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Study on the ammonia diffusion combustion characteristics under active thermal atmosphere effects

Fuels - Alternative & New Fuels

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ABSTRACT

Ammonia is a carbon-free fuel with broad application prospects, and the application of ammonia promises to significantly reduce carbon emissions from internal combustion engines. However, due to the properties of ammonia, its combustion in internal combustion engines faces challenges such as low combustion stability, slow flame propagation, and high nitrogen oxide emissions, which are the key issues restricting its application in internal combustion engines. The present research indicates that ammonia premixed combustion is constrained by the low flame propagation speed, resulting in low combustion efficiency, high NOx emissions, and high unburned ammonia emissions, and making it difficult to increase the ammonia substitution rate. In contrast, the diffusion combustion mode with ammonia high-pressure in-cylinder direct-injection can significantly improve ammonia combustion efficiency and reduce unburned ammonia emissions. Consequently, this study innovatively proposes the ammonia direct-injection thermal atmosphere compression ignition (TACI) combustion mode to achieve efficient and clean combustion in ammonia engines. Stable ammonia diffusion combustion was achieved by utilizing the active thermal atmosphere generated by n-heptane premixed combustion.

This paper experimentally investigated the stable ignition mechanism, comustion characteristics, engine performance and pollutant emissions of ammonia TACI combustion mode. Meanwhile, the ammonia diffusion combustion characteristics under thermal atmosphere effects were studied, focusing on the impacts of thermal atmosphere on ammonia diffusion combustion characteristics.The experimental results show that ammonia TACI combustion mode can achieve efficient combustion and exhibits high thermal efficiency. Additionally, the results reveal that due to the "locally rich-burn, overall lean-burn" characteristic of ammonia diffusion combustion, it demonstrates favorable NOx and unburned ammonia emissions. By optimizing the ammonia injection strategy, low NOx emissions and low unburned ammonia emissions can be achieved. Moreover, since the combustion of n-heptane generally increases the in-cylinder temperature, this combustion method hinders the formation of N2O. By controlling the ammonia injection timing, ultra-low N2O emissions were observed. This paper provides an in-depth study of ammonia TACI combustion mode and ammonia diffusion combustion characteristics, which promotes the application of ammonia fuel in CI engines.

1 INTRODUCTION

The transportation sector contributes nearly 1/4 of the total carbon emissions [1]. Therefore, reducing the carbon emissions from transportation is essential to solve the global warming issue caused by the greenhouse effect. Internal combustion engine (ICE) is one of the most important power sources of transportation and contributes significantly to carbon emissions due to the combustion of fossil fuels. The application of carbon-free fuels (e.g. ammonia, hydrogen) is expected to reduce the carbon emissions of ICE and has been drawing increasing attentions worldwide. While hydrogen still faces major concerns in expensive application cost and high explosion risk [2], ammonia appears as a better choice in contain scenarios due to its advantages in energy density, storage, transportation and safety over hydrogen [3]. The International Maritime Organization (IMO) considers ammonia one of the main solutions for achieving zero-carbon emissions in future shipping [4,5].

Producing ammonia by renewable energy and utilizing ammonia in engines can achieve carbon-free cycle and promote the efficient utilization of renewable energy [6]. Consequently, the application of ammonia fuel plays an important role in reducing greenhouse gas (GHG) emissions and popularizing renewable energy [7]. Ammonia has great application potential as an engine fuel. However, the high auto-ignition temperature (930 K [8]), high minimum ignition energy (8 mJ [8]) and low burning velocity (7 cm/s [8]) of ammonia cause difficulties in achieving stable ignition and efficient combustion in both compression-ignition (CI) and spark-ignition (SI) engines [9,10].

Another high-reactivity fuel is usually required to facilitate the ammonia combustion, but the challenges remain in increasing ammonia substitution rate, improving thermal efficiency and reducing pollutant emissions [11]. Therefore, the most critical problem of ammonia engine is the lack of mature combustion method that can achieve high ammonia substitution rate, efficient combustion and low pollutant emissions [12]. At present, the ammonia combustion methods under consideration include ammonia/hydrogen premixed combustion mode [13-16], ammonia/diesel port-injection dual-fuel combustion mode [17-20] and ammonia/diesel direct-injection dual-fuel combustion mode [21-24].

The fuel burning rate in premixed combustion mode is controlled by the flame propagation speed. Therefore, the ultra-low flame propagation speed of ammonia leads to low combustion efficiency and high unburned NH_3 emissions in premixed combustion mode. The fuel burning rate in diffusion combustion mode is controlled by fuel/air mixing rate and fuel combustion reaction rate. Though ammonia is a low-reactivity fuel with slow combustion reaction rate, the time scale of chemical reaction is much smaller than that of ammonia/air mixing rate, thus ammonia diffusion combustion is determined by ammonia/air mixing rate. Consequently, adopting diffusion combustion method can avoid the adverse effect of ammonia properties. Compared to the premixed combustion method, ammonia direct-injection diffusion combustion method exhibits higher combustion efficiency and can reach higher ammonia substitution rate [25,26]. Furthermore, the studies on inner selective non-catalytic reduction (SNCR) effect show that NOx can be more efficiently reduced by SNCR effect in ammonia diffusion combustion mode due to the local rich-burn features [24]. By optimizing the fuel injection strategies, the combustion performance and pollutant emissions can be improved in ammonia diffusion combustion mode [23,24].

Zhang et al. [21] and Pires et al. [22] have tested the ammonia/diesel direct-injection dual-fuel combustion mode on the two-stroke and four-stroke engine, respectively. The results show that ammonia diffusion combustion exhibits high combustion efficiency and low NOx emissions. However, the ammonia/diesel direct-injection dual-fuel combustion mode requires two separate direct-injectors for the two fuels, thus faces challenges in engine design and applications due to the hardware complexity [21,22]. In addition, optimal combustion performance requires developing the dual-fuel injector to achieve coaxial injection for ammonia and diesel, while the two-injector method is prone to reduce the combustion stability and cause more N_2O and unburned NH_3 emissions [22]. However, it is so difficult to develop the ammonia/diesel dual-fuel injectors and solve the problem of high application cost and low operating reliability.

In the current work, ammonia thermal atmosphere compression ignition (TACI) combustion mode was proposed as a solution to achieve efficient and clean combustion in ammonia engines. The ammonia diffusion combustion characteristics under thermal atmosphere compression ignition conditions were studied in this paper, focusing on the impacts of thermal atmosphere on ammonia diffusion combustion characteristics. This paper provides an in-depth investigation of ammonia TACI combustion mode and ammonia diffusion combustion characteristics, which has great significance for the application of ammonia TACI combustion mode and the development of ammonia diffusion combustion theory.

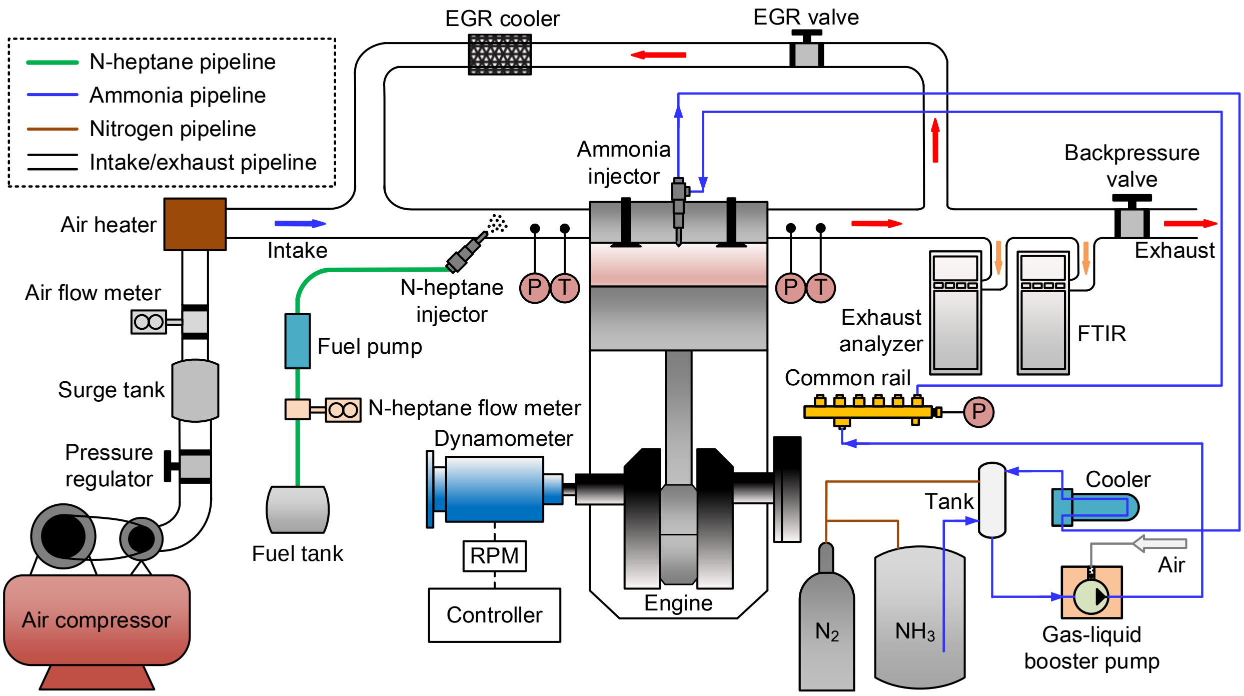

Figure 1. Schematic diagram of the experiment system.

2 SETUP AND METHODS

2.1 Experimental setup

The test engine is modified from a 6-cylinder diesel engine, and the main engine parameters are shown in Table 1. An independent intake/exhaust system and a fuel supply system are provided for the sixth cylinder (the test cylinder). The test cylinder was individually controlled and monitored during the experiment. The other five cylinders (non-test cylinders) were controlled by the original engine control unit. The dynamometer was used to control the load and speed of the non-test cylinders, providing a stable engine speed (RPM) for the test cylinder.

The experiment system consists of an ammonia high-pressure direct-injection system, a n-heptane port-injection system, an intake/exhaust system, an exhaust analyzer, a Fourier Transform Infrared (FTIR) spectrometer, a data acquisition system, a control system and the test engine, as shown in Figure 1. The ammonia high-pressure injection system consists of a liquid ammonia storage tank, a buffer tank, a gas-liquid booster pump, a common rail, a high-pressure injector, and a reflux cooler. Nitrogen was introduced into the tank to pressurize the liquid ammonia, achieving stable liquid phase storage and stable supply for the booster pump. The n-heptane port-injection system enables the quantitative injection though a fuel pump and a gasoline injector. The intake air for the test cylinder was supplied by an air compressor, equipped with a pressure regulator and a surge tank to provide stable intake pressure for the test cylinder. Additionally, an intake air heater is installed to control the intake air temperature. The control system can manage the engine speed, ammonia injection, and n-heptane injection.

Table 1. Engine specifications.

Parameters	Value
Engine type	Four strokes
Bore (mm)	105
Stroke (mm)	125
Connecting rod (mm)	210
Compression ratio	16
Intake valve open (°CA)	343
Intake valve close (°CA)	587
Exhaust valve open (°CA)	125
Exhaust valve close (°CA)	377
Ammonia injector type	Diesel injector
Nozzle number and diameter	7×0.24 mm

The key parameters need to measure in experiments include in-cylinder pressure and various pollutant emissions. The in-cylinder pressure of the test cylinder was collected using a pressure sensor (Kistler 6125C) and sent though a charge amplifier (Kistler 5018A1003), which was synchronized by a crank angle resolved sensor. The CO, THC, and CO_2 emissions were measured by the exhaust analyzer (Horiba MEXA-7100DEGR). The NOx ($NO+NO_2$), N_2O, and unburned NH_3 emissions were measured by the FTIR (Bruker Omega 5). The measurement uncertainty of the exhaust analyzer and the FTIR is < 0.5 % and < 2 %, respectively. Additionally, the experimental parameters such as intake pressure, intake temperature, intake mass flow rate, exhaust pressure, and exhaust temperature were also measured in experiments.

2.2 Experimental conditions

Table 2. Engine operating conditions of ammonia TACI combustion mode.

Operating conditions	Condition 1	Condition 2	Condition 3
Engine speed (r/min)	1500	1500	1500
Ammonia injection pressure (MPa)	60	60	60
Ammonia injection pulse (μs)	1640	1640	1640
Ammonia injection mass (kg/h)	3.9	3.9	3.9
N-heptane injection mass (kg/h)	1.019	0.898	0.805
Ammonia energy proportion (%)	61	64	67
Intake pressure (bar)	1.496	1.509	1.502
Intake temperature (K)	302.9	301.9	302.4
Air flow rate (kg/h)	73.5	75.6	75.9
Intake equivalence ratio	0.21	0.18	0.16
Overall equivalence ratio	0.53	0.49	0.47

This paper studied the ammonia diffusion combustion characteristics under different n-heptane injection quantity conditions. The specific operating parameters of each operating condition are shown in Table 2. In the current study, three different n-heptane injection rates of 1 kg/h, 0.9 kg/h, and 0.8 kg/h were set with an intake pressure of 1.5 bar, namely Condition 1, Condition 2 and Condition 3, respectively. The formed intake equivalence ratios are 0.21, 0.18, and 0.16, respectively. Except for changing the n-heptane injection mass, the other boundary conditions remained unchanged in the experiment.

3 RESULTS AND DISCUSSTION

3.1 Characteristics and mechanism of ammonia TACI combustion mode

In ammonia TACI combustion mode, ammonia diffusion combustion is achieved under the active thermal atmosphere effects generated by n-heptane combustion. As a basis for the subsequent discussion, the operating mechanism of ammonia TACI combustion mode were explained first, as illustrated in Figure 2. The combustion process of ammonia TACI combustion mode is shown in Figure 2(a)-(d). The n-heptane/air mixture in the cylinder burns first under the compression effect. The combustion of n-heptane increases the in-cylinder temperature and produces a large number of active radicals. After ammonia is injected into the cylinder via a high-pressure injector, it evaporates rapidly and ignites under the active thermal atmosphere effects, forming a diffusion flame.

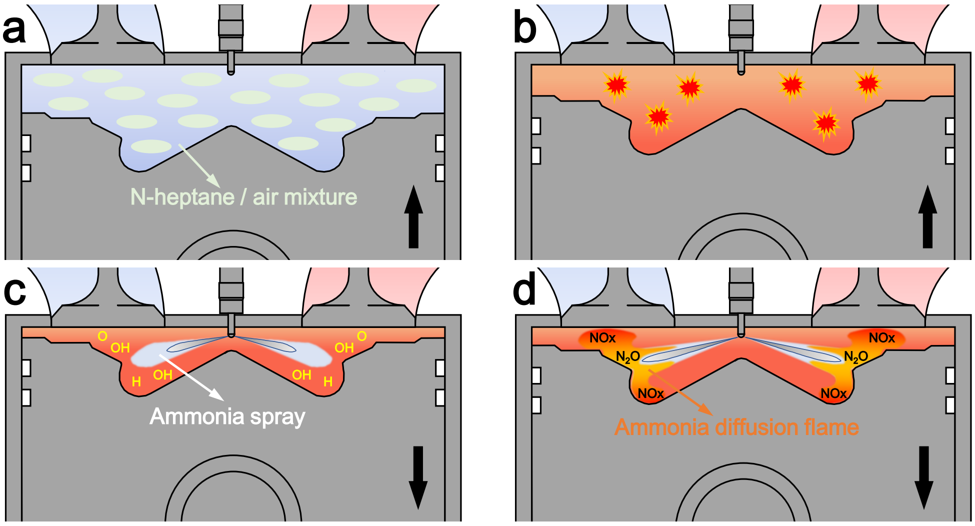

Figure 2. Schematic diagram of ammonia TACI combustion mode: (a) Compression; (b) N-heptane HCCI combustion; (c) Ammonia high-pressure injection; (d) Ammonia diffusion combustion.

N-heptane is supplied into the intake manifold and introduced into the cylinder together with the intake air during the intake stroke. Then n-heptane auto-ignited with the continues compression effect and undergoes homogeneous charge compression ignition (HCCI) combustion. The combustion of n-heptane has two stages: low-temperature reaction stage and high-temperature combustion stage, as shown in Figure 3. After n-heptane combustion, ammonia is injected into the cylinder and auto-ignited under active thermal atmosphere effects (high-pressure, high-temperature and active radicals). Figure 3 demonstrates that the in-cylinder pressure and temperature increase to 9.6 MPa and

1495 K before ammonia ignition, respectively. For a four-strokes engine, it is important to clarify that 0°CA represents the top dead center (TDC) for firing. As a result, negative values indicate events occurring before TDC, while positive values indicate events occurring after TDC in this paper.

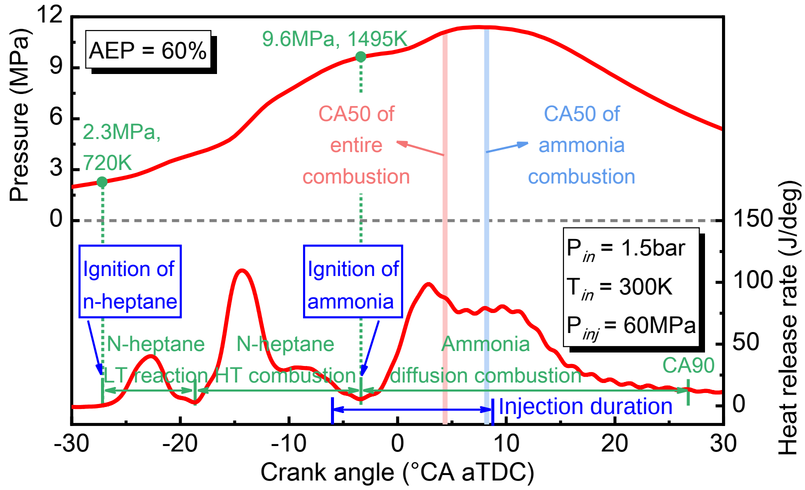

Figure 3. Combustion characteristics of ammonia TACI combustion mode.

The significant reaction pathway of ammonia TACI combustion mode was revealed in Figure 4. Ammonia and n-heptane undergo three combustion stages in TACI combustion mode: n-heptane low-temperature (LT) reaction stage, n-heptane high-temperature (HT) combustion stage, and ammonia diffusion combustion stage. The combustion of n-heptane produces a large number of significant active substances, including H_2, H_2O_2, HO_2, H, OH, O, etc. These species play a crucial role in promoting ammonia ignition. The ammonia combustion reaction pathway can be roughly divided into four parts: dehydrogenation, oxidation (NOx formation), reduction (NOx reduction), and polymerization reactions.

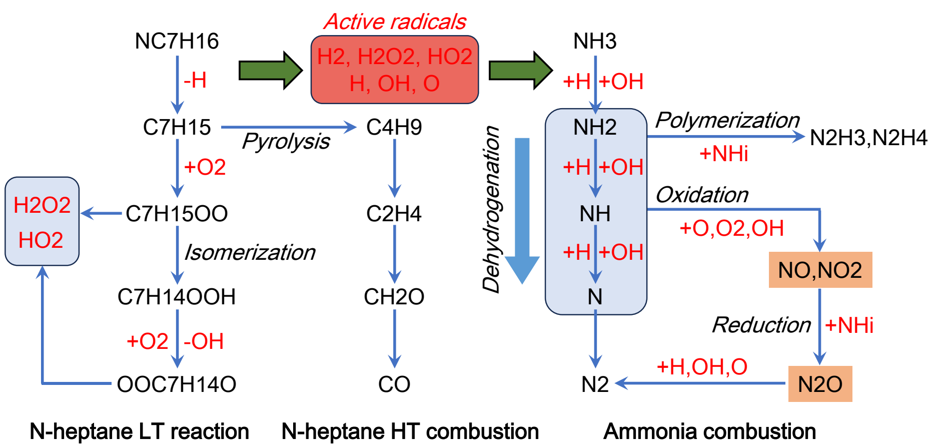

Figure 4. Significant reaction pathway of ammonia TACI combustion mode.

3.2 Ammonia diffusion combustion characteristics under different operating conditions

In this section, the influence of n-heptane injection quantity on ammonia diffusion combustion characteristics was investigated, focusing on the in-cylinder pressure, in-cylinder temperature, ammonia ignition features and heat release trends. The combustion of different n-heptane injection quantity releases different heat, thus forming different thermal atmosphere conditions in the cylinder. Therefore, by using different n-heptane injection quantity in ammonia high-pressure direct-injection engine experiment, the ammonia diffusion combustion characteristics under different thermal atmosphere conditions were explored.

Figure 5-7 present the in-cylinder pressure, temperature, and heat release rate (HRR) curves under different n-heptane injection quantities. Firstly, by comparing the in-cylinder pressure and heat release rate of different ammonia injection timings, the influence of ammonia injection timing on ammonia diffusion combustion was analyzed. It can be seen from Figure 5 that the ammonia injection time has a significant impact on the heat release trend of ammonia diffusion combustion. When ammonia injection timing is advanced, the ignition delay time of ammonia is extended, leading to more premixed ammonia/air mixture. Consequently, the ammonia combustion rate is faster, the heat release becomes more concentrated, the peak value of heat release rate curve increases, and the maximum in-cylinder pressure and temperature gradually rise. As ammonia injection timing delayed, ammonia diffusion combustion tends to slow down, the heat release rate decreases, and the ammonia combustion duration extends.

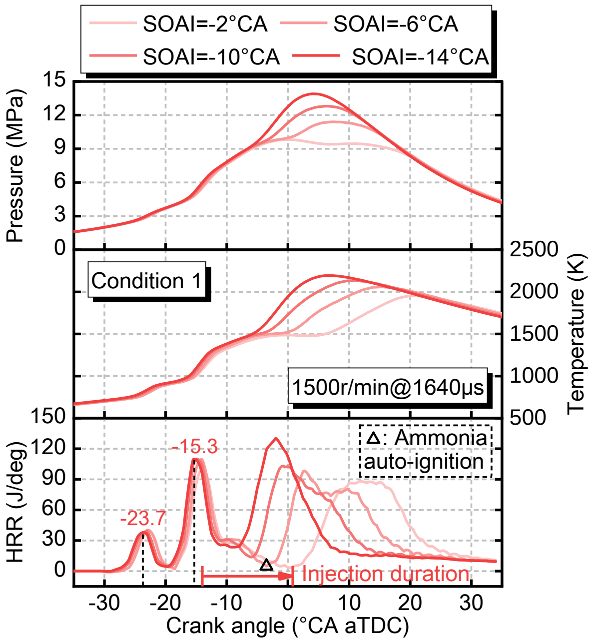

Figure 5. In-cylinder pressure, temperature, and heat release rate under Condition 1.

As can be seen from Figure 6, when n-heptane injection quantity decreases, the in-cylinder pressure and combustion temperature both decrease significantly. However, the reduction of n-heptane injection quantity does not change the impact of ammonia injection timing on ammonia diffusion combustion features. Under Condition 2, the heat release rate of ammonia diffusion combustion still significantly decreases with ammonia injection timing delayed, and the combustion phase significantly delays. This trend becomes even more evident when n-heptane injection quantity reduced.

By comparing Figure 5 and Figure 6, it was demonstrated that reducing n-heptane injection quantity prolongs the ammonia ignition delay time. A portion of ammonia/air combustible mixture forms during the ammonia ignition delay time, so a prolonged ignition delay time increases the ammonia premixed ratio. The more premixed ammonia results in more concentrated combustion, leading to a higher heat release rate and a shorter combustion duration.

As shown in Figure 6, ammonia cannot achieve stale and efficient combustion when ammonia injection timing is over-delayed. Meanwhile, a large amount of unburned ammonia severely deteriorates n-heptane combustion. The heat release rate curves in Figure 6 indicate that both n-heptane LT and HT combustion phases are delayed when n-heptane injection quantity reduced (compared with Figure 5). The n-heptane combustion phase is slightly delayed due to the reduction of n-heptane under stable combustion conditions, while it is significantly delayed due to the impact of unburned ammonia under deteriorated combustion conditions. The heat release rate curves of deteriorated n-heptane combustion exhibit significant differences, with a marked delay in n-heptane combustion phase, as the results of -2°CA and -6°CA in Figure 6. Conversely, the heat release rate curves of stable n-heptane combustion nearly overlap, as the results of -10°CA and -14°CA in Figure 6.

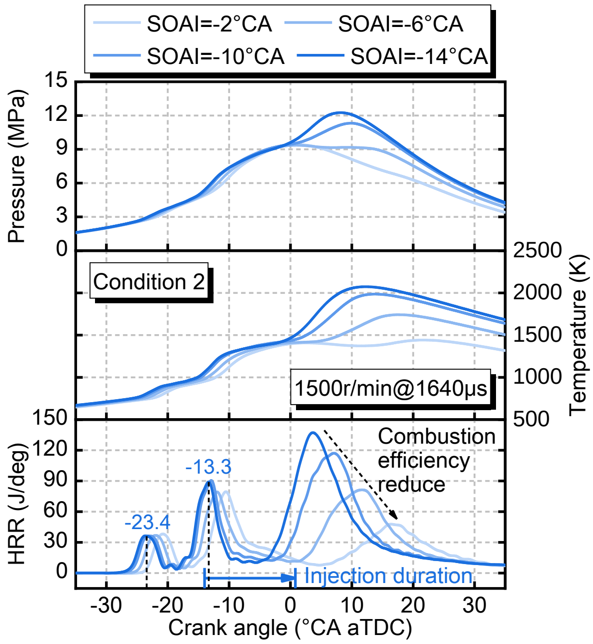

Figure 6. In-cylinder pressure, temperature, and heat release rate under Condition 2.

The reduction of n-heptane leads to a decrease in heat release rate of n-heptane combustion, significantly lowering in-cylinder pressure and temperature. By comparing the heat release rate curves under different conditions, it can be observed that the reduction of n-heptane has a pronounced impact on ammonia ignition and combustion. Particularly, ammonia diffusion combustion deteriorates severely under Condition 3, with significantly delayed ammonia ignition timing and notably reduced heat release rate, as shown in Figure 7. The curves in Figure 7 are the average in-cylinder pressure curves of 100 cycles and the average temperature and heat release rate curves calculated by the average in-cylinder pressure. Therefore, even if there is obvious heat release under Condition 3, the ammonia combustion in most working cycles is misfire.

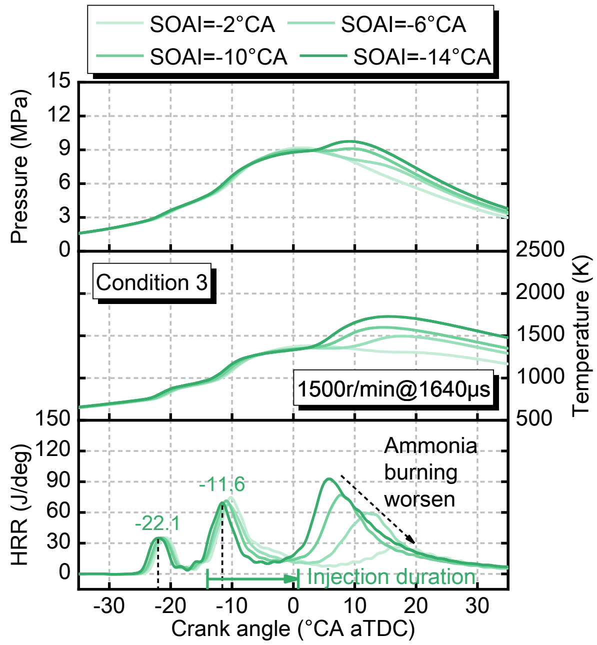

Figure 7. In-cylinder pressure, temperature, and heat release rate under Condition 3.

The further analysis on ammonia ignition delay time was conducted to reveal the ammonia ignition characteristics under different thermal atmosphere conditions, as shown in Figure 8. The ammonia ignition delay time is defined as the interval between ammonia injection timing and ammonia ignition timing. The ammonia ignition timing is identified as the point of the minimum heat release rate (extreme point) between n-heptane combustion stage and ammonia combustion stage, as marked by the triangle in Figure 5. Figure 8 indicates that the reduction of n-heptane significantly prolongs the ammonia ignition delay time. The ammonia ignition delay time increases more significantly from Condition 1 to Condition 2. It can be seen from Figure 8 that the ammonia ignition delay time shows a trend of initially decrease and then increase as ammonia injection timing delayed. This trend remains consistent under different n-heptane injection quantities.

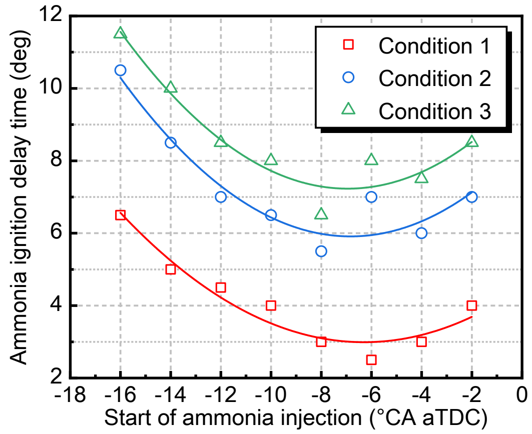

Figure 8. Ammonia ignition delay times under different conditions.

3.3 Performance and emissions under different operating conditions

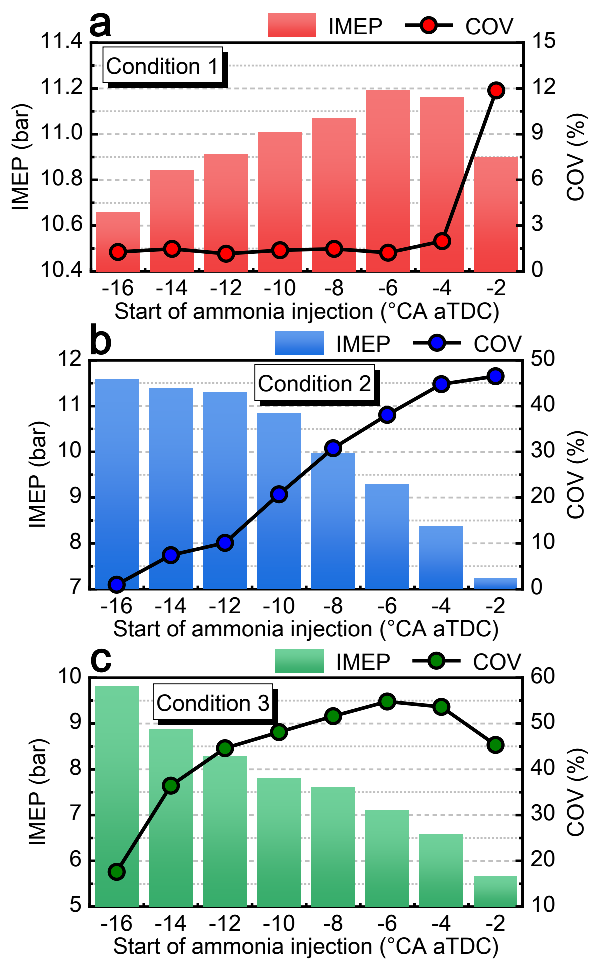

Figure 9. The measured IMEP and COV under different n-heptane injection quantities.

In this section, the combustion stability, performance, and emission features over a wide range of ammonia injection timing (-2°CA to -16°CA) were provided to reveal the ammonia diffusion combustion characteristics under different n-heptane injection quantities. In addition, the optimal operating points can be identified to evaluate the performance of ammonia TACI combustion mode under different thermal atmosphere conditions.

Figure 9 shows the measured IMEP (Indicated Mean Effective Pressure) and COV (Coefficient of Variation) under different n-heptane injection quantities. The results indicate that stable ammonia diffusion combustion can only achieved under Condition 1. Condition 2 represents a critical condition, where ammonia combustion is on the verge of misfire. Under Condition 3, ammonia combustion deteriorates significantly, with severe misfire and COV far exceeding the threshold of stable combustion (COV ≤ 5%).

The COV shown in Figure 9 illustrates that the combustion stability significantly decreases when ammonia injection timing is over-delayed. Under Condition 1, when ammonia injection timing is delayed to -2°CA, the COV increases significantly to around 12 %. Under Condition 2, the COV gradually decreases as ammonia injection timing advanced, which also proves that advancing the ammonia injection timing can promote ammonia stable combustion.

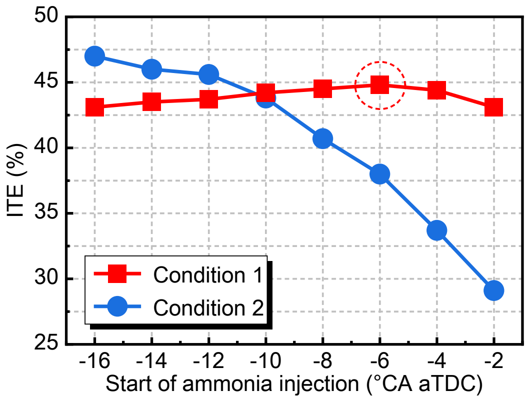

Figure 10. Indicated thermal efficiency (ITE) under different n-heptane injection quantities.

Figure 10 illustrates the indicated thermal efficiency (ITE) under different n-heptane injection quantities. It can be seen that the ITE of ammonia TACI combustion presents different variation trends under different n-heptane injection quantities. ITE initially increases and then decreases as ammonia injection timing delayed under Condition 1, with the highest ITE observed at -6°CA. Under Condition 2, the advanced ammonia injection timing promotes ammonia stable combustion, resulting in a continuous increase in ITE. Condition 3 is a severe fire condition, so its performance cannot be evaluated.

Under Condition 2, when ammonia injection timing advanced to -12°CA, the ITE exceeds Condition 1. This demonstrates that reducing the n-heptane injection quantity decreases the negative work of n-heptane combustion and reduces energy consumption. Thus, the ITE of stale ammonia combustion under Condition 2 is higher than that under Condition 1.

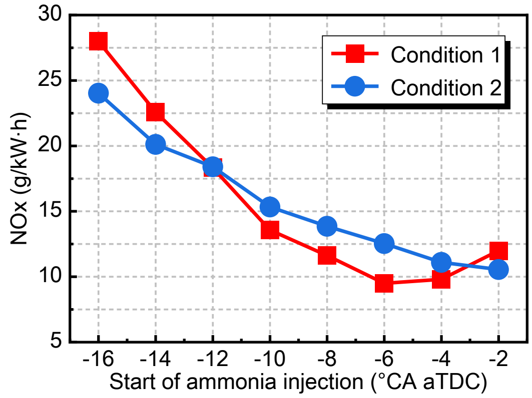

Figure 11. NOx ($NO+NO_2$) emissions under different n-heptane injection quantities.

Figure 11 shows that the NOx emissions decrease significantly as ammonia injection timing delayed, which is mainly caused by the reduction of in-cylinder temperature. NOx is mainly generated at the temperature above 2000 K and equivalence ratio below 1 (high-temperature and lean-burn conditions). Meanwhile, there are also a few fuel-NOx provoked by the nitrogen content in ammonia at low temperature range of 1500-2000 K. Delaying the ammonia injection timing results in a reduction of in-cylinder temperature, as shown in Figure 5, and thus lowering the NOx generation. However, when ammonia injection timing is too late, the drastic decrease in thermal efficiency causes NOx emissions to increase instead.

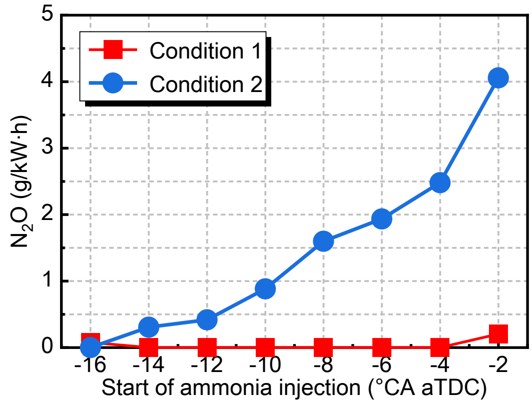

Figure 12. N_2O emissions under different n-heptane injection quantities.

It can be concluded from the in-cylinder temperature results of ammonia TACI combustion mode that the in-cylinder temperature before ammonia ignition reaches 1500 K, as illustrated in Figure 5. N_2O is mainly generated at the low temperature range of 1000-1500 K, the excessive in-cylinder temperature hinders N_2O generation. Consequently, ammonia TACI combustion mode has significant advantages in N_2O emissions. Figure 12 shows that Condition 1 has excellent N_2O emission performance: near-zero N_2O emission is observed within the ammonia injection timing range of -14°CA to -4°CA. In addition, Figure 12 reveals that when ammonia combustion stability decreases in Condition 2, N_2O emissions gradually increase.

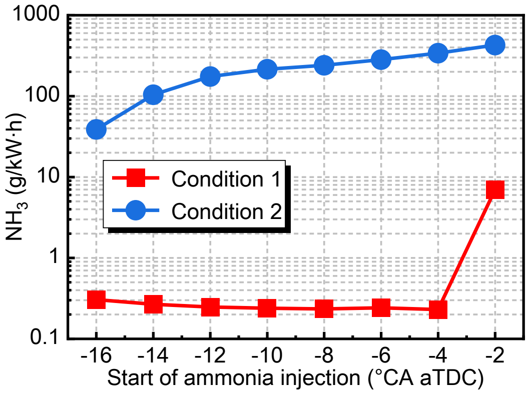

Figure 13. NH_3 emissions under different n-heptane injection quantities.

Figure 13 and Figure 14 depict the unburned NH_3 and THC emissions, representing the combustion efficiency of ammonia and n-heptane. The unburned NH_3 and THC emissions are low under Condition 1, indicating high combustion efficiency. The results demonstrate that stable ammonia diffusion combustion exhibits ultra-low unburned NH_3 emissions, as shown in Figure 13. When ammonia injection timing is over-delayed, the unburned NH_3 emissions increase significantly due to the unstable burning of ammonia in the low temperature conditions.

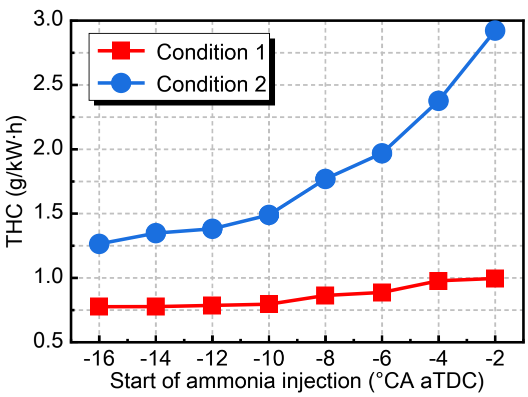

Figure 14. THC emissions under different n-heptane injection quantities.

Figure 13 and Figure 14 shows that the unburned NH_3 and THC emissions gradually increase as ammonia injection timing delayed under Condition 2. This also suggests that the reduction of combustion stability severely impacts ammonia combustion efficiency. The increased unburned ammonia in exhaust introduces more ammonia into the subsequent cycle, adversely affecting n-heptane combustion. Particularly, n-heptane combustion significantly deteriorates when ammonia misfire severely, leading to noticeable reductions in combustion efficiency and sharp increases in THC emissions, as shown in Figure 14. In addition, the HCCI combustion of n-heptane generates CO emissions, which are low under stable combustion conditions and rapidly increase when combustion stability decreases, as shown in Figure 15.

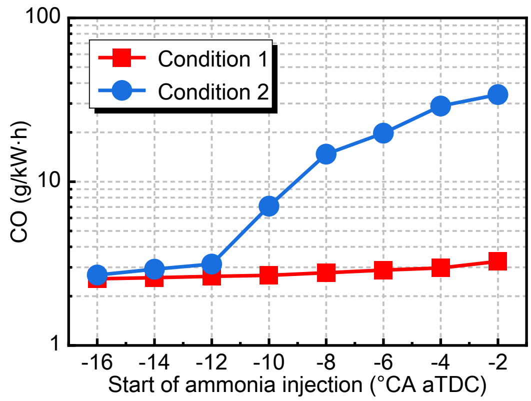

Figure 15. CO emissions under different n-heptane injection quantities.

According to the experimental results, ammonia TACI combustion mode has low N_2O and low unburned NH_3 emissions. The n-heptane HCCI combustion produces some CO and THC emissions. However, it is worth noting that the CO and THC emissions can be easily eliminated in the aftertreatment like DOC (Diesel Oxidation Catalyst). N_2O is an important byproduct of NOx reduction reactions and is difficult to eliminate in aftertreatment devices. Therefore, it is necessary to focus on the NOx, N_2O and unburned NH_3 emissions in ammonia engines, especially the N_2O emissions. The ultra-low N_2O emissions and ultra-low unburned NH_3 emissions of ammonia TACI combustion mode make it has significant potential and application value.

In addition, ammonia TACI combustion mode has enormous potential in GHG reduction because of the extremely low N_2O emissions. Due to the thermal atmosphere required for ammonia ignition, the GHG emissions of ammonia TACI combustion mode mainly come from n-heptane combustion. It can be predicted that ammonia TACI combustion mode can reach a greater GHG reduction under higher engine load conditions. The further optimizations on engine operating strategy to reduce the required n-heptane quality can make ammonia TACI combustion mode has greater potential in GHG reduction, which will be presented in the subsequent work.

4 CONCLUSIONS

In this paper, the ammonia TACI combustion mode and ammonia diffusion combustion characteristics under active thermal atmosphere effects were investigated. According to the investigation results, ammonia diffusion combustion exhibits high thermal efficiency, low NOx emissions, ultra-low N_2O and unburned NH_3 emissions, with great potential in GHG reduction. Therefore, ammonia diffusion combustion method has significant application advantages in internal combustion engines. The conclusions of this paper were summarized as follows:

(1) The experimental results show that ammonia can achieve stable ignition and efficient diffusion combustion under active thermal atmosphere conditions. The entire combustion process of ammonia TACI mode can be divided into three stages: n-heptane low-temperature reaction stage, n-heptane high-temperature combustion stage and ammonia diffusion combustion stage.

(2) Ammonia injection timing has significant influences on ammonia diffusion combustion characteristics. Adjusting the ammonia injection timing can obtain the highest thermal efficiency for ammonia diffusion combustion, which is mainly determined by the ammonia combustion phase. The combustion stability and thermal efficiency significantly decrease when ammonia injection timing is over-delayed, while N_2O and unburned NH_3 emissions significantly increase.

(3) Due to the increased in-cylinder temperature caused by high-reactivity fuel combustion, ammonia TACI combustion mode has great advantages in N_2O and unburned NH_3 emissions. Ultra-low N_2O and NH_3 emissions were observed in ammonia TACI combustion mode. However, a large amount of CO and THC emissions need to be eliminated by the aftertreatment devices like DOC. Meanwhile, SCR is also necessary for ammonia TACI engine to meet the strict NOx emission regulations.

(4) Both n-heptane LT and HT combustion phases are delayed when n-heptane injection quantity reduced, with significantly reduced heat release rate. The reduction of n-heptane leads to delayed ammonia ignition timing, higher heat release rate and shorter ammonia combustion duration. However, the over-reduced n-heptane injection quantity leads to severe deterioration in both n-heptane and ammonia combustion.

(5) The current work not only evaluates the ammonia TACI combustion mode, but more importantly, explores the characteristics of ammonia diffusion combustion by utilizing the active thermal atmosphere method. Therefore, the significance of the current study lies in exploring the methods to achieve efficient ammonia combustion and studying the ammonia diffusion combustion characteristics, which promotes the application of ammonia fuel in CI engines.

5 ACKNOWLEDGEMENTS

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