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Study on Ammonia/Diesel Coaxial Injection Combustion Based on a Rapid Compression Expansion Machine

Basic research & advanced engineering - new concepts

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ABSTRACT

Ammonia/diesel coaxial injection is an emerging fuel injection strategy designed to enhance combustion efficiency and reduce emissions in internal combustion engines. Traditional injection methods face challenges in managing N2O and unburned ammonia emissions, making the optimization of injection strategies essential.This study found that the ammonia/diesel coaxial injection mode, by directly injecting ammonia into the diesel flame region, significantly improves combustion efficiency, optimizes heat utilization, and exhibits a unique three-peak heat release characteristic. This strategy effectively reduces unburned ammonia and N2O emissions, though it requires balancing the increase in NO emissions due to higher combustion temperatures. Further research shows that the injection interval significantly impacts combustion characteristics and emissions. A reasonable injection interval (0~2°CA) ensures smooth ignition and stable combustion, while premature ammonia injection can lead to flame extinction. Although extending the injection interval slightly reduces combustion efficiency, it has minimal effect on N2O and NO emissions. However, an excessively large injection interval may increase unburned ammonia emissions. Therefore, optimizing the injection interval is crucial for achieving efficient combustion, reducing unburned ammonia emissions, and maintaining low N2O and NO emissions.Additionally, the injection pressure and orifice diameter of the ammonia injector significantly influence the coaxial injection combustion process and emissions. Higher injection pressure and smaller orifice diameter enhance fuel atomization, accelerate combustion, and advance the combustion phase, increasing the heat release rate peak. The study found that as injection pressure increases and orifice diameter decreases, unburned ammonia emissions initially decrease and then increase, N2O emissions decrease linearly, and NO emissions remain largely unaffected. Considering combustion efficiency and emission control, an 80 MPa injection pressure and 0.82 mm orifice diameter are recommended for balancing these factors.

1 INTRODUCTION

As the living environment for humans continues to deteriorate, the issue of greenhouse gas (GHG) emissions has become one of the most urgent problems to address. The shipping industry, as a vital pillar of global trade, contributes significantly to global GHG emissions, accounting for approximately 3% of the total emissions worldwide [1]. In response to this challenge, the International Maritime Organization (IMO) has proposed comprehensive decarbonization targets, aiming to reduce carbon emissions by 40% by 2030 compared to 2008 levels, and to achieve a 70% reduction by 2050 [2]. However, due to the high efficiency and economic benefits of marine diesel engines, they remain the main propulsion equipment in the shipping industry. Currently, emission after-treatment technologies and combustion optimization technologies have limited impact on reducing carbon emissions. Therefore, exploring low-carbon or carbon-free alternative fuels has become a key focus of current research.

Hydrogen (H_2), as a zero-emission fuel, is considered the ultimate solution to the carbon emissions problem. However, its widespread use is currently limited by challenges in storage, transportation, and the complexity of building the necessary infrastructure [3]. In contrast, ammonia (NH_3), as a hydrogen carrier, offers advantages such as easier storage and transportation, along with an existing global distribution network, making it a promising alternative fuel for marine engines [4]. Furthermore, ammonia combustion only produces nitrogen (N_2) and water (H_2O), which theoretically enables zero carbon emissions. However, its direct application in engines faces technical challenges due to ammonia's higher autoignition temperature, lower flame propagation speed, and narrow flammability limits.

To overcome the challenges mentioned above, dual-fuel combustion technology has become one of the key directions for developing ammonia-fueled marine engines. This technology combines high-reactivity fuels (such as diesel) and low-reactivity fuels (such as ammonia) to achieve reliable ignition and stable combustion. Currently, research on the combustion characteristics of ammonia engines primarily focuses on two modes: low-pressure premixed combustion and high-pressure direct injection (HPDI) combustion. Research on low-pressure premixed combustion started earlier and has made significant progress. Notable studies, such as those by Reiter and Kong [5], have found that the optimal fuel consumption occurs when the ammonia energy ratio is between 40-60%, although this results in ammonia (NH_3) emissions of 1000-3000 ppm. Niki et al. [6, 7] showed that higher ammonia energy ratios increase NH_3 and N_2O emissions. They suggested that adjusting engine speed, torque, and boosting could raise the combustion temperature, thereby reducing N_2O formation and improving ammonia combustion efficiency. Research by Yousefi et al. [8, 9] indicated that the ammonia energy fraction significantly influences thermal efficiency, NOx, N_2O, and unburned ammonia emissions in premixed combustion engine. They found that controlling diesel injection strategies can help optimize combustion behavior and reduce emissions. However, NH_3 emissions in premixed combustion remain relatively high, reaching several thousand ppm. Research on high-pressure direct injection (HPDI) combustion of ammonia started later and has mainly focused on marine engines. Shin et al. [10] found that in a high-pressure ammonia/diesel dual-fuel marine engine, through proper injection strategy control, unburned ammonia emissions could be reduced to below 60 ppm, while NO emissions were lower than those of diesel engines, resulting in a 91% reduction in GHG emissions. Liu et al. [11, 12] investigated high-pressure direct injection of ammonia in marine low-speed engines and found that it could achieve an extremely low diesel energy fraction of around 1%, with NOx emissions potentially meeting Tier III standards, significantly reducing GHG emissions, and keeping unburned ammonia emissions below 100 ppm. Zhou et al. [13] compared low-pressure premixed and high-pressure direct injection modes in marine low-speed engines. Their study found that both modes achieved more than 50% indicated thermal efficiency (ITE) at a 98-99% diesel replacement rate. However, NOx emissions were much higher in the premixed mode, while unburned ammonia emissions in the high-pressure mode were almost negligible.

