

A Systematic Analysis of Progress in Doping Combustion Characterization of Ammonia-Fueled Engines

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Abstract. In the global environment of carbon emission reduction, diesel engine emissions of carbon dioxide, nitrogen oxide and other harmful gases seriously polluting the environment has been boycotted by governments around the world. Ammonia, as a clean, environment-friendly, easy-to-transport green energy, has broad application prospects. However, due to its poor combustion performance and high calorific value, there are some limitations in its application. In this paper, the mechanism, combustion characteristics and emission characteristics of an engine fueled with ammonia-hydrogen fuel and ammonia-carbon-based fuel are reviewed. Hydrogen fuel and diesel fuel with low ignition energy and fast laminar flame spread characteristics, can make up the shortage of pure ammonia fuel, reduce nitrogen oxide emissions. Among them, hydrogen ammonia fuel has become the mainstream and the most promising fuel, compared with pure ammonia fuel and ammonia diesel fuel has the advantages of clean, low transport costs, fast combustion and so on, will become the future engine main application fuel.

Keywords: Ammonia fuel, Ammonia-doped combustion, Engine operating conditions, Emission characteristics.

1. Introduction

With the deterioration of the global environment and ecology, countries are focusing on the control of carbon emissions and releasing relevant policies, in which diesel emissions pollution of air has become a major public health problem for all mankind, and its main combustion products carbon dioxide, nitrogen oxides seriously damage the ecological environment, and the storage cost is relatively high. Currently, a carbon-free fuel, ammonia (NH_3), has become a major research target [1]. Its high volumetric energy density which is lower than that of hydrogen and natural gas, easy storage and environmental friendliness and cleanliness have significant application prospects. However, because ammonia has the highest minimum ignition energy, it requires high energy ignition, burns slowly and the combustion product NO_x causes acid rain, which has a certain risk of affecting the environment. Doping combustion is gradually being utilized. Ammonia-hydrogen fuel is considered to have a wide range of applications. Hydrogen has the characteristics of accelerated combustion speed, fast ignition, environmental protection, etc., as a combustion accelerant to make up for the shortcomings of the pure ammonia engine, has a high potential for application, and is now gradually used in ship engines and other fields.

All in all, in the face of the pressure to reduce carbon emissions, ammonia-fueled engines using blended fuels have broader prospects, including ammonia-hydrogen fuels and ammonia-carbon-based fuels related to the research and summary. This paper mainly summarizes the research on the operation principle of ammonia-fueled engines and the characteristics and emissions of ammonia-blended fuel combustion.

2. Combustion Analysis of Ammonia Blended Fuel Under Engine Conditions

Based on the characteristics that ammonia fuel is not easy to burn and requires greater ignition energy, spark plug ignition pure ammonia engine and dual-fuel engine become the main technical routes [2]. In the first spark plug ignition pure ammonia engine, the ignition energy of the spark plug is not enough for ammonia combustion, so other combustion aids are needed to improve the

combustion condition in the ammonia engine cylinder. This makes dual-fuel engines an implementable route. Hydrogen and carbon-based fuels with shorter ignition delay and faster laminar flow combustion are blended with ammonia and hydrogen or carbon-based fuels to enhance the combustion performance of ammonia [3]. Hydrogen or carbon-based fuels are blended with ammonia as a mainstream second fuel to enhance engine performance.

2.1. Ammonia-Diesel Dual-Fuel Engines

The ammonia-diesel dual-fuel engine is fed with intake manifold multipoint sequential injection as shown in Fig. 1, and this method avoids the escape of gaseous fuel at the valve overlap to a certain extent, which reduces fuel waste and environmental pollution.

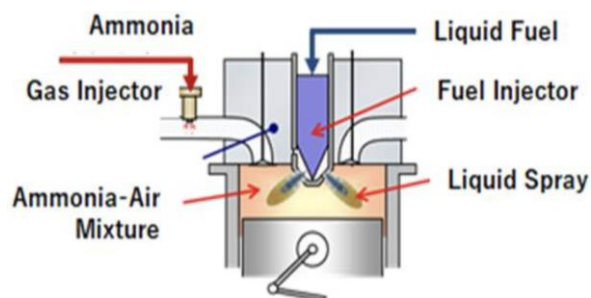


Figure 1. Schematic diagram of manifold injection dual-fuel engine [3]

The gas injection valve injects gas into the intake manifold according to the controller signal and forms a combustible mixture with air. At the end of the compression stroke, diesel fuel is injected into the cylinder and is compression ignited, and power is output during combustion. The engine can be divided into five modules, which are high pressure common rail fuel system, gas supply system, cylinder system, dynamics system and intake and exhaust system as shown in Fig. 2.

