An optical study of the combustion and flame development of ammonia-diesel dual-fuel engine based on flame chemiluminescence

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Abstract

Under the background of the "carbon peak and carbon neutrality", the development and utilization of zero-carbon fuels, represented by green ammonia and green hydrogen, has gained attention from all walks of life. Among them, the problems of transportation and storage of hydrogen restrict its industrial development, while ammonia has significant advantages as a suitable hydrogen energy carrier for the power systems. The ammonia-diesel dual-fuel engine enables the mixture to be stratified in a time-activated multi-point ignition mode to promote efficient and clean combustion of ammonia. To investigate the combustion and flame development of the ammonia-diesel dual-fuel engine, an optical diagnostic study was carried out on a self-refit dual-fuel optical engine. The results

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show that the combustion inertia and lower flame temperature of ammonia can inhibit combustion and lead to lower cyclic heat release in the ammonia-diesel dual-fuel combustion (ADDC) mode, which in turn reduces the indicated mean effective pressure (IMEP). Different from the yellow-white flame produced by the high-temperature soot radiation in pure diesel combustion (PDC) mode, the flame in the ADDC mode appears orange. The peak of flame area (FR) percentage and flame natural luminosity (FNL) of the 80% ammonia ratio ADDC mode decrease by 60% and 92%, respectively, compared to the peaks at PDC mode. The ammonia combustion flame is mainly concentrated around the diesel flame, and at the same time achieves good ignition performance at all ammonia ratios. In contrast to the PDC mode where the FR and FNL decrease rapidly as the diesel injection timing (DIT) advances, the flame pattern of the ADDC mode does not respond significantly to the DIT.

Keywords: Ammonia-diesel dual-fuel combustion; Combustion characteristics; Flame development; Ammonia ratio; Diesel injection timing

Highlights:

- An optical study of the ADDC mode was conducted.
- Ammonia premixing leads to lower cyclic heat release and IMEP.
- The ammonia flame is mainly concentrated around the diesel flame.
- The effect of flame pattern on DIT is not significant in the ADDC mode.

Abbreviations

ICE	Internal combustion engine	FNL	Flame natural luminosity
CI	Compression-ignition	HRR	Heat release rate
SI	Spark ignition	ATDC	After top dead center
HEI	High energy ignition	COV	Coefficient of cyclic variation
ADDC	Ammonia-diesel dual-fuel combustion	DIT	Diesel injection timing
SCR	Selective catalytic reduction	CD	Combustion duration
LIF	Laser-induced fluorescence	ID	Ignition delay
LII	Laser-induced incandescence	CA	Crank angle
PIV	Particle imaging velocimetry	CN	Cetane number
SRS	Stimulated Raman scattering	RON	Research octane number
EGR	Exhaust gas recirculation	IMEP	Indicated mean effective pressure
FR	Flame area	PDC	Pure diesel combustion

1. Introduction

In order to overcome the greenhouse effect of carbon dioxide on the global ecology, governments have put forward " carbon peak and carbon neutrality goals " in recent years [1]. In the circumstance, the transformation of the global energy structure has received widespread attention, and zero-carbon renewable energy, represented by wind energy, solar energy, and ocean energy, has been rapidly developed [2-4]. However, renewable energy sources are subject to significant fluctuations due to weather, time, geography, and season, so the development of renewable energy must be combined with the progress of energy storage technologies. Among all the energy storage, chemical energy storage is the most flexible one, which can be moved, stored, and distributed at a low cost [5, 6]. Currently, chemical energy storage, represented by carbon-neutral fuels such as green hydrogen, green ammonia, biomass fuels, and green electric synthetic liquid fuels, is one of the most popular form of zero-carbon energy storage. Among them, ammonia and hydrogen have a clear application prospect in the short term due to its relatively mature technology system [7-9].

At present, hydrogen, as an efficient and clean secondary zero-carbon energy, is attracting widespread attention in the application of hydrogen fuel cells and hydrogen internal combustion engines (ICEs) [10, 11]. However, hydrogen still faces a series of technical challenges in terms of production, transportation, storage, and end-use applications, and the consequent long-tail effect restricts its industrial development [12]. Ammonia (NH_3) as a suitable carrier of hydrogen energy, with its complete combustion products of nitrogen and water, is also a carbon-neutral fuel. Ammonia has clear advantages over hydrogen as the powertrain fuel for several reasons [13]. Firstly, ammonia can be completely liquefied at 298.15 K and 0.9 MPa, and the hydrogen content density (106.4 kg/m^3) and low heat value (11.213 GJ/m^3) of liquid ammonia are higher than those of liquid hydrogen (70.8 kg/m^3 and 9.168 GJ/m^3). Secondly, the economic cost of ammonia is relatively low, with the unit energy price of ammonia (13.3 USD/GJ) being lower than that of hydrogen (35.2 USD/GJ) and gasoline (29.1 USD/GJ), while the storage cost of ammonia is only 1/26th to 1/30th of that of hydrogen [14]. In addition, the technology for large-scale industrial production of ammonia is well established. The production efficiencies have been reached over 90% and the associated infrastructures have been globally arranged [15]. Finally, ammonia combustion is characterized by a slow flame speed and narrow combustion limits, which makes it less likely to cause an explosion, so it is of high security. As a result, ammonia is expected to be the ideal solution for the green transformation of future energy systems as a source of energy for thermal and power equipment [16, 17].

The physicochemical properties of ammonia make it suitable for use as a fuel in power systems, so it has a promising market in power generation, automobiles, ships, aircrafts, and rockets. In particular, the application of ammonia in the widely used ICEs is of strategic importance [18-20]. However, ammonia is more difficult to burn in the ICEs than fossil fuels such as petrol and diesel [21]. In the early years, the US military had conducted several experiments with pure ammonia as a fuel in the compression-ignition (CI) engine, and the results showed that the compression ratio needed to be increased to 35:1 to ensure stable combustion of the pure ammonia engine. Subsequent research showed that pure ammonia can be burned in an ignition engine using the technique of variable compression ratio and multiple sparks plug ignition, but the slow flame propagation of ammonia combustion and the significant quenching effect led to unstable and inefficient combustion [22]. As a result, it is difficult to use ammonia as an ICE fuel alone and reactivity enhancer is required to improve its combustion performance [23]. Ammonia is currently used by two main ways in ICEs. In the spark ignition (SI) engine, ammonia is mixed with one or more reactive enhancer such as hydrogen and then ignited by high energy ignition (HEI) or jet ignition. In the CI engine, ammonia is used as a premixed fuel and ignited by the high reactivity fuel such as diesel [24, 25]. Among them, the ammonia-premixed ignition combustion mode enables the mixture to be stratified by flexibly adjusting the fuel injection strategy, which promotes efficient and clean combustion of ammonia by means of multi-point ignition. Thus, the ammonia-premixed ignition combustion mode is expected to be the ideal solution for the heavy-duty ammonia-fueled engines [26, 27]. In addition, ammonia is suitable for use in CI engines with high compression ratio to improve thermal efficiency due to the high octane number and excellent anti-explosion property. Also, the CI engines provide better torque characteristics and power coverage for a wider range of applications. Consequently, ammonia-fueled CI engines based on ammonia-premixed ignition combustion have great potential for applications in heavy truck power, marine power, and power generation [28, 29]. Reiter et al. achieved stable operation of ammonia-diesel dual-fuel combustion (ADDC) mode in a CI engine and increased the engine combustion efficiency to over 95% at the ammonia ratios of 40-60% [30]. Niki et al. further investigated the ADDC mode and found that a multiple injection strategy could achieve thermal efficiency equivalent to that of the conventional diesel engine. However, the low flame speed, quenching, and gaping effects of ammonia led to low ammonia combustion efficiency and deteriorating emissions [31]. Sun et al. suggested that selective catalytic reduction (SCR) technology has considerable potential for reducing NOx and unburned ammonia emissions from ADDC engines [32]. Accordingly, the ADDC mode requires in-depth optimization of its combustion process to exploit the performance potential of ammonia-fueled CI engines.

The development of optical measurement technology has provided new means and methods for the research of ICEs [33, 34]. In contrast to traditional thermodynamic investigations, which focus on the macroscopic combustion and emission characteristics of ICEs, the optical measurements focus on the internal combustion processes of ICEs, which provide an excellent insight into the development of combustion flame and the pollutant generation mechanism under different combustion modes [35-37]. The main optical measurement techniques currently used in ICE research include flame chemiluminescence, laser-induced fluorescence (LIF), laser-induced incandescence (LII), particle imaging velocimetry (PIV) and stimulated Raman scattering (SRS), which provide a full range of diagnostics for fuel spray, mixture forming, ignition processes, combustion processes and pollutant formation in ICEs [38, 39]. Among them, the use of high-speed photography combined with flame chemiluminescence provides a deep analysis of flame development and flame morphology during the combustion processes of ICEs, which is important for understanding the spatial and temporal evolution of the in-cylinder flame under different combustion modes and boundary conditions [40, 41]. Ihracska et al. studied the flame characters of a spark-ignited engine using high-speed imaging, fitting image projections of flame to circles and ellipses, followed by statistical evaluation of the flame centroid, flame perimeter, and flame shape [42]. Hult et al. arranged multiple high-speed cameras in a marine two-stroke optical engine to map the spatial position of the in-cylinder flame and reconstruct the 3D flame profile to extract characteristics such as flame length, flame height, ignition source position, and flame direction [43]. Lee et al. studied the influence of various conditions such as injection timing, exhaust gas recirculation (EGR), and swirl ratio on the flame propagation process based on an optical engine, and clarified the effect of swirl on the spray and flame morphology [44]. Therefore, an optical diagnostic study on the ADDC mode is significant for a deep understanding on many combustion details, as well as proposing combustion control strategies to improve the performance of ammonia-fueled engines.

This study investigates the ADDC mode in a modified single-cylinder CI optical engine using flame luminescence combined with high-speed photography. The combustion characteristics and flame development of the ADDC mode are analyzed in depth from the thermodynamic and optical perspectives respectively. The influence mechanism of the fuel injection strategy on the ADDC engine is clarified and the regulation direction of combustion boundary conditions to achieve fast and stable combustion in ammonia-fueled engines is proposed.

2. Experimental apparatus and procedure

2.1 Optical engine and operating conditions

The optical engine used in this study had been refitted from a single-cylinder, four-stroke, CI, upright engine. The piston of the optical engine had been converted to a "Bowditch" type extended piston. The extended piston had a transparent piston top with a lowered 45-degree reflector, forming a light path for viewing the combustion process in the cylinder. The optical engine was dragged by a three-phase asynchronous motor to a stable speed, and the fuel was injected in the specific cycle to achieve skip fire. The specifications of the optical engine are shown in **Table 1**.

Table 1. The specifications of the optical engine

Category	Properties
Geometric compression ratio	13
Cylinder diameter / mm	105
Piston stroke / mm	114.3
Connecting rod length / mm	190
The number of nozzles holes	7
Engine valve lift / mm	11
Engine valve count	4

The support systems had also been designed and developed to form an optical test platform together with the optical engine. The support systems included a high-pressure common-rail fuel injection system, an ammonia injection system, an intake and exhaust system, a variable valve system, a high-speed photography system, and a combustion analysis system. The schematic diagram of the optical test platform is shown in **Fig. 1**. The key parameters of the high-speed camera are shown in **Table 2**. And the more details on the platform and high-speed photography method can be found in previous work [40]. The RGB images obtained by the high-speed photography method were cropped, denoised, and enhanced. Then the treatments of Di Iorio and Zhang et al. were referred to obtain information on the flame area (FR), flame natural luminosity (FNL), and flame center [45 46]. Based on the above information, it is possible to explore the influence of the combustion and flame development process on the ADDC, and to reveal the essential mechanism of the impact on macroscopic combustion characteristics and engine performance. In addition, the combustion analysis system is comprised of AVL GH12D pressure sensor, KISTLER 2614B encoder, and PowerMAC CA300A8 combustion analyzer, with a sampling resolution of 0.1°CA. The HRR (heat release rate) was calculated based on the multivariate exponential algorithm and the Rassweiler and Withrow model.

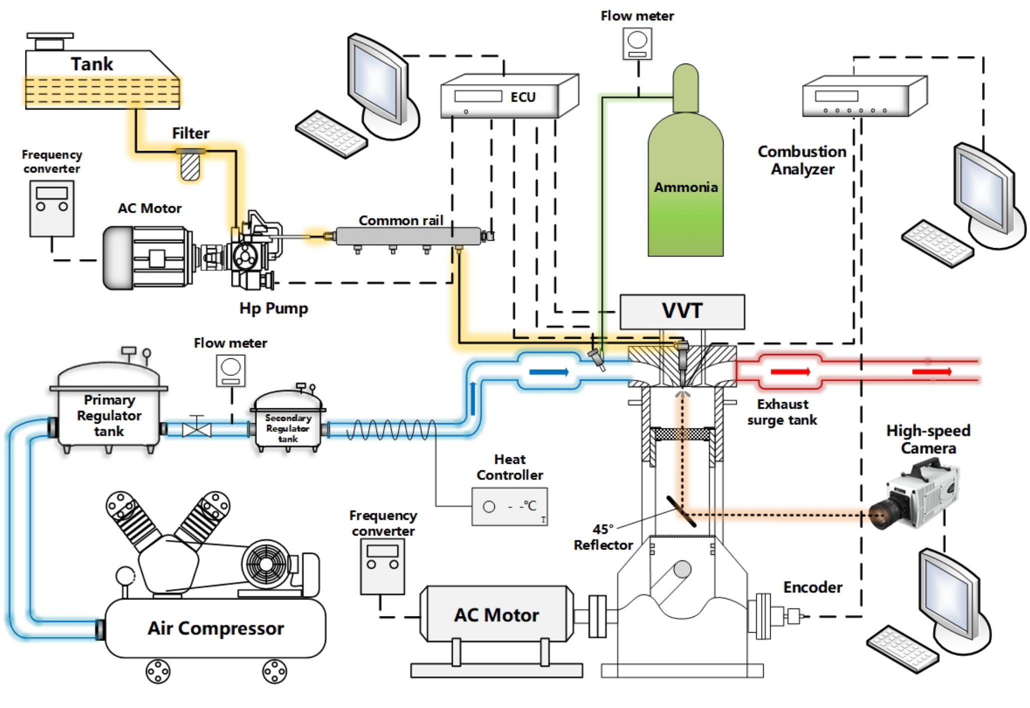


Fig. 1 The schematic diagram of the optical test platform

Table 2. The key parameters of the high-speed camera

Category	Parameters
Resolution	512*512

Exposure time / μs	30
Aperture level	7

2.2 Experimental procedure

In this study, the engine speed was kept at 1000 ± 5 r/min, the in-cylinder injection energy was maintained at 1438 J/cycle and the common rail pressure was fixed at 100 ± 3 MPa. The ammonia was delivered at -300°CA after top dead center (ATDC) in the intake stroke using port injection with a pressure of 3 bar. To ensure proper combustion during the test conditions, the intake air and the cooling water were heated to 353 ± 2 K and 358 ± 2 K, respectively, and the intake mass was adjusted to 60 ± 1 kg/h. Due to the limitations of the structural strength of the optical engine, three tests were conducted for each operating condition the data were considered valid when the coefficient of cyclic variation (COV_{imep}) of the three tests was within 5%. Firstly, the experiment was conducted by fixing the diesel injection timing (DIT) at -9°CA ATDC and investigating the effect of ammonia ratios on the ADDC mode. The heat value of ammonia was adjusted to 0%, 20%, 30%, 40%, 50%, 60%, 70%, and 80% of the total heat value of the in-cylinder fuel. After that, the DIT was adjusted between -5°CA ATDC and -13°CA ATDC (2°CA interval) at the 50% ammonia ratio (based on the heat value) to study the effect of DIT on the ADDC mode. The main physical-chemical characteristics of the ammonia and diesel used in this study are shown in **Table 3**.

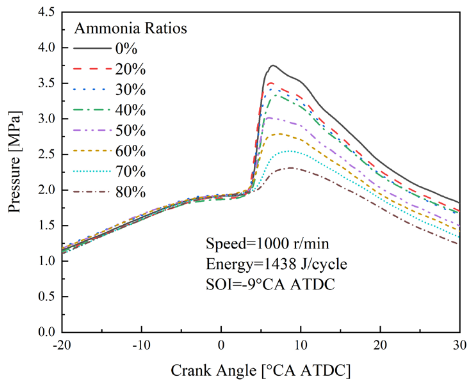
Table 3. The main physical-chemical characteristics of the test fuels

Fuel properties	Ammonia	Diesel
Hydrogen content by mass / (%)	17.7	12.6
Boiling point / (°C)	-33.4	180-360

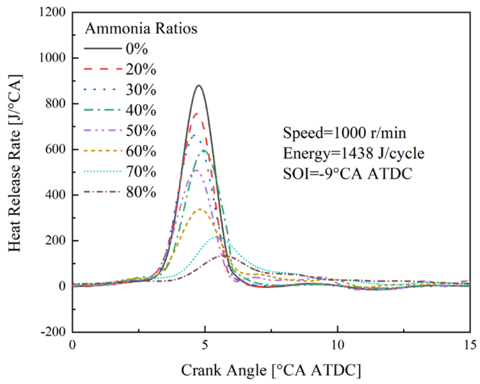
Latent heat of vaporization / ($kJ \cdot kg^{-1}$)	~	0.27
Low heat value / ($MJ \cdot kg^{-1}$)	18.6	42.69
Laminar flame speed / ($m \cdot s^{-1}$)	0.07	~
Minimum ignition energy / (MJ)	680	~
Cetane number (CN)	~	52
Research octane number (RON)	130	15-25
Theoretical air-fuel ratio	6.06	14.3

177 ## 3. Results and discussions

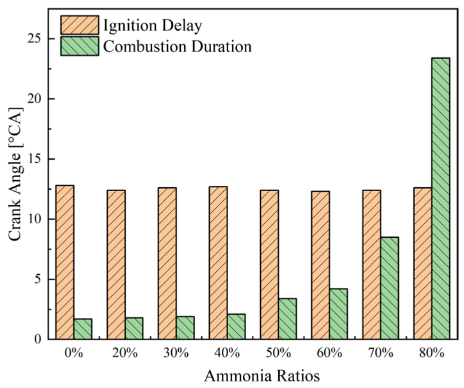
178 ### *3.1 Effects of ammonia ratios on the combustion characteristics of the ADDC engine*



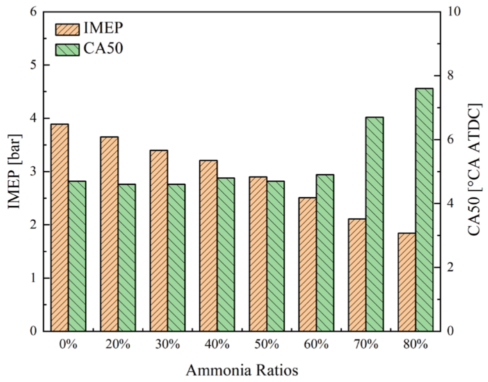
（a）Cylinder pressure



（b）HRR



（c）Ignition delay (ID) and Combustion



（d）Indicated mean effective pressure

duration (CD) (IMEP) and CA50

Fig. 2 Effects of ammonia ratios on the combustion characteristics of the ADDC engine

Fig. 2 shows the effects of ammonia ratios on the combustion characteristics of the ADDC engine. As shown in the **Fig. 2a** and **Fig. 2b**, the peak cylinder pressure and peak HRR of the ADDC engine gradually decrease as the ammonia ratio increases because of the slow combustion velocity and low combustion temperature of ammonia. Although the premixed ammonia in the engine inlet can form a homogeneous fuel-air mixture in the intake stroke, the ammonia can only be ignited by the diesel and cannot self-ignite in the ADDC engine. Therefore, the primary exothermic process of the ADDC mode is mainly determined by the combustion velocity of the diesel injected into the cylinder. The increase in the ammonia ratio is accompanied by a decrease in the diesel ratio, so that the combustion rate of engine slows down, resulting in a gradual decrease in the peak cylinder pressure and peak HRR as the ammonia ratio increases. This indicates that a high proportion of ammonia premixing can lead to deterioration in combustion under the conditions of low equivalence ratios, and therefore a larger proportion of pilot fuel or other combustion strategies are required to enhance combustion and thus overcome the combustion inertia of ammonia in such conditions.

As can be seen in **Fig. 2c**, the change in ammonia ratio mainly affects the CD and has no significant effect on the ID. This illustrates that the ID of the ADDC mode is primarily determined by the diesel with high CN, while the combustion process is influenced by the combined effect of ammonia and diesel. Among them, when the ammonia ratio is below 40%, due to the high amount of diesel-air mixture formed before the combustion, the higher combustion temperature of the initial combustion stage facilitates the subsequent diffusion combustion process and thus leads to an overall shorter CD. However, the CD increases rapidly when the ammonia ratio is further increased, reaching a CD of more than 20°CA at an 80% ammonia ratio. On the one hand, the reduced diesel ratio makes it difficult to form sufficient premixed gases and results in low initial combustion temperature. On the other hand, the low flame temperature of the ammonia further inhibits the combustion process. Finally, it can be seen from **Fig. 2d** that the IMEP of the engine decreases continuously as the ammonia ratio increases. The CA50 almost keeps constant at most ammonia ratios, except at the ammonia ratios of 70% and 80%, where there is a significant delay due to the low diesel injection mass. Combined with the HRR curves, it can be observed that the main reason for the decrease in IMEP with the increase in the ammonia ratio is the decrease in total cyclic heat release due to the lower combustion efficiency. Accordingly, it can be concluded that restoring the work capacity of the ammonia-fueled engine is primarily a solution for overcoming the combustion inertia and quenching effects of ammonia, thereby improving the overall combustion efficiency.

3.2 Effects of ammonia ratios on the flame development of the ADDC engine

To further explore the combustion process of the ADDC mode in-depth, this section provides further analysis of the flame development history and flame characteristics using the high-speed photography. The flame images during the main combustion period are selected for comparative analysis.

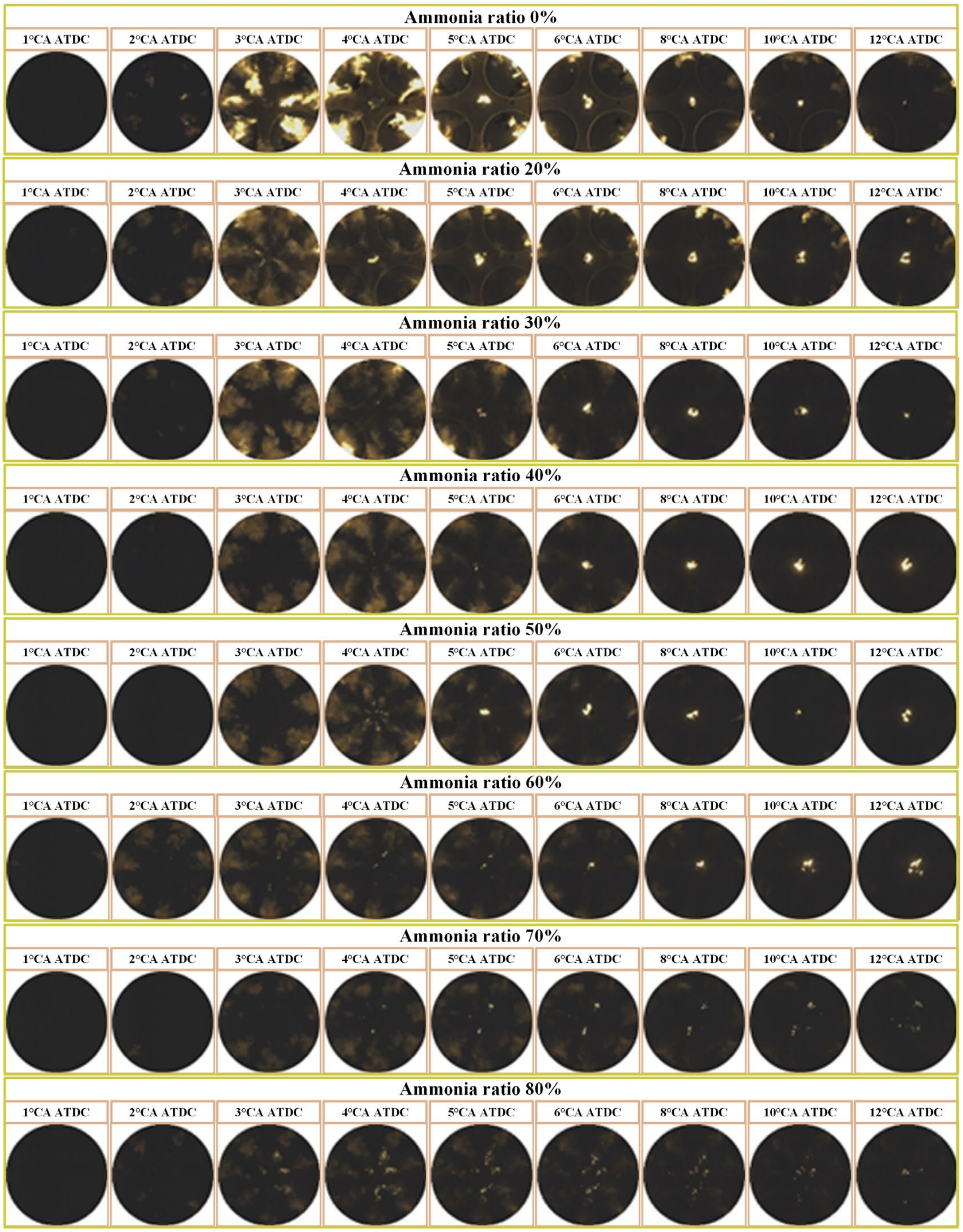


Fig. 3 Flame development history of the ADDC mode at different ammonia ratios

Fig. 3 shows the flame development history of the ADDC mode at different ammonia ratios. It can be observed that a large area of high-brightness yellow-white flame appears in the region covered by the diesel spray during the pure diesel combustion (PDC) mode. The large area of high-brightness yellow-white flame disappears after the introduction of ammonia, and only a small high-brightness yellow-white flame appears in the central area of the cylinder. The appearance of the high-brightness yellow-white flame is due to the formation of the fuel-rich region in the diesel spray region, which shows obvious diffusion combustion, and the carbon soot generation as well as the combustion temperature during diffusion combustion is higher, thus forming an obvious high-brightness flame. In addition, the small amount of high-brightness yellow-white flame in the cylinder center is due to diffusion combustion caused by insufficient injection pressure when the solenoid valve of diesel injector is seated. As the proportion of ammonia increases, the in-cylinder flame gradually changes from a yellow-white flame to a relatively low-brightness orange flame. The reason is that different from the combustion luminescence of carbon-based fuel which is mainly caused by the high-temperature carbon soot radiation, the luminescence of ammonia combustion comes mainly stems the radiation produced by intermediate products of ammonia combustion such NO_2 and NH_2.

It can also be seen from **Fig. 3** that the flame generally starts at the end of the diesel spray and then gradually spreads along the diesel spray to the cylinder center in the ADDC mode. Furthermore, due to the relatively low equivalence ratio used in this study (the equivalence ratios of PDC mode and 80% ammonia ADDC mode are 0.241 and 0.235, respectively), it can be seen that the ammonia flame is mainly concentrated around the diesel flame and the flame propagation distance is short. This is mainly due to the fact that ammonia has a relatively inert and quench-prone combustion, which is further exacerbated by the strong in-cylinder flow of CI engines which is used to enhance the mixing of the diesel spray. In addition, the combustion process of the ADDC mode is more concentrated when the ammonia ratio is low. Among them, a large ammonia burning flame occurs during 2°CA ATDC - 4°CA ATDC at a 20% ammonia ratio, while the flame that appears after 5°CA

ATDC is mainly due to the evaporative burning of the diesel attached to the cylinder wall. As the ammonia ratio increases, the duration of the main combustion process is prolonged, which shows an obvious ammonia combustion flame at 2°CA ATDC -7°CA ATDC under the condition of an 80% ammonia ratio. This may be due to the fact that although a large amount of diesel can increase the combustion temperature when the ammonia ratio is low, the ammonia flame is more easily quenched due to the relatively low ammonia equivalence ratio. When the ammonia ratio is higher, although the energy introduced into the cylinder by diesel is lower, the stability of ammonia combustion enhances due to the increase in the ammonia equivalence ratio. Furthermore, since the flame in the ADDC mode is concentrated in the region covered by the diesel spray, the injection strategy and injector structure parameters can be adjusted so that the diesel spray covers a larger volume of the combustion chamber and thus increases the combustion efficiency.

To quantify the influence of the ammonia ratio on the flame behavior of the ADDC engine, the flame center movement curves during combustion, the image hue and saturation of the brightest moments of the flame were further extracted, as shown in **Fig. 4** and **Fig. 5** respectively, while the FR percentage and FNL of the combustion process were extracted, as shown in **Fig. 6**.

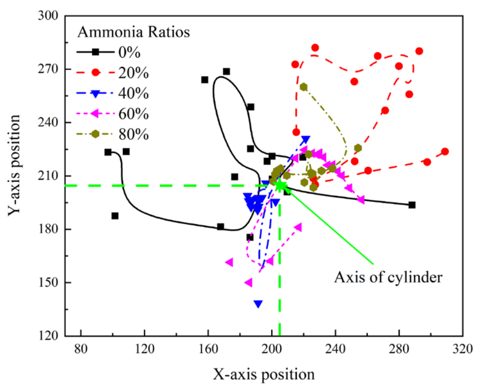


Fig. 4 The flame center movement curves of

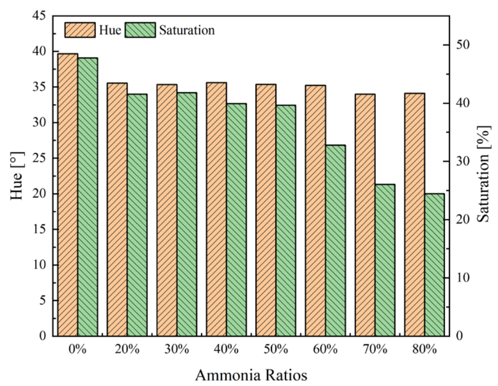


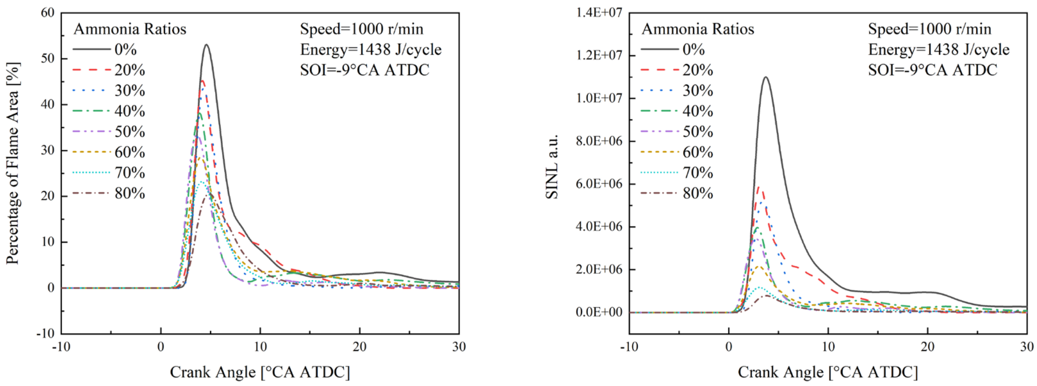
Fig. 5 The hue and saturation of combustion

the ADDC mode at different ammonia ratios

images of the ADDC mode at different ammonia ratios

As can be seen in **Fig. 4**, the movement of the flame center during the combustion process is evident when the ammonia ratio is low, and the flame center gradually stabilizes around the cylinder axis as the ammonia ratio increases. This is because the diffusion combustion is more obvious when the ammonia ratio is lower, and the in-cylinder airflow movement during diffusion combustion has a greater impact on the fuel volatilization and the combustion process, so the center position of the flame changes more significantly. At the same time, the flame center is shifted considerably in the later stage of combustion due to the volatilization of the wet wall fuel caused by the large injection mass of diesel. It is evident that the flame center moves within a wide range at the condition of pure diesel and 20% ammonia ratio. When the ammonia ratio is high, a more homogeneous ammonia/air mixture is formed in the cylinder, while the combustion velocity and flame propagation speed of ammonia are slow, and the effect of in-cylinder airflow movement on the flame distribution of ammonia combustion is reduced.

From **Fig. 5**, it can be seen that the flame hue of the PDC mode is 39.7, and the flame color tends to be yellow, while the ADDC mode appears as an orange flame with a hue of around 35. The flame hue of the ADDC mode almost keeps constant at the different ammonia ratios, which also indicates that the ammonia flame is wrapped around the outside of the diesel flame in the ADDC mode, and that the images captured by high-speed photography are the ammonia flame on the outside. In addition, it can be demonstrated that the hue of ammonia flame does not vary significantly with the equivalence ratio under the test conditions and that the flame hue cannot represent the intensity of ammonia combustion. Furthermore, it can also be seen that the flame saturation of the PDC mode is 47.8, while the saturation gradually decreases with the addition of ammonia. It is worth noting that the flame saturation does not change much when the ammonia ratio is in the range of 20%-50%, while it decreases rapidly as the ammonia ratio increases in the range of 60%-80%. This may be related to the difference in in-cylinder temperature caused by the change in HRR at the initial stage of combustion.



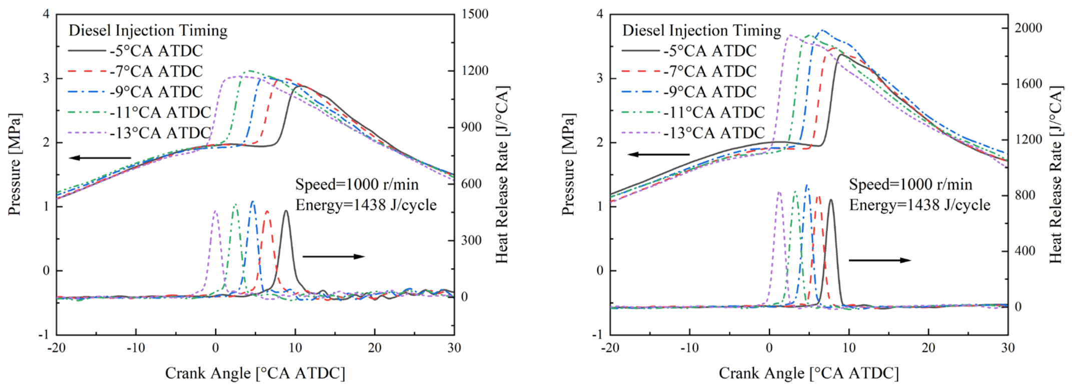
(a) FR percentage (b) FNL

Fig. 6 Effect of ammonia ratios on FR percentage and FNL of the ADDC mode

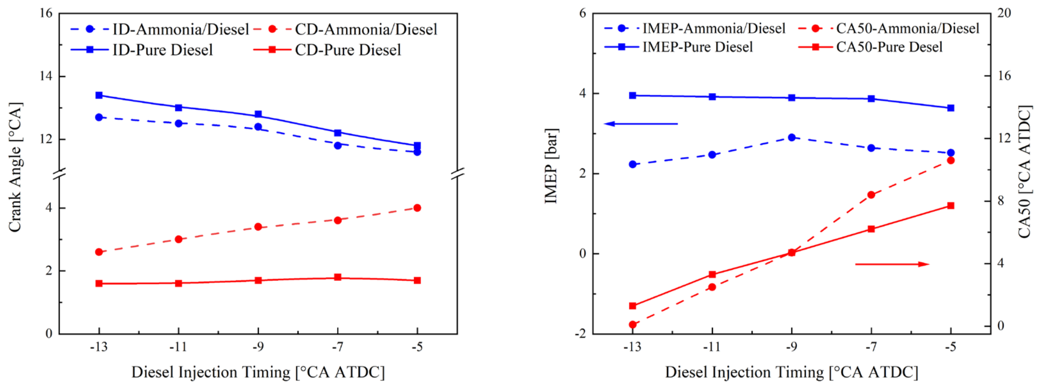
The FR shows the distribution of the flame in the combustion chamber, while the FNL characterizes the intensity of the combustion to some extent, but the FNL is influenced by localized regions of high brightness. As can be seen from **Fig. 6**, there is a difference in the effect of the ammonia ratio on the FR and FNL. The peak of the FR percentage decreases as the ammonia ratio increases, but the FR percentage curves are wider simultaneously. It means that although the diesel ignition amount is relatively reduced with the increase in ammonia ratio, the duration of ammonia combustion increases and the combustion efficiency of ammonia does not decrease significantly in this way. In addition, the ammonia ratio has a greater effect on the FNL, compared to the effect on the FR percentage, with the FNL decreasing rapidly as the ammonia ratio increases. The peak of FR percentage and FNL of the 80% ammonia ratio ADDC mode decrease by 60% and 92%, respectively, compared to the peaks at PDC mode. This is partly due to the reduction in the FR percentage, and the main reason is that the flame from the bright carbon soot luminescence caused by diesel combustion transforms into the radical radiation luminescence of ammonia combustion, and the brightness of the ammonia flame radiation luminescence is much less than that of the carbon soot luminescence.

3.3 Effects of DIT on the combustion characteristics of the ADDC engine

For the ADDC engine, the DIT directly determines the ignition timing and the subsequent combustion process. This section provides further insight into the effect of DIT on the combustion and flame development of the ADDC engine. The potential to improve the combustion process of the ADDC engine by adjusting the DIT is explored.



(a) ADDC mode (b) PDC mode



(c) ID and CD (d) IMEP and CA50

Fig. 7 Effect of DIT on combustion characteristics of the ADDC mode and PDC mode

Fig. 7 shows the effect of DIT on combustion characteristics of the ADDC mode and PDC mode. Since the ammonia introduced into the intake burns slowly and quenches easily, compared to the PDC mode, the ADDC mode has the lower peak cylinder pressure and peak HRR at different DITs. And the peak cylinder pressure and peak HRR for both the two combustion modes do not change significantly as the DIT advances. As the ignition timing of the ADDC mode depends principally on the DIT, it can be seen from **Fig. 7c** that the IDs of both the two combustion modes are slightly prolonged with the advancement of the DIT but the overall change are not significant. As a result, the ignition timing advances with the advanced DIT, and the combustion phases corresponding to the peak cylinder pressure and peak HRR also advance. Moreover, it can also be seen from **Fig. 7c** that the effects of DIT on CDs is different for the two combustion modes. The CD of the PDC mode hardly varies with the DIT, whereas the CD of the ADDC mode shortens with the advance of the DIT. The reason is that the introduction of ammonia slows down the combustion of diesel and this effect is strongly influenced by the in-cylinder temperature and pressure. As the combustion process gradually approaches the TDC with the advanced DIT, the higher temperature and pressure near the TDC lead to a faster combustion rate and a shorter CD.

As can be observed in **Fig. 7d**, the CA50s in both combustion modes are advanced and close the TDC with the advancement of DIT, but the IMEPs of the two combustion modes show different trends. In the PDC mode, the IMEP increases slightly as the DIT advances due to the CA50 being close to the TDC and thus the increased timeliness of combustion. In the ADDC mode, the IMEP tends to increase and then decrease as the DIT advances. The highest IMEP is reached at the DIT of

-9° CA ATDC. Combined with the HRR curves in **Fig. 7a**, it can be seen that although the HRR curves for the ADDC mode at different DITs all show a single-peaked trend, the HRR of the initial combustion stage slows down as the DIT advances. As a result, the long CD caused by the delayed injection facilitates the ignition of the ammonia, while the total heat release decreases as the DIT is advanced, thus contributing to the decrease in IMEP. In combination with the effect of CA50 changes on IMEP, the IMEP of the ADDC mode shows a trend of increasing and then decreasing.

3.4 Effects of DIT on the flame development of the ADDC mode

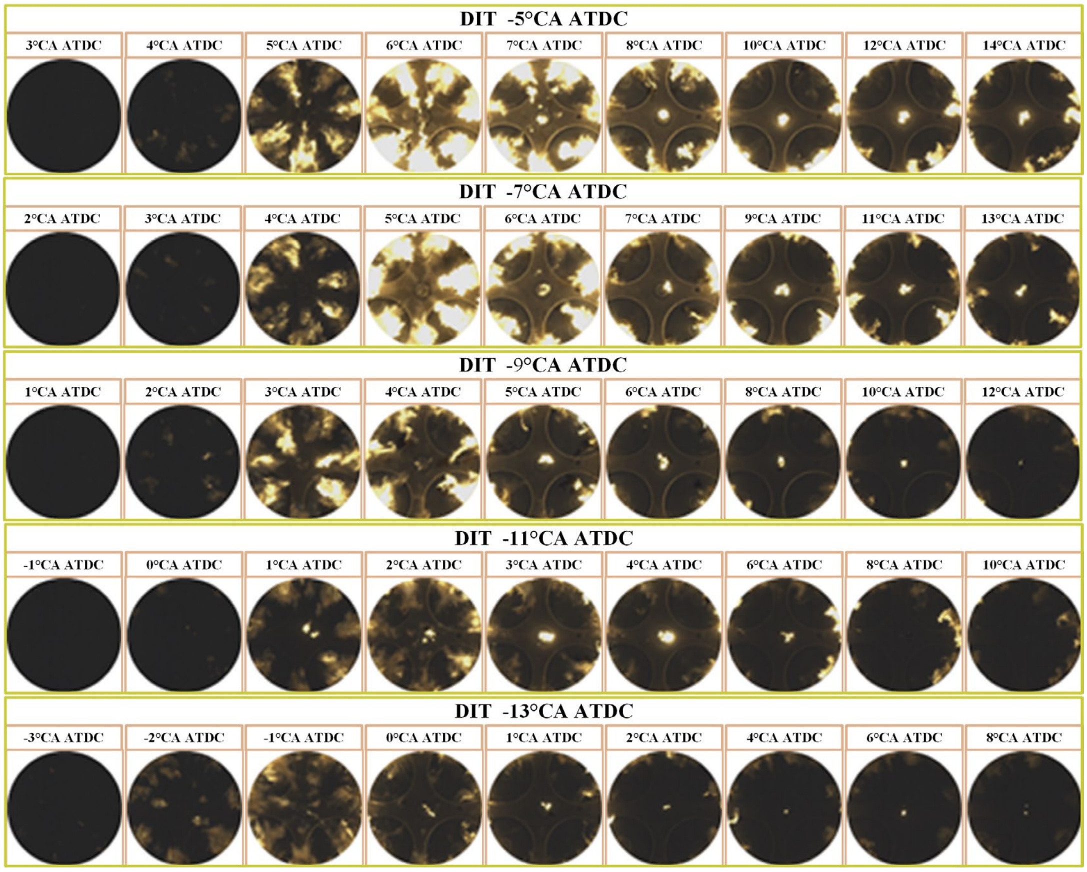


Fig. 8 Flame development history of the PDC mode at different DITs

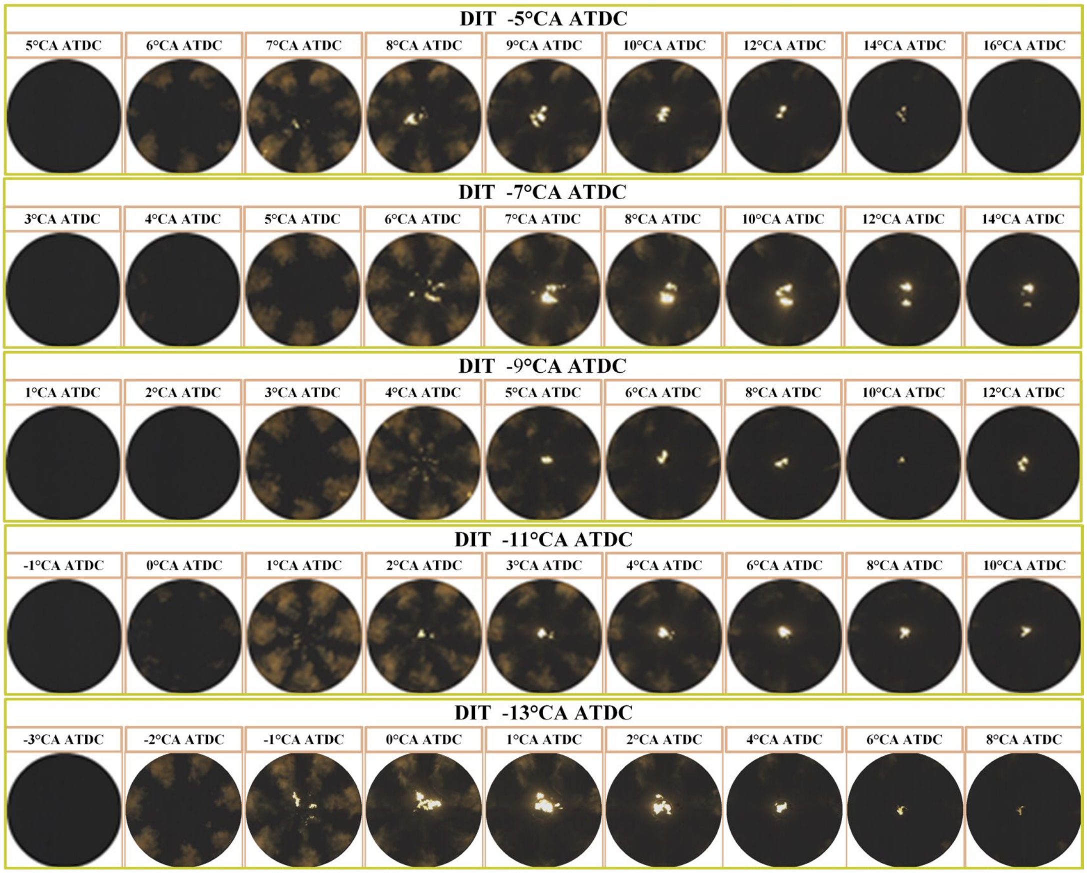
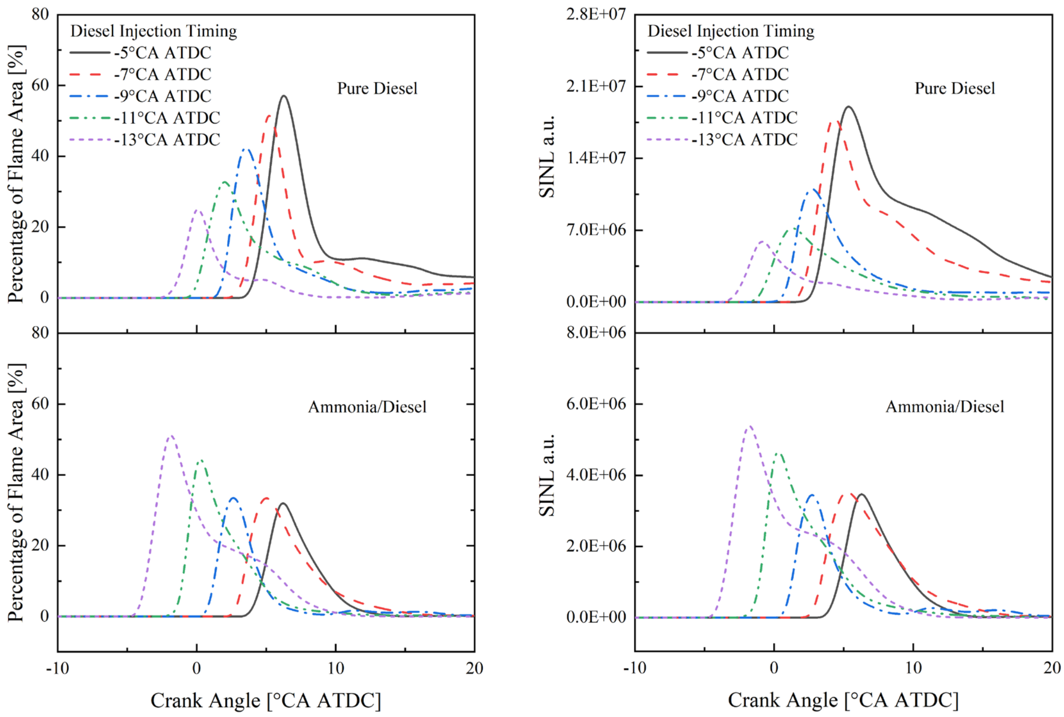


Fig. 9 Flame development history of the ADDC mode at different DITs

Fig. 8 and **Fig. 9** show the flame development history of the PDC mode and ADDC mode at different DITs, respectively. As can be seen in **Fig. 8**, the flame luminescence in the PDC mode consists mainly of high-brightness yellow-white carbon soot luminescence, and the FR and FNL decrease significantly with the advance of DIT. Combined with the thermodynamic data, it can be seen that the ID is shorter when the DIT is postponed, the fuel cannot be adequately mixed and the tendency for diffusion combustion is more obvious, resulting in distinct carbon soot luminescence. When the DIT is advanced, there is sufficient time for the diesel to be mixed and thus a more uniformly distributed mixture is formed, so that the increase in premixing combustion ratio results in less high-brightness luminescence from carbon soot. As can be noticed in **Fig. 9**, unlike the yellow-white flame in the PDC mode, the flame in the ADDC mode is mainly the orange ammonia flame. In addition, different from the PDC mode where the FR and FNL vary considerably with the DIT, the ADDC mode maintains high FRs and FNLs at different DITs. This is because the ammonia in the ADDC mode forms a more homogeneous fuel-air mixture during the intake stroke, and the smaller diesel injection mass in this mode makes it easier to form a homogeneous mixture during the ID. So, the DIT has an insignificant effect on the flame pattern of the ADDC mode.



(a) FR percentage (b) FNL

Fig. 10 Effect of DIT on FR percentage and FNL of the PDC mode and ADDC mode

Fig. 10 shows the effect of DIT on FR percentage and FNL of the PDC mode and ADDC mode. From **Fig. 10**, it can be seen that the FR and FNL for the two combustion modes show exactly opposite trends with the DIT. The FR and FNL of the PDC mode decrease rapidly with the advancement of the DIT due to the reduction of the diffusion combustion percentage. The peak of FR percentage and FNL of the PDC mode at the DIT of -13°CA ATDC decrease by 32.4% and 1.36E7, respectively, compared to the peaks at DIT of -5°CA ATDC. However, for the ADDC mode, the FR and FNL increase instead as the DIT advances, but the change is smaller compared to that in the PDC mode. The peak of FR percentage and FNL of the ADDC mode at the DIT of -13°CA ATDC increase by 22.3% and 2.25E6, respectively, compared to the peaks at the DIT of -5°CA ATDC. Among them, the increased FR and FNL may be due to the combustion process is close to the TDC, where the high temperature and pressure condition favors the radioluminescence of the carbon soot as well as the intermediate products of ammonia combustion. The small variation in the FR and FNL at different DITs indicates that the diesel with high reactivity still has a good ignition performance when the DIT is postponed.

Combined with **Fig. 7d**, it can be noticed that although the advanced DIT optimizes combustion timeliness, the IMEP decreases instead at the ADDC mode. This is probably due to the fact that when the diesel is injected in advance, the CD is shorter, which is not conducive to the ignition of ammonia, while when the DIT is postponed, the in-cylinder temperature and pressure are lower, and the slower combustion of diesel promotes the ignition of more ammonia. This indicates that different from the PDC mode where more premixed combustion needs to be organized to increase the combustion timeliness of engine, more diesel diffusion combustion needs to be organized to promote the combustion of ammonia and thus obtain a higher indicated power in the ADDC mode. At the condition of low equivalence ratios in the ADDC mode, it is possible to delay the injection of diesel to promote the combustion of ammonia but it is necessary to ensure that the combustion gravity is not delayed excessively.

4. Conclusions

In this study, an optical diagnostic of the ADDC mode is conducted using a self-built optical engine. The flame development and combustion process of the ADDC mode are analyzed in-depth using high-speed photography and combustion analysis methods. The combustion enhancement method and control strategy of the ammonia-fueled engine are proposed. The key findings can be obtained as follows:

(1) The ignition timing of the ADDC mode is mainly determined by the DIT, while the combustion process is influenced by both the premixed ammonia and the diesel injected into the cylinder. The combustion inertia and low flame temperature of ammonia lead to a decrease in the peak cylinder pressure and peak HRR with an increasing ammonia ratio, while the CA50 is severely delayed when the ammonia ratio is too high. Compared to the PDC mode, ammonia premixing leads to lower cyclic heat release and therefore lower engine IMEP.

(2) In contrast to the yellow-white flame produced by the radiation of high-temperature carbon soot in the PDC mode, the orange flame in the ADDC mode is mainly derived from the radiation produced by intermediate products of the ammonia combustion process such as NO_2 and NH_2. The peak of FR percentage and FNL of the 80% ammonia ratio ADDC mode decrease by 60% and 92%, respectively, compared to the peaks at PDC mode. The ammonia flame of the ADDC mode is mainly concentrated around the diesel flame, which has a short flame propagation distance. The ADDC mode achieves good ignition performance at different ammonia ratios.

(3) Different from the PDC mode in which the CD is almost independent of the DIT, the ADDC mode has a significantly longer CD and a gradually delayed CA50 as the DIT is postponed. Combining the effects of the heat release and CA50, the IMEP of the PDC mode increases slightly as the DIT advances, while the IMEP of the ADDC mode shows a tendency to increase and then decrease.

(4) The effects of the DIT on the FR and FNL in the PDC mode and the ADDC mode show the

opposite trends. The FR and FNL in the PDC mode decrease rapidly with the advance of the DIT, and the flame pattern in the ADDC mode does not respond significantly to the DIT. The distinct ammonia combustion flame can be observed in the ADDC mode at all the DITs. Compared to the PDC mode, the ADDC mode requires an appropriate postponement of the DIT to organize more diffusive combustion of the diesel, and thus to promote the ammonia combustion for higher indicated thermal efficiency.

Notes

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