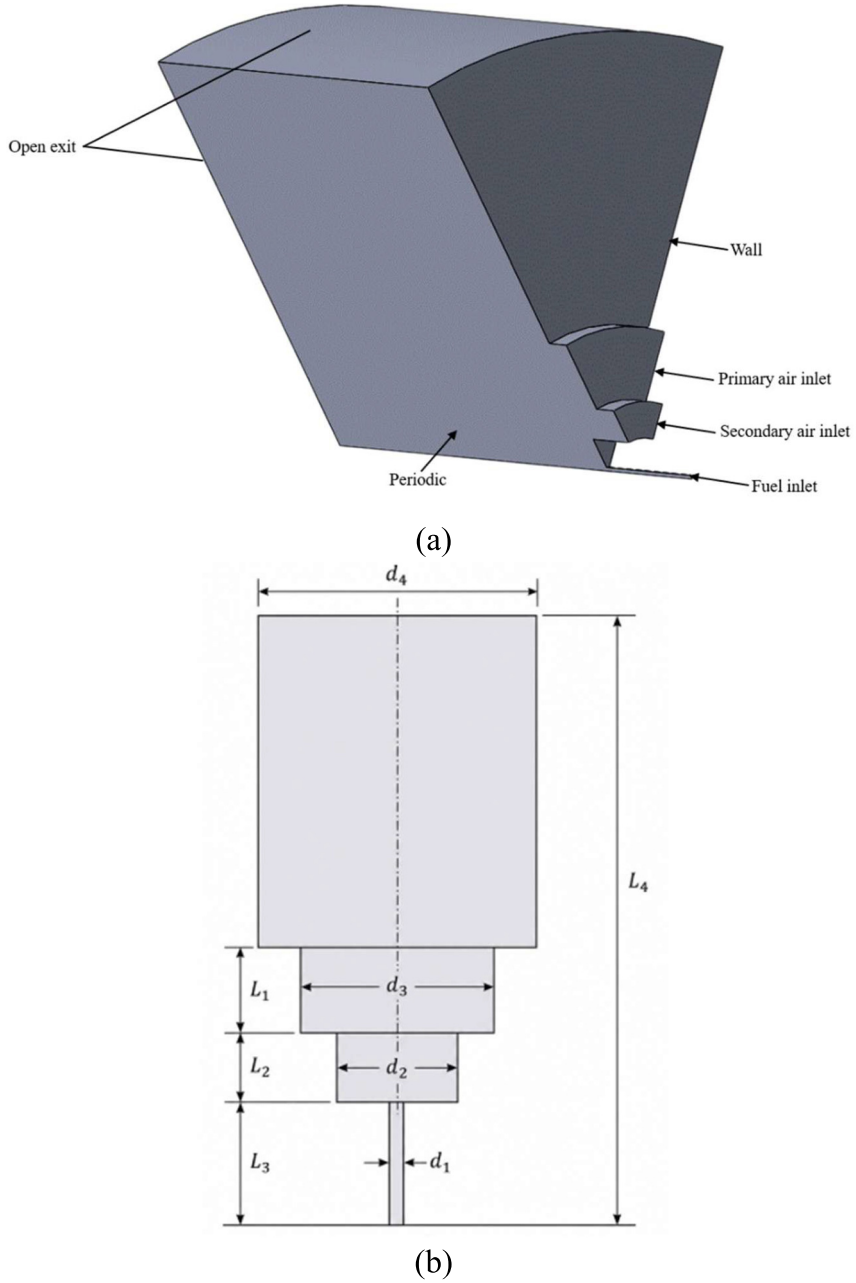

Figure 1. Experimental setup. (a) Geometry and (b) key dimensions of the domain

the flame continued to exit the combustor, creating a high-temperature region at the outlet. However, the peak temperature in this case was closer to those with higher swirl angles, such as cases 1, 4, 5, and 7.

The vorticity path line in Figure 5 offers an insight into the flow dynamics, swirl motion, flame stability, and heat generation, as it demonstrates the rotational motion of the flow. This clearly shows that a higher vorticity leads to a stronger swirling motion, resulting in better air-fuel mixing and improved flame stabilization. As in cases 1, 2, 4, and 6, a uniform flow was achieved with less vorticity and almost no recirculation zones at lower angles, resulting in a uniform temperature distribution, as shown in the corresponding contours in Figure 4. As the swirl angle was increased, strong vortices with large recirculation zones were formed. This resulted in a more effective fuel-air mixing, as well as significantly increased the peak temperature.

3.2. Effect of the Swirl Configuration on the NOx Emissions. Figure 4 illustrates the NOx distributions in the various configurations studied. Using an angle of 30° for both co-flows, as illustrated in Case 1, resulted in the lowest NOx emission, with a maximum of almost 19 parts per million (ppm). Increasing one angle slightly in Case 2 caused a slight increase in the NOx emissions, increasing the maximum to 172.48 ppm. However, introducing an angle of 55° caused a sharp increase in the emissions, as demonstrated in case 3, to 1699.40 ppm.

Additionally, fixing the first co-flow at 45° and changing the second co-flow to 30° and 45° in cases 4 and 5, respectively, demonstrated a high but acceptable range with maximum values of 204.79 and 361.24 ppm, respectively. However, applying a 55° angle in Case 6 resulted in a significant increase, to a maximum of 853.01 ppm. Comparing cases 2 and 7 shows that switching the angles between the two co-flows significantly reduced the maximum NOx emissions from 1699.40 ppm to 199.81 ppm. Using an angle of 55° for the first co-flow did not show the same reduction. As illustrated in cases 8 and 9, very high NOx concentrations were detected, and a maximum of 440.61 and 1035.06 ppm were computed, respectively.

A more detailed statistical analysis is presented in Figure 5. The highest NOx emissions occurred in Case 3 with a value of 32.90 ppm. These results indicate that high angles result in a strong mixing, which leads to higher temperatures and greater NOx formation. Moderate values of 2.12, 2.55, and 6.43 ppm were captured for cases 2, 4, and 8, respectively. Additionally, the lowest NOx emissions were captured in Case 1, with an average of 1.28 ppm. This suggests a weaker swirl intensity and lower air-fuel mixing efficiency, with reduced NOx formation. An inconsistency was identified for Case 7. Although a large swirl angle was employed, the NOx formation remained low, averaging 3.84 ppm. This indicates that higher angles do not always increase NOx formation, as adjusting the angles reduced the average by approximately 151.69%. The average NOx emission at

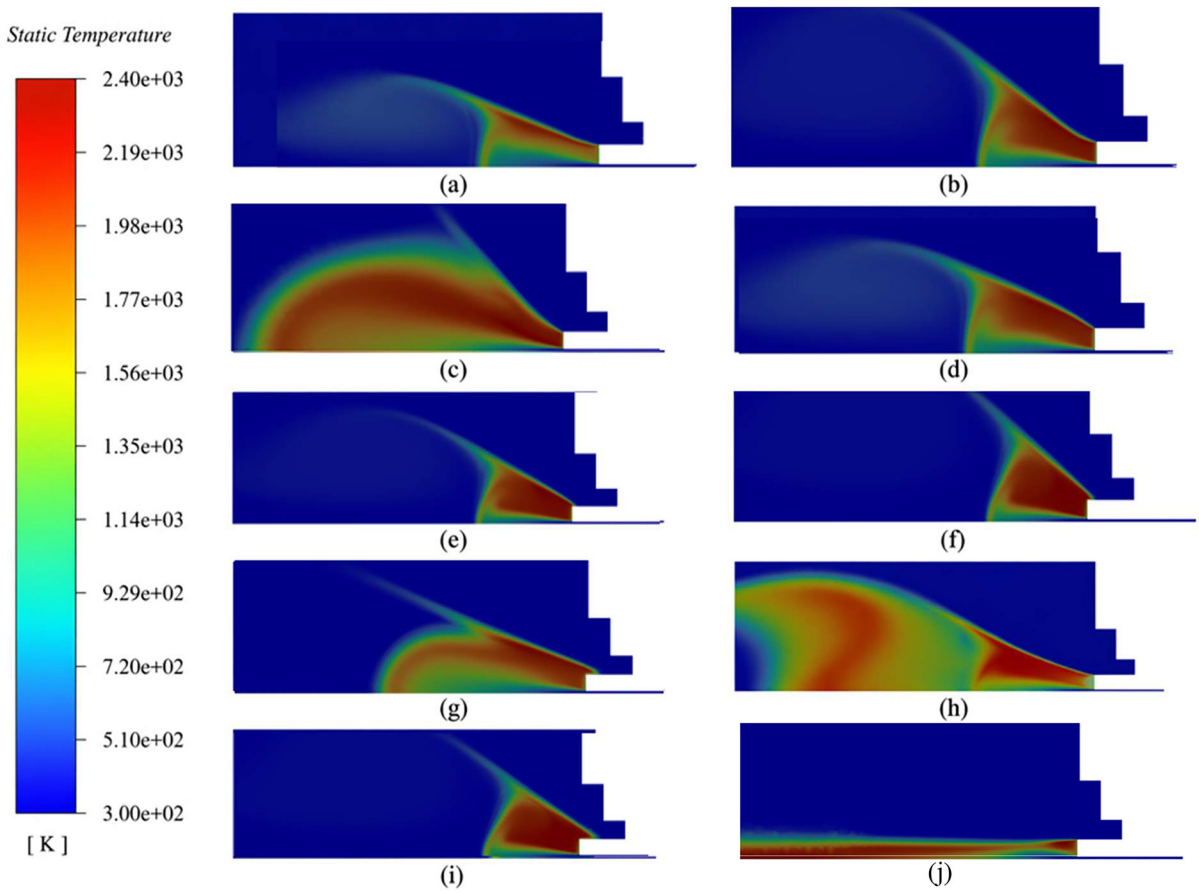

Figure 2. Temperature contours on the central axial plane of the combustor for cases (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, (g) 7, (h) 8, (i) 9, and (j) base case (no swirling)

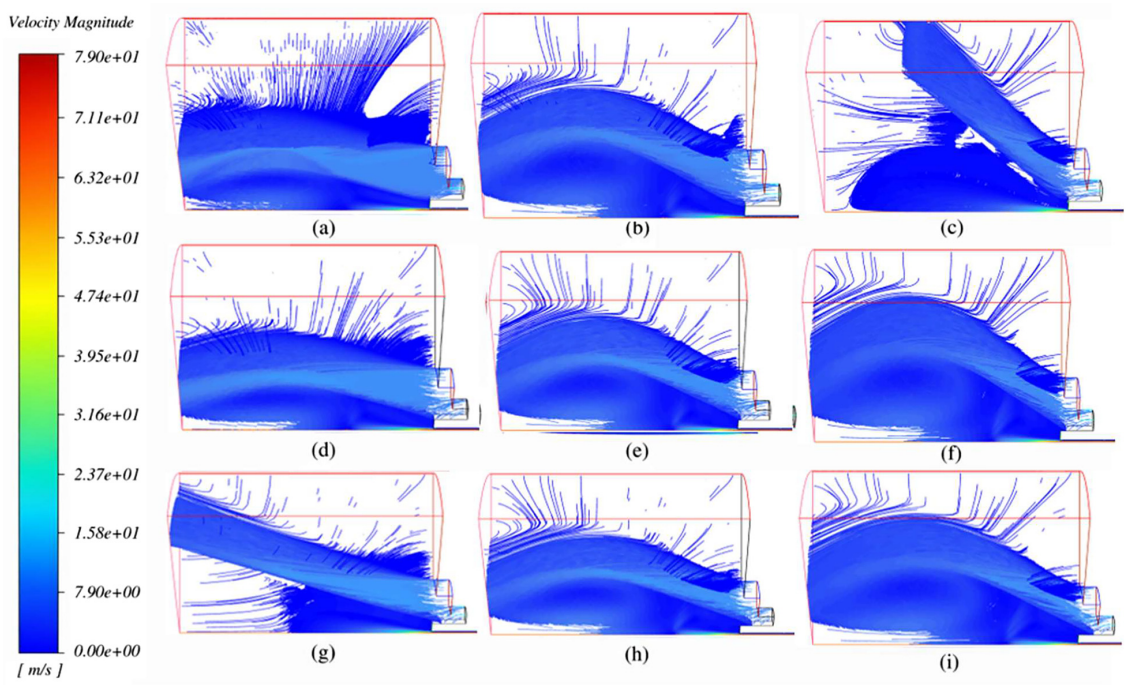

Figure 3. Velocity streamlines on the central axial plane of the combustor for cases (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, (g) 7, (h) 8, and (i) 9

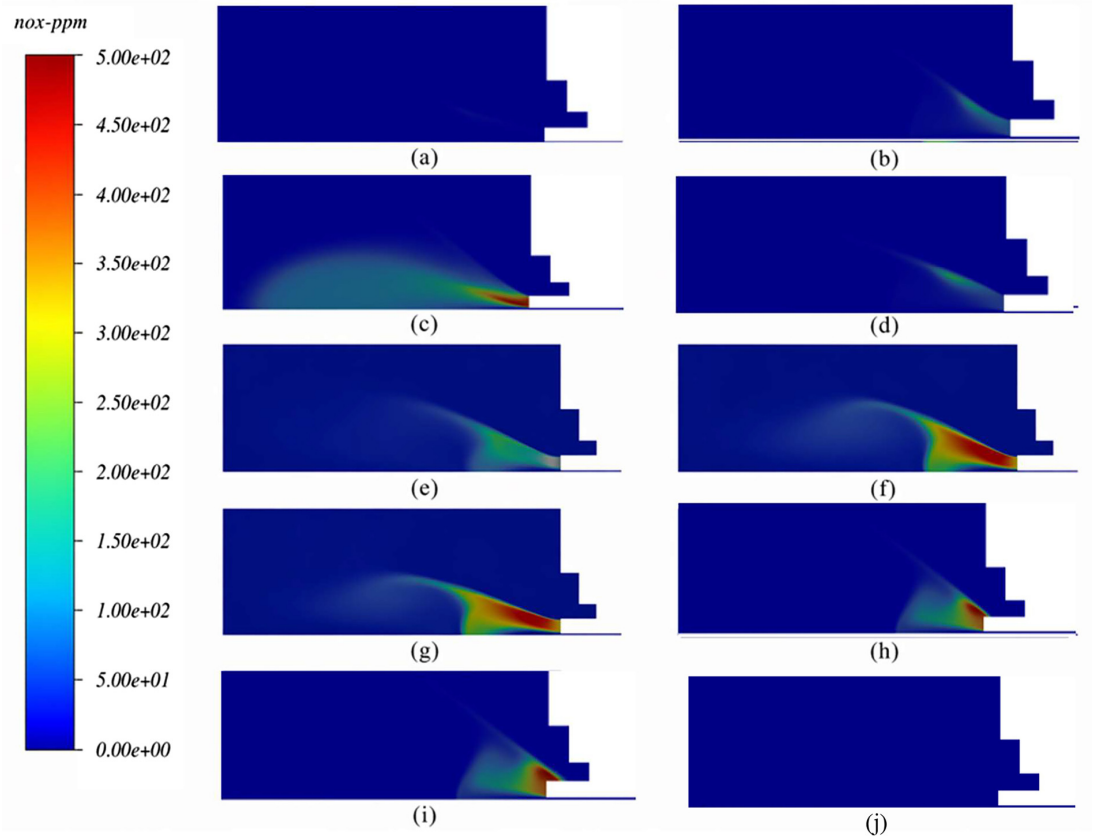

Figure 4. NOx contours on the central axial plane of the combustor at cases (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, (g) 7, (h) 8, (i) 9, and (j) base case (no swirling)

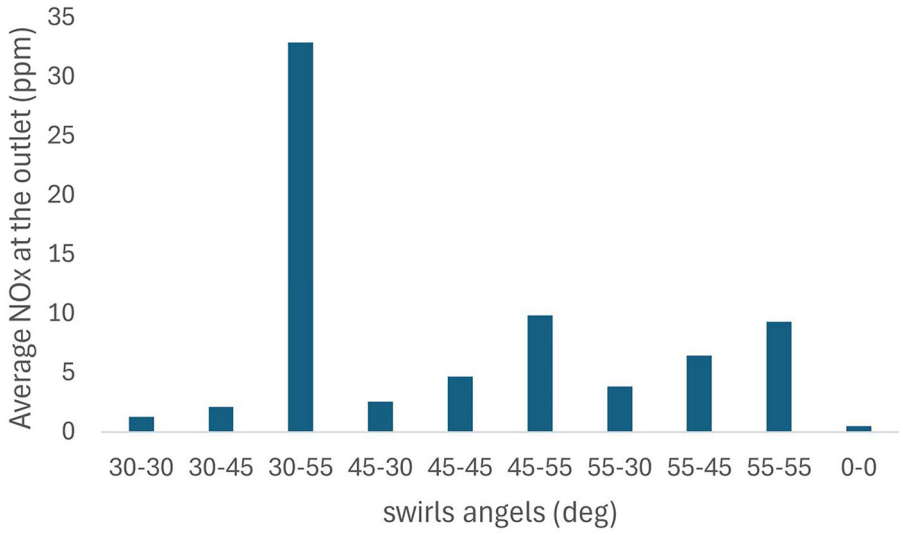

Figure 5. Average NOx generated at $z = 150$ mm from the inlets

the outlet of the base case was significantly lower (approximately 0.202 ppm).

Notably, the maximum NOx value reported in Figure 4 corresponds to the peak local NOx concentration inside the combustion chamber, whereas the values presented in Figure 5 represent the average NOx concentration at the combustor outlet. The combustion products experienced a reduction in the temperature and species dilution as they moved downstream toward the outlet, owing to the combustor length. As thermal NOx formation is highly dependent on the temperature, reducing the temperature away from the primary reaction zone resulted in significantly lower NOx concentrations at the outlet. Consequently, the outlet-averaged NOx values were substantially lower than the maximum local NOx values observed in the combustor domain.

4. CONCLUSIONS

This study investigated the flow behavior and combustion characteristics of a dual-swirl H_2 combustor with different angular configurations. It assessed the temperature distribution, thermal NOx formation, air-fuel mixing, and flame stability at a chosen angle. The following key conclusions can be drawn based on the consistent numerical analysis results:

- Varying the swirl angle strongly affected the flame stabilization, temperature distribution, and NOx formation.
- Higher swirl angles resulted in stronger recirculation zones and better flame stabilization, leading to an efficient fuel–air mixing, which improves the combustion efficiency at the expense of increasing the NOx emission.
- Lower swirling angles had weaker recirculation zones and less efficient mixing, reducing the stability of the flame. However, the temperature distribution was more uniform and the peak temperature was lower, which indicates lower NOx formation.
- Unusual patterns appeared in Case 7. The NOx formation was the highest for case 3, but switching between the flow angles unexpectedly reduced the NOx formation significantly and resulted in a lower average NOx emission at the outlet.
- Among the investigated configurations, Case 1 is recommended as the optimal operating condition, providing the best compromise between the flame stability, combustion efficiency, and NOx emissions. This configuration produced a compact, stable flame structure with moderate temperatures, while maintaining NOx levels within a comparatively lower range than the other swirling cases. Such a configuration can enable efficient combustion with a low NOx formation.
- By comparing the base case with the swirling cases, we demonstrated that combusting H_2 without a swirler can produce a stable flame at low temperatures and very low NOx emissions. Comparing with the non-swirling configuration indicated that H_2 combustion can maintain the flame stability even without swirl assistance, owing to its high reactivity and fast flame speed. However, introducing a moderate swirl can still improve the mixing characteristics and flame anchoring, while maintaining acceptable NOx levels when appropriate swirl angles are selected. Comparing the results of non-swirling to the lowest NOx in Case 1, introducing a small-angle swirler increased the NOx formation by 40%.

The obtained results are consistent with those of previous studies on swirl-stabilized combustion, wherein increasing the swirl intensity enhanced the recirculation zone and improved fuel-air mixing, leading to improved flame stabilization and combustion efficiency. However, stronger recirculation and enhanced mixing also increased the local flame temperature, thereby promoting thermal NOx formation. These findings confirm the strong relationship between the swirl intensity, flame structure, and NOx production reported in the literature. In addition, the asymmetric behavior observed between cases 3 and 7 demonstrated that the interaction between the primary and secondary swirlers played a significant role in controlling the combustion characteristics and emission behavior.

The results of this study contribute to understanding the impact of swirl angle on H_2 combustion in terms of the flame stability, temperature distribution, and NOx formation. We found that moderate angles balance the combustion efficiency and NOx

formation. Future work may explore the effect on multi-fuel combustion, and employ a transient model to simulate the dynamic flow behavior, as in real-world applications.

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