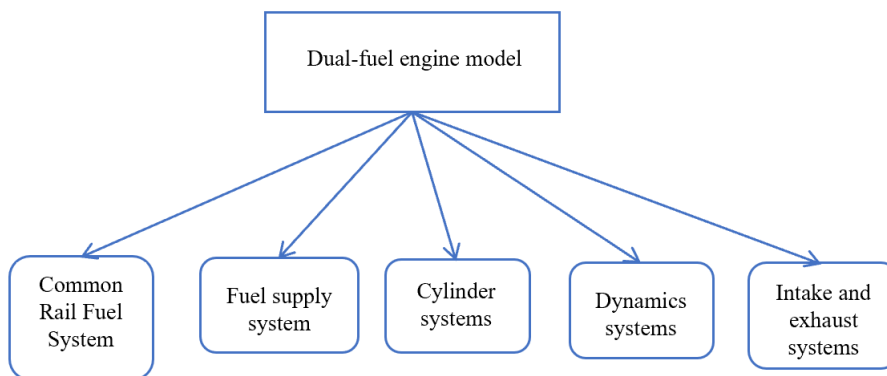


Figure 2. 5 modules of the engine [4]

The high-pressure common rail system is responsible for controlling the high-pressure fuel rail pressure and fuel injection process. The gas supply system is carried out with multi-point sequential injection from the intake manifold. In the cylinder system, the fuel outputs chemical energy into mechanical energy and outputs power in the cylinder. In the kinetic system, the combustible mixture in the cylinder is expanded by heat and pushes the piston to move. The intake and exhaust system provides the mixture for the intake stroke and removes the exhaust gases in the exhaust stroke [5].

2.2. Hydrogen-Ammonia Dual-Fuel Engines

Hydrogen fuel is a zero-carbon clean fuel, which is considered as a good combustion aid due to its high combustion temperature and low minimum ignition energy, which can realize the complementary performance of ammonia-hydrogen doping combustion. The structure of hydrogen-ammonia dual fuel engine has a sweeper box, sweeper port, cylinder liner, cylinder head, exhaust valve, and injector. During the sweeping process, hydrogen is injected into the intake pipe and enters the cylinder. As the piston moves upward, some of the hydrogen forms a premixed gas, and when it

reaches the upper stop, liquid ammonia enters the cylinder in the form of a direct jet, which is ignited by the action of an internal fire nucleus. By adjusting the injection rate of liquid ammonia to adjust the intensity of the in-cylinder fire, the fuel consumption rate is reduced and the engine power is increased [4].

3. Ammonia Engine Doping Combustion

Table 1 shows that pure ammonia has a high ignition temperature, slow laminar flame propagation and low calorific value. Therefore, higher ignition energy and time are required and more ammonia is needed for combustion.

Table 1. Combustion characteristics of various fuels [5]

Fuels	Molecular Formula	Molecular Weight	Carbon content/%	Hydrogen content/%	Liquid density	Gaseous density	Ignition temperature	Explosion limit	Octane rating	Laminar flame speed
Ammonia	NH ₃	17	0	17.6	680	0.771	651	16-25	130	6-8
Hydrogen	H ₂	2	0	100	70.8	0.09	585	4-76.5	---	180
Methane	CH ₄	16	75	25	430	0.717	540	5-15	107.5	40
Diesel	C ₄ H ₁₀ -C ₁₂ H ₂₆	148-170	90	13.5	820-845	---	120	---	>45	35

In recent years, scholars have found that due to the slow flame velocity of pure ammonia laminar flow, it is easy to be affected by the buoyancy effect, and the accuracy of the pure ammonia laminar flow flame velocity is low. For example, in Mei's fixed-volume bomb experiments, when increasing the oxygen content to 45%, the laminar flame velocity at room temperature and pressure reaches 43cm/s [6]. It greatly increases the pure ammonia laminar propagation velocity. The bomb is still at a low level. In order to reduce the limitations of the application of pure ammonia fuel, two research lines of ammonia-fueled engines are introduced ammonia-carbon-based fuel combustion and ammonia-hydrogen fuel combustion.

In the experiments conducted by Hayakawa, the laminar combustion rates for ammonia/air premixed flames were examined under varying pressures, with an equivalent ratio of 0.7. The tests were carried out using a constant volume cylindrical combustor across several pressure levels: 0.8, 0.9, 1.0, 1.1, 1.2, and 1.3. The initial mixing pressures were set at 0.1MPa, 0.3MPa, and 0.59MPa, with an initial temperature of 298 K [7]. The combustor, having an internal diameter of 270mm and a length of 410mm, holds a volume of approximately 23 liters, which is comparable to the volume of a sphere with a diameter of 355mm. The ignition of the mixture was achieved using a spark electrode placed near the chamber's center, featuring a diameter of 1.5mm and a spark gap of 2mm. A capacitor discharge ignition (CDI-RRB) circuit, charged with an electrostatic energy of 2.8 J, was employed for ignition. The findings from these experiments revealed that the flame velocity tends to decrease as the initial mixture pressure increases.