A review of the existing literature reveals that while progress has been made in the combustion characteristics and emission control of ammonia in the low-pressure premixed mode, unburned ammonia (NH_3) and nitrogen oxide (N_2O) emissions remain relatively high, indicating a need for further optimization and improvement. In contrast, the high-pressure direct injection (HPDI) mode of ammonia has garnered increasing attention due to its significant potential to reduce unburned NH_3 and NOx emissions, as well as its ability to achieve higher ammonia replacement rates. This mode, particularly in marine low-speed engines, has shown distinct advantages. Low-speed engines are characterized by high compression end temperatures, large cylinder volumes, larger nozzle sizes, and strong swirl effects. These features provide ample time and space for ammonia fuel, which has lower combustion reactivity and high volumetric energy density, to undergo efficient combustion. Since the combustion process in ammonia-diesel high-pressure direct injection mode is highly dependent on precise control of the injection strategy and combustion organization, the development of more efficient and cleaner ammonia engine HPDI combustion technology is crucial.

This study, based on a rapid compression expansion machine (RCEM), employs numerical simulation to thoroughly investigate the characteristics of the ammonia-diesel high-pressure dual direct injection combustion mode. The focus is on comparing and analyzing the differences in combustion and emission characteristics between the novel coaxial injection combustion mode and the traditional direct injection combustion mode. Additionally, for the coaxial injection mode, the study examines in detail how the injection strategy influences the combustion process. By revealing the key role of the ammonia-diesel coaxial injection strategy in combustion organization and emission formation, the research provides theoretical support for the development of efficient, low-emission dual direct injection combustion technology for marine low-speed engines.

2 MODEL AND METHODOLOGY DESCRIPTIONS

The research was conducted using a RCEM developed by the Technical University of Munich. A schematic of the apparatus is shown in Figure 1 [14, 15]. In the setup, the lateral distance between the ammonia injector and the diesel injector is defined as a, and the longitudinal distance is defined as b. In the experiments, the values of a and b were 5 mm and 10 mm, respectively. The counterclockwise rotation angle of the ammonia injector relative to the diesel injector is defined as α, which is set at 7.5°. The basic parameters of the rapid compression expansion machine are provided in Table 1.

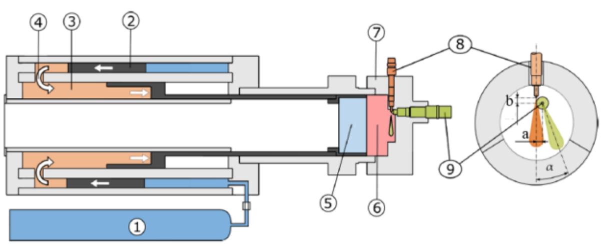


Figure 1 RCEM driving system and cylinder head: ① driving-air bottles, ② driving piston, ③ hydraulic fluid, ④ flow orifice, ⑤ working piston, ⑥ combustion chamber, ⑦ cylinder head, ⑧ diesel injector, ⑨ ammonia injector [14].

Table 1. RCEM specifications

Parameters	Value
Bore/(mm)	220
Compression ratio	20.5
Engine speed/(rpm)	1000
Fuel injection temperature/(K)	293
TDC temperature /(K)	920
TDC pressure /(MPa)	12.5

In this study, 3D numerical simulations were performed using the CONVERGE software to model the RCEM. The model consists of the cylinder head, cylinder wall, and a moving piston at the bottom. The numerical simulation model is shown in Figure 2. The simulation of the spray combustion process requires the use of a series of appropriate sub-models. Turbulence was modeled using the RNG k-ε [16], while the Kelvin-Helmholtz and Rayleigh-Taylor (KH-RT) models [17] were applied to simulate the droplet breakup and atomization processes of diesel and liquid ammonia. The No Time Counter (NTC) method [18] and the Frossling Correlation [19] were used to simulate droplet collision and evaporation, respectively. Combustion progress was described using the SAGE model [20], with n-heptane serving as a surrogate for diesel. A custom dual-fuel reaction mechanism combining n-heptane and ammonia was utilized for the dual-fuel combustion simulation. The n-heptane mechanism was based on the work of Mehl [21] from the Lawrence Livermore National Laboratory (LLNL), while the ammonia mechanism was derived from Otomo's research [22]. In previous work, we have verified the ignition characteristics of this mechanism and shown relatively satisfactory prediction accuracy [23].

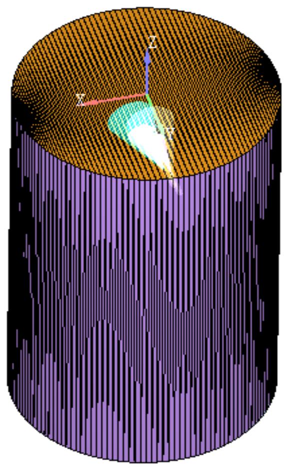


Figure 2 Numerical simulation model of RCEM

Accurate simulation of the engine spray process is crucial for analyzing the combustion process. Therefore, in this study, the ammonia spray process was validated based on the RCEM. The relevant operating conditions are listed in Table 2, where the orifice diameter of the ammonia injector closely matches the orifice size requirements for marine engine injectors.

Table 2. Spray operation condition

Nozzle A	
Parameters	Value
Spray angle/(°)	25.5
injection pressure/(MPa)	26.5
Area contraction coefficient	0.81
Discharge coefficient	0.51
Orifice diameter/(mm)	0.98
Nozzle B	
Parameters	Value
Spray angle/(°)	24
injection pressure/(MPa)	53
Area contraction coefficient	0.81
Discharge coefficient	0.55
Orifice diameter/(mm)	0.94
Average ambient temperature/(K)	915
Average ambient density/(kg/m^3)	44.5

The ammonia spray process for injectors with different orifice diameters was validated, and the results are shown in Figure 3. It can be observed that, for different base mesh sizes (ranging from 4 to 10 mm), the simulated spray penetration distance aligns well with the experimental data. Additionally, the penetration distance shows good mesh convergence, indicating that a base mesh size of 10 mm can still meet the required calculation accuracy. Therefore, in the subsequent combustion simulations, a base mesh size of 10 mm was used, with a three-level adaptive refinement applied to the temperature and velocity fields, resulting the minimum mesh size was controlled to 1.25 mm. The comparison of spray profile simulation and experimental results is shown in Figure 4. It can be observed that there is a high consistency between the simulation and the experimental results.

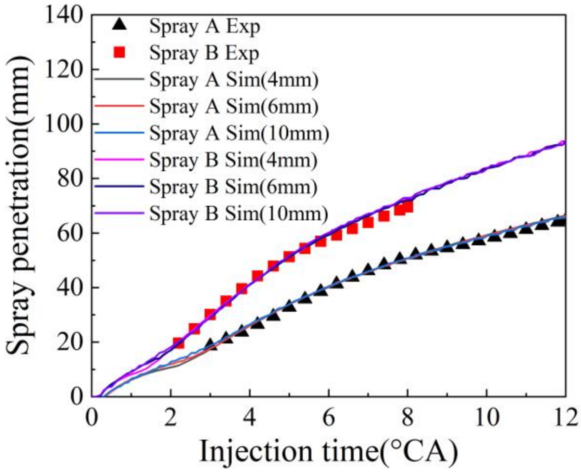


Figure 3 Spray penetration calibration. Experiment data is from ref. [14]

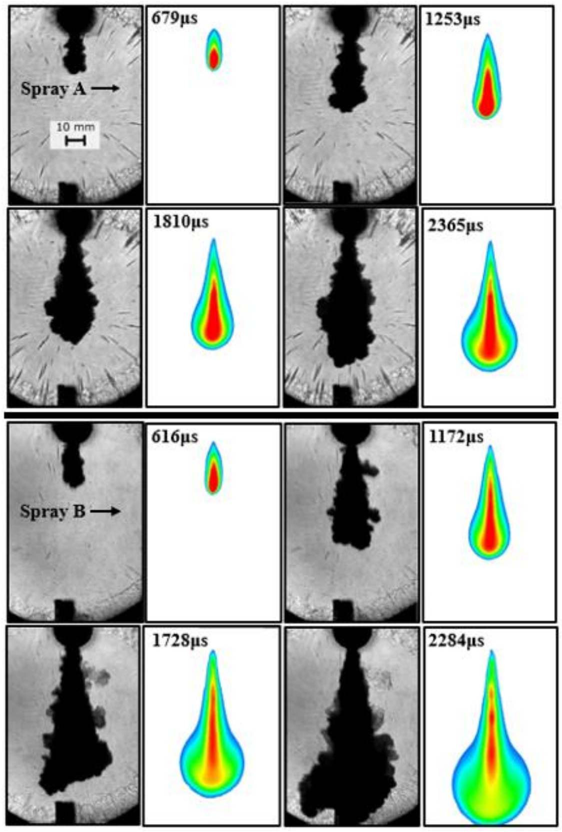


Figure 4 Spray vapor profile. The left side shows the experimental results, while the right side displays the simulation results. Experiment results are from ref. [14]

To validate the combustion simulation, a combustion process was carried out for an ammonia injector with a nozzle diameter of 0.94 mm, with the verification setup conditions listed in Table 3. The heat release rate comparison is shown in Figure 5. It can be observed that the model provides satisfactory prediction accuracy for both the diesel ignition process and the ammonia diffusion combustion process. This demonstrates that the developed RCEM combustion simulation model is reliable for subsequent research.

Table 3. Combustion operation condition

Parameters	Value
Start of diesel injection/(°CA ATDC)	-12
diesel injection duration/(°CA)	3.12
Diesel injection mass/(mg)	5
Diesel orifice diameter/(mm)	0.2
Diesel injection pressure/(MPa)	200
Start of ammonia injection/ (°CA ATDC)	-9
Ammonia injection duration/(°CA)	16.2
Ammonia injection mass/(mg)	210
Ammonia orifice diameter/(mm)	0.94
Ammonia l injection pressure/(MPa)	48

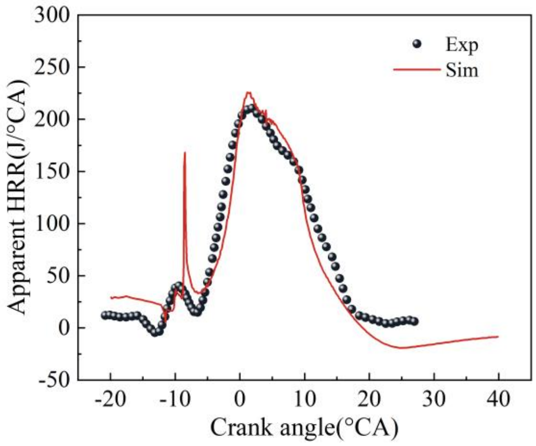


Figure 5 Apparent HRR calibration. Experiment data is from ref. [15].

3 RESULTS AND DISCUSSION

3.1 Comparative study of different injection modes

In this section, the combustion processes of the conventional ammonia-diesel dual direct injection mode and the coaxial stratified injection mode are systematically compared. A total of eight cases were designed for the study. Cases 1 to 7 represent the conventional dual direct injection mode, achieved by varying the lateral distance (a) and angle (α) between the ammonia and diesel injectors. The definitions of parameters are illustrated in Figure 1. Case 8 represents the coaxial stratified injection mode, where the ammonia and diesel injectors are perfectly aligned, resulting in fully coaxial spray plumes for both fuels. The details of all cases are summarized in Table 4, with the injection parameters for ammonia and diesel specified in Table 4.

Table 4. Parameter design for different combustion modes

Case	a/(mm)	b/(mm)	α/(°)
Case 1	5	10	7.5
Case 2	10	10	-5
Case 3	10	10	-10
Case 4	10	10	-15
Case 5	20	10	-5
Case 6	20	10	-10
Case 7	20	10	-15
Case 8	0	0	0

Figure 6 shows the comparison of the chemical heat release rate (HRR) for different cases. The analysis indicates that the position of the ammonia-diesel injectors has a significant impact on the heat release characteristics. Except for Case 4 and Case 8, the heat release rates for most operating conditions exhibit a distinct double-peak feature: the first heat release peak originates from diesel combustion, while the second peak is due to ammonia ignition and combustion. Notably, during the diesel ignition, the heat release rate of ammonia increases relatively gradually. However, Case 8 displays a distinctly different triple-peak characteristic, while Case 4 also shows a triple-peak, though less pronounced than Case 8. Figure 7 presents temperature slices for different cases, showing that the ammonia spray in the coaxial injection mode is surrounded by the flame, leading to higher flame utilization. This phenomenon suggests that after diesel ignition, ammonia is injected directly into the diesel flame region and burns rapidly, resulting in a very short ignition delay for ammonia. As observed in Figure 6, this leads to the formation of the third heat release peak. This triple-peak characteristic reflects the unique advantage of ammonia-diesel coaxial injection combustion in fully utilizing the heat from the diesel flame, contributing to efficient and stable combustion performance.

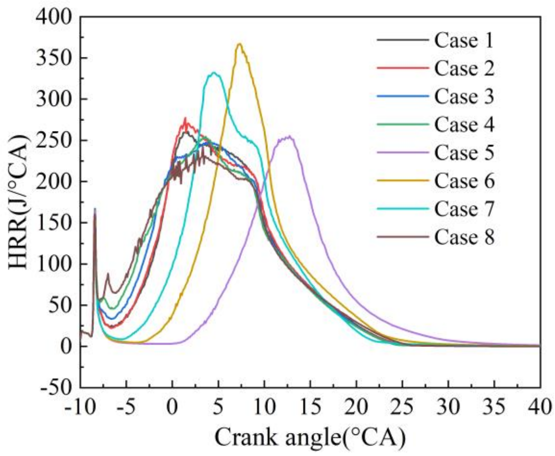
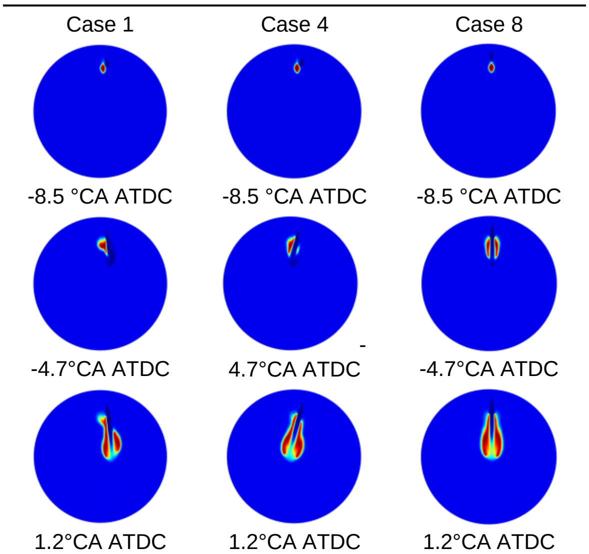


Figure 6. HRR of different cases



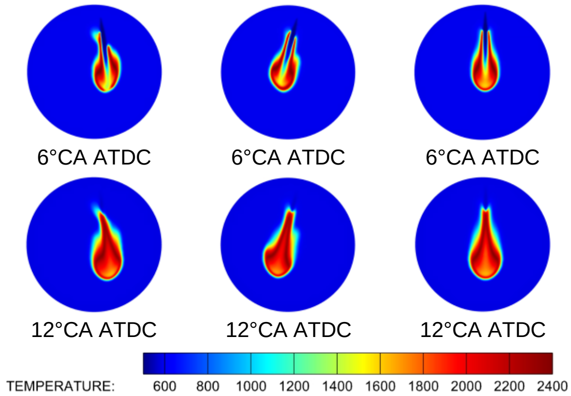


Figure 7. Temperature slices of different cases

Figure 8 shows the comparison of combustion efficiency for different cases. The analysis reveals that Case 8 achieves the highest combustion efficiency, reaching 96.8%. This indicates that the ammonia/diesel coaxial injection mode significantly enhances combustion efficiency by directly delivering ammonia to the flame combustion zone, demonstrating the superiority of this injection strategy. Additionally, it is important to note that the combustion efficiency of the traditional ammonia/diesel dual direct injection mode is highly sensitive to the injector layout. By optimizing the injector arrangement, the combustion efficiency can reach approximately 95%. This suggests that the injector placement strategy plays a critical role in improving combustion efficiency, providing valuable design insights for optimizing ammonia/diesel dual-fuel combustion systems.

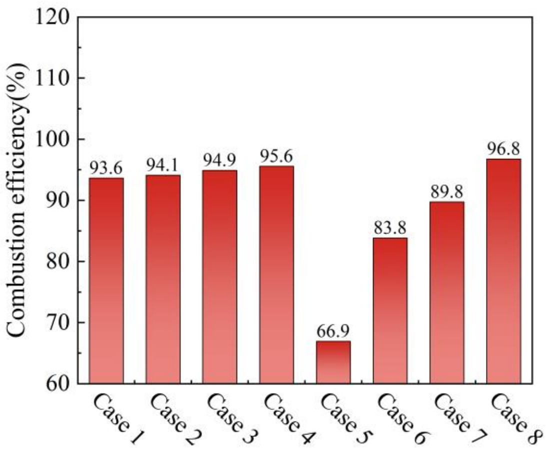


Figure 8. Combustion efficiency of different cases

Figure 9 shows the generation results of key emissions: NO, NH_3 (unburned ammonia), and N_2O for different cases. It can be observed that the trends in unburned ammonia and N_2O emissions are generally consistent, and there is a clear trade-off relationship with NO emissions. In general, the emissions of unburned ammonia and N_2O decrease as the combustion temperature increases, while NO generation is positively correlated with temperature. For Case 8, since ammonia fuel is directly injected into the flame zone, combustion efficiency is significantly improved, and most of the ammonia is fully combusted under high-temperature conditions. As a result, the emissions of unburned ammonia and N_2O in Case 8 are much lower than in other operating conditions. However, this also leads to higher combustion temperatures, which increases NO emissions. Overall, the analysis indicates that optimizing the injection strategy (such as the ammonia/diesel coaxial injection in Case 8) can effectively reduce unburned ammonia and N_2O emissions, while requiring a trade-off due to the increased NO emissions caused by higher combustion temperatures.

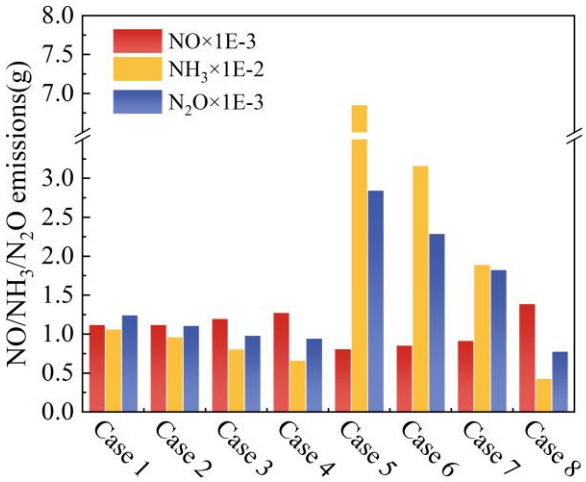


Figure 9. Emissions of different cases

3.2 Influence of Injection Interval on ammonia/diesel Coaxial Injection

In the ammonia-diesel coaxial injection mode, the time interval between the end of the pilot diesel injection and the start of ammonia injection was studied. Five different time intervals were analyzed, and the heat release rate results are shown in Figure 10. It is important to note that a time interval of -1°CA indicates that ammonia injection occurs 1°CA before the end of diesel injection. As seen in Figure 10, when the injection interval is -1°CA, flame extinction occurs. This suggests that in the ammonia-diesel coaxial injection mode, ammonia injection should not occur before the pilot diesel injection ends, as ammonia's high latent heat of evaporation may lead to flame extinction. As the injection interval increases, the heat release phase shifts later, and stable ignition and combustion are achieved at all time intervals, with the peak of the maximum heat release rate remaining nearly constant. As shown in Figure 11, ammonia spray, when injected within an appropriate time interval after diesel ignition, quickly reaches the flame zone and ignites, with the spray head rapidly being surrounded by OH radicals. This phenomenon indicates that a proper ammonia/diesel injection time interval is crucial for ensuring stable combustion. Premature ammonia injection may negatively impact flame stability.

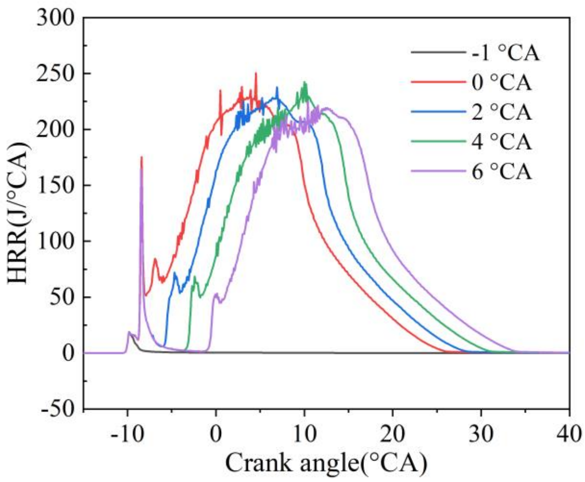


Figure 10. Impact of injection interval on heat release rate

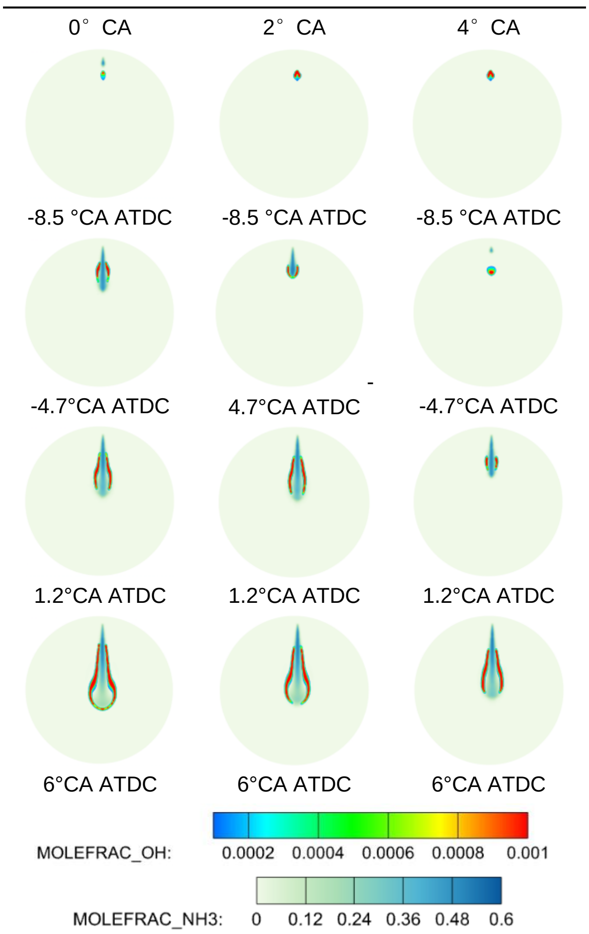


Figure 11. The OH and NH_3 slices for different injection interval

Figure 12 shows the cumulative heat release curves for different injection intervals. It can be observed that, in the stratified injection mode, as the injection interval between ammonia and diesel increases, the cumulative heat release decreases. This suggests that, under the same fuel supply energy conditions, increasing the injection interval may slightly reduce combustion efficiency. However, within the limited range of injection interval adjustments, this change is relatively small.

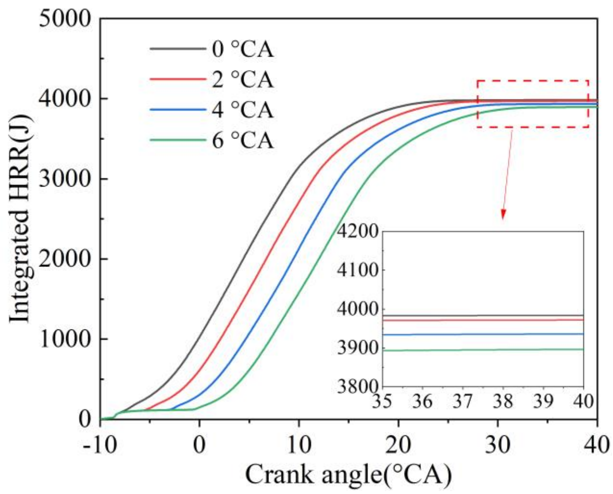


Figure 12. Integrated HRR for different injection interval

Figure 13 shows the emissions generated under different ammonia-diesel injection intervals. It is evident from the figure that as the injection interval increases, the emissions of unburned ammonia increase. This is primarily due to the reduced continuity of combustion with larger injection intervals, which causes some ammonia to be insufficiently burned, leading to higher emissions of unburned ammonia. It is noteworthy that the emissions of N_2O and NO remain relatively unchanged across different injection intervals. This may be because, although the continuity of combustion is affected by a larger injection interval, the overall combustion temperature and reaction conditions do not vary significantly, resulting in no substantial impact on the generation mechanisms of N_2O and NO. Therefore, the adjustment of the injection interval primarily affects ammonia combustion efficiency, with minimal impact on N_2O and NO emissions. These results suggest that when optimizing ammonia-diesel injection strategies, it is essential to balance the injection interval to minimize unburned ammonia emissions while maintaining low levels of N_2O and NO emissions. This approach can help achieve more efficient combustion and cleaner emissions.

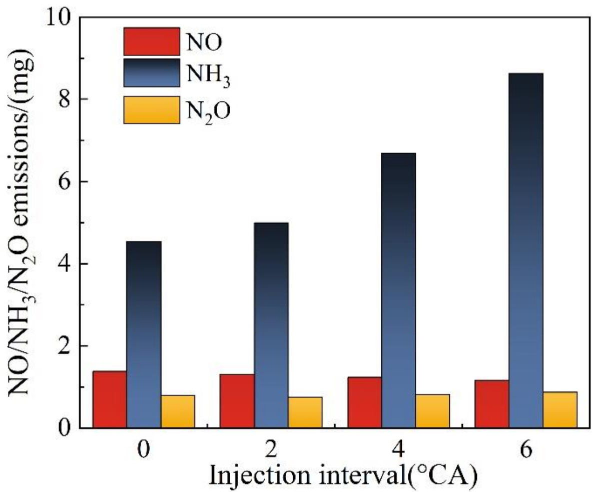


Figure 13. Emissions of different injection interval

3.3 Influence of Injection pressure and orifice diameter on ammonia/diesel Coaxial Injection

This section discusses the combined effects of ammonia injector injection pressure and orifice diameter on the coaxial injection combustion process. In the simulation, the ammonia injector's injection pressure and orifice diameter were adjusted to ensure that the injection duration was the same as the original injector (as shown in Table 3), while also maintaining consistent injection flow. The parameters of the diesel injector were kept consistent with those in Table 3. Figure 14 shows the heat release rate curves under different ammonia injector injection pressure and orifice diameter combinations. It is evident from the figure that as the injection pressure increases and the orifice diameter decreases, the combustion phase shifts significantly earlier. This indicates that higher injection pressure and smaller nozzle diameter lead to better fuel atomization, faster combustion rates, and an earlier start of combustion. Furthermore, this combination results in a slight increase in the peak heat release rate. Since the ammonia mass supply remains constant, using a combination of high injection pressure and small orifice diameter causes more fuel to burn before top dead center, with the heat release concentrated in this phase. As a result, the combustion temperature is higher, and the heat release process is noticeably shortened towards the end of combustion. Figure 15 further illustrates that the high-pressure, small orifice diameter combination increases the flame propagation distance, which leads to a faster combustion rate.

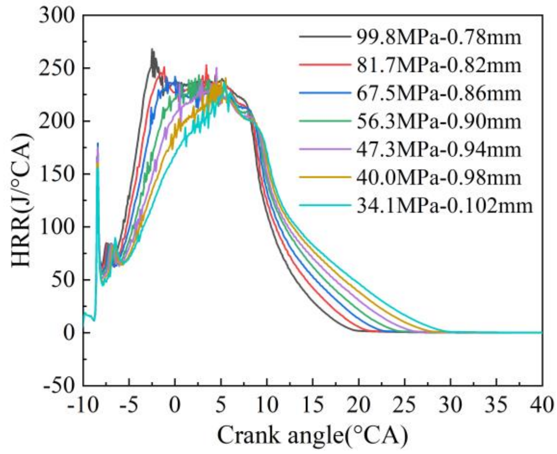


Figure 14. HRR for different injection pressure and orifice diameter

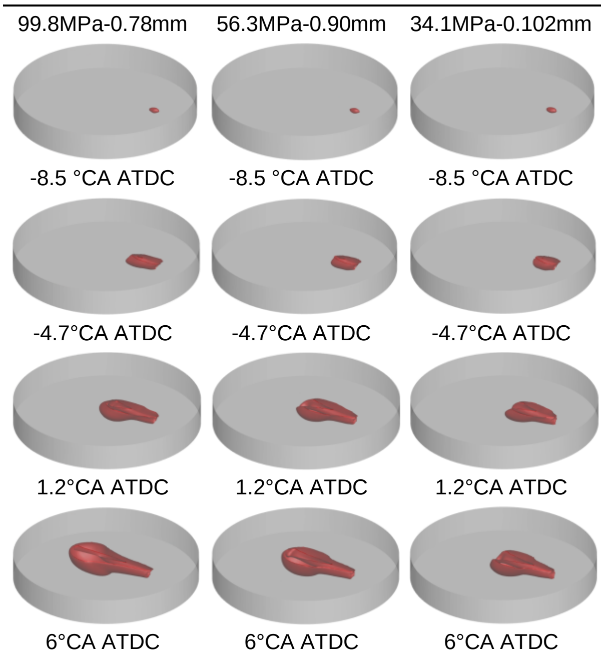


Figure 15. 1800K temperature iso-surface for different injection pressure and orifice diameter

Figure 16 shows the impact of different ammonia injector injection pressures and nozzle diameters on the generation of key combustion emissions. From the figure, it is clear that, while maintaining the same injection duration and mass flow rate, the combinations of different injection pressures and nozzle diameters have little impact on NO emissions, but significant effects on NH_3 (unburned ammonia) and N_2O emissions. As injection pressure increases and orifice diameter decreases, the emission of unburned ammonia initially decreases and then increases, while N_2O emissions decrease almost linearly. This phenomenon can be attributed to the fact that increasing the injection pressure significantly boosts the combustion rate, causing more fuel to burn before top dead center, which results in higher combustion temperatures. Since N_2O decomposes easily at high temperatures, its emissions decrease with increased injection pressure and smaller orifice diameters. For unburned ammonia emissions, higher combustion temperatures typically improve combustion completeness. However, excessively high injection pressures may cause ammonia to penetrate the diesel flame and deviate from the combustion zone in the coaxial injection process. As a result, some ammonia may not be effectively distributed around the flame, explaining the increase in unburned ammonia emissions under high injection pressure and small nozzle diameter conditions. For NO generation, although the high temperatures early in combustion promote an increase in the cylinder's average temperature, the reduction process inherent in ammonia diffusion combustion may offset some of the NO production. This complex reduction mechanism likely explains the relatively small variation in NO emissions. These results suggest that appropriately controlling the injection pressure and nozzle diameter can not only optimize the combustion process but also effectively control the generation of key emissions. A recommended combination is an injection pressure of around 80 MPa matched with a 0.82 mm nozzle diameter, as this may achieve better combustion while keeping emissions as low as possible.

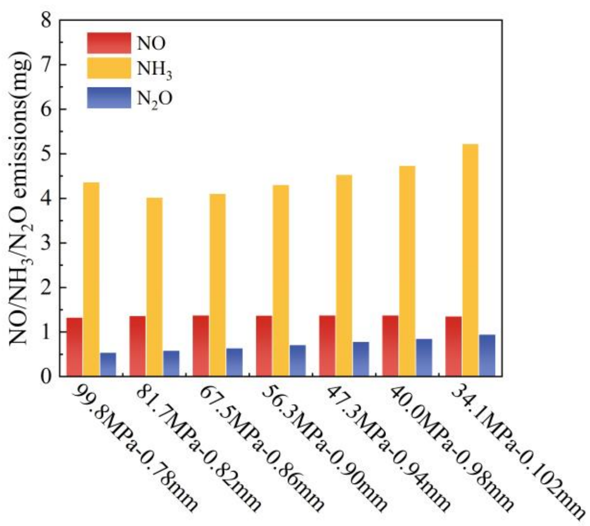


Figure 16 Emissions for different injection pressure and orifice diameter

4 CONCLUSIONS

In this study, based on a RCEM, numerical simulations were systematically used to compare and investigate the combustion characteristics of the traditional dual direct injection (DI) mode and the coaxial injection mode for ammonia-diesel combustion. The study further explored the impact of different injection strategies on the combustion process. The key findings are summarized as follows:

- The ammonia-diesel coaxial injection mode significantly improved combustion efficiency by directly injecting ammonia into the diesel flame region, optimizing the utilization of combustion heat, and exhibiting a unique three-peak heat release characteristic. At the same time, this injection strategy effectively reduced unburned ammonia and N_2O emissions, although it requires balancing the increase in NO emissions caused by elevated combustion temperatures. This suggests that optimizing the injection mode plays a crucial role in enhancing combustion performance and controlling emissions.

- In the ammonia-diesel coaxial injection mode, the injection interval has a significant impact on combustion characteristics and emission generation. A reasonable injection interval (0~2°CA) ensures smooth ignition and stable combustion, while premature injection of ammonia may lead to flame extinction. Although increasing the injection interval may slightly reduce combustion efficiency, it has little effect on N_2O and NO emissions. However, if the injection interval is too large, it could lead to increased unburned ammonia emissions. Therefore, optimizing the injection interval is meaningful for achieving efficient combustion, reducing unburned ammonia emissions, and maintaining low levels of N_2O and NO emissions.

- The injection pressure and orifice diameter of the ammonia injector significantly affect the coaxial injection combustion process and its emission characteristics. Higher injection pressure and smaller orifice diameter notably improve the fuel atomization, accelerate the combustion rate, and result in an earlier combustion phase with an increased heat release rate peak. Moreover, unburned ammonia emissions initially decrease and then increase with higher injection pressures and smaller orifice diameters, while N_2O emissions decrease linearly, and NO emissions remain largely unaffected. Considering both combustion efficiency and emission control, it is recommended to use a combination of approximately 80 MPa injection pressure and 0.82 mm orifice diameter, as this provides good combustion efficiency while effectively controlling the generation of emissions.

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Combustion and emission control technologies research for ammonia-fueled marine engines based on the Diesel cycle.

6 REFERENCES

[1] Issa M, Ilinca A, Martini F. Ship energy efficiency and maritime sector initiatives to reduce carbon emissions. *Energies*, 2022, 15(21): 7910.

[2] Joung T H, Kang S G, Lee J K, et al. The IMO initial strategy for reducing Greenhouse Gas (GHG) emissions, and its follow-up actions towards 2050. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, 2020, 4(1): 1-7.

[3] Wang Y, Zhou X, Liu L. Study on the mechanism of the ignition process of ammonia/hydrogen mixture under high-pressure direct-injection engine conditions. *International Journal of Hydrogen Energy*, 2021, 46(78): 38871-38886.

[4] Machaj K, Kupecki J, Malecha Z, et al. Ammonia as a potential marine fuel: A review. *Energy Strategy Reviews*, 2022;44:100926.

[5] Reiter AJ, Kong SC. Combustion and emissions characteristics of compression-ignition engine using dual ammonia-diesel fuel. *Fuel*,2011, 90:87–97.

[6] Niki Y, Yoo D-H, Hirata K, Sekiguchi H. Effects of ammonia gas mixed into intake air on combustion and emissions characteristics in diesel engine. In: ASME 2016 internal combustion engine division fall technical conference. South Carolina, USA: Greenville; 2016. V001T03A004.

[7] Niki Y, Nitta Y, Sekiguchi H, Hirata K. Emission and combustion characteristics of diesel engine fumigated with ammonia. In: ASME 2018 internal combustion engine division fall technical conference. San Diego: California; 2018. V001T03A016.

[8] Yousefi A, Guo H, Dev S, Liko B, et al. Effects of ammonia energy fraction and diesel injection timing on combustion and emissions of an ammonia/diesel dual-fuel engine. *Fuel*, 2022, 314: 122723

[9] Yousefi A, Guo H, Dev S, et al. A study on split diesel injection on thermal efficiency and emissions of an ammonia/diesel dual-fuel engine. *Fuel*, 2022, 316: 123412.

[10] Shin J, Park S. Numerical analysis and optimization of combustion and emissions in an ammonia-diesel dual-fuel engine using an ammonia direct injection strategy. *Energy*, 2024, 289: 130014.

[11] Liu L, Wu Y, Wang Y, et al. Exploration of environmentally friendly marine power technology-ammonia/diesel stratified injection. *Journal of Cleaner Production*, 2022, 380: 135014.

[12] Liu L, Wu J, Liu H, et al. Study on marine engine combustion and emissions characteristics under multi-parameter coupling of ammonia-diesel stratified injection mode. *International Journal of Hydrogen Energy*, 2023, 48(26): 9881-9894.

[13] Zhou X, Li T, Wang N, et al. Pilot diesel-ignited ammonia dual fuel low-speed marine engines: A comparative analysis of ammonia premixed and high-pressure spray combustion modes with CFD simulation. *Renewable and Sustainable Energy Reviews*, 2023, 173: 113108.

[14] Scharl V, Lackovic T, Sattelmayer T. Characterization of ammonia spray combustion and mixture formation under high-pressure, direct injection conditions. *Fuel*, 2023, 333: 126454.

[15] Scharl V, Sattelmayer T. Ignition and combustion characteristics of diesel piloted ammonia injections. *Fuel Communications*, 2022, 11: 100068.

[16] Han Z, Reitz R D. Turbulence modeling of internal combustion engines using RNG κ-ε models. *Combustion science and technology*, 1995, 106(4-6): 267-295.

[17] Beale J C, Reitz R D. Modeling spray atomization with the Kelvin-Helmholtz/Rayleigh-Taylor hybrid model. *Atomization and sprays*, 1999, 9(6).

[18] Schmidt D P, Rutland C J. A new droplet collision algorithm. *Journal of Computational Physics*, 2000, 164(1): 62-80.

[19] Miller R S, Harstad K, Bellan J. Evaluation of equilibrium and non-equilibrium evaporation models for many-droplet gas-liquid flow simulations. I*nternational journal of multiphase flow*, 1998, 24(6): 1025-1055.

[20] Senecal P K, Pomraning E, Richards K J, et al. Multi-dimensional modeling of direct-injection diesel spray liquid length and flame lift-off length using CFD and parallel detailed chemistry. *SAE trans-actions*, 2003: 1331-1351.

[21] Mehl, M. Pitz, W. J. and Westbrook, C. K. Kinetic modeling of gasoline surrogate components

and mixtures under engine conditions. *Proceedings of the Combustion Institute*, 2011, 33(1): 193-200.

[22] Otomo, J. Koshi, M. Mitsumori, T. Chemical kinetic modeling of ammonia oxidation with improved reaction mechanism for ammonia/air and ammonia/hydrogen/air combustion. *International Journal of Hydrogen Energy*, 2018, 43(5): 3004-3014.

[23] Liu L, Wu Y, Wang Y. Numerical investigation on the combustion and emission characteristics of ammonia in a low-speed two-stroke marine engine. *Fuel*, 2022, 314: 122727.

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