Lhuillier studied laminar flame velocities at high temperature (473K) and atmospheric pressure at room temperatures of 298; 323; 373; 423; 473 (K), respectively. At a pressure of 0.1 (PA) it was tested using a 4.2 DM3 stainless steel spherical vessel and heated to 473k by a built-in resistance coil. Set the rest phase to 10 seconds to avoid any unnecessary fluid movement [8]. Then, due to two 1-mm tungsten electrodes, the discharge energy is transferred to the center of the chamber for ignition. The spark gap is adjusted between 1 mm and 3 mm to facilitate ignition. The experimental results show that the correction factor is always applied to the correlation of GD.

3.1. Ammonia-Diesel Blending Combustion and Emissions

In ammonia-diesel engines, with the injection of ammonia, the maximum pressure in the cylinder decreases, the moment of ignition is delayed, NH₃ and N₂O emissions increase, and CO₂ emissions decrease. Although ammonia fuel reduces CO₂ emissions at the source, it does not completely eliminate NO_x. At the same time, another pollutant, NO₂, is generated [9]. The pollutants emitted by the ammonia-diesel dual-fuel engine that have a greater impact on the greenhouse effect are CO₂ and N₂O, of which CO₂ is mainly generated by the reaction between diesel fuel and O₂, and N₂O by the combustion reaction between NH₃ and O₂. The advancement of the injection moment leads to an

increase in the degree of engine work, a relatively low temperature in the cylinder when diesel is injected, an increase in the stagnation period, an increase in the proportion of diesel premixed, and a more uniform distribution of air, ammonia, and diesel fuel in the cylinder, which improves the combustion process, but the emission of NO_x increases.

Several scientists have carried out ammonia-carbon co-combustion experiments in recent years, e.g., Han experimented with the heat flux combustor, he used the Several scientists have conducted ammonia-carbon co-combustion experiments in recent years, such as Han on a heat flux burner and Wang using a porous sensor to combine ammonia with synthesis gas [10].

In Tian's study involving low-pressure experimental modeling of a premixed $\text{NH}_3/\text{CH}_4/\text{O}_2/\text{AR}$ flame, a newly constructed beam line derived from the radiation of a wiggler was employed. The experiment utilized a 1M Seya-Namioka monochromator to disperse synchrotron radiation from the beam line connected to the 800MeV electron storage ring. This setup was integrated with a 6cm diameter movable McKenna burner housed within a flame chamber. The flame was sampled using a tapered quartz nozzle equipped with 40 orifices, each with an angle and a tip size of $500\mu\text{m}$ [11]. The extracted gas formed a molecular beam, which was subsequently directed through a nickel skimmer into the differential pumping ionization region. Within the photoionization chamber, the molecular beam intersected with tunable VUV light, and the resulting photoions were collected and analyzed using a reflective tube time-of-flight mass spectrometer (RTOF-MS). The findings indicated that as the parameter R increased, the reaction zone expanded, leading to higher mole fractions of H_2O , NO , and N_2 , while the mole fractions of H_2 , CO , CO_2 , and NO_2 exhibited a decreasing trend. The computational analysis confirmed that the proposed mechanism accurately predicts the concentration distribution of the primary species and intermediates.

Gill assessed the impact of partial decarbonization of diesel engines by refueling with ammonia dissociation. The experiment was carried out on a single-cylinder direct injection diesel engine. Because of its high flame resistance, gaseous NH_3 is introduced into the intake manifold under the charge of fresh air [12]. This approach does not require any changes to the Fuel injection. The Thringe Titan thyristor type DC dynamometer is used to carry the motor and load the engine. In the combustion performance. The experimental results show that the addition of pure H_2 is the most promising in the engine mode tested in this study, with improved ignition delay. The pure h_2 -dosing mode also performs best in the emission performance at high load and low load, and its beneficial effect is comparable to that of conventional diesel fuel.

Valera-Media's research focuses on the combustion of ammonia-methane mixtures in a tangential swirl burner, designed for gas turbine power generation applications. This rig is equipped with a versatile premixed swirl burner that consists of a main body for receiving premixed air and fuel gases, along with a spray gun for liquid fuel injection, although the spray gun was not used in these particular experiments. The entire setup is constrained by a quartz tube mounted within the system, which serves to contain and limit the flame [13]. The flame is captured by a high-definition camera at each stabilization stage and provides qualitative insights into the behavior of the flame. The experimental results show that the medium swirl number may be unfavorable to the stability of the flame using ammonia, so the residence time is reduced, thus promoting further cracking of NH_3 in the presence of less oxygen and reactive free radicals and requiring assessment of lower eddy numbers to improve these properties, ensure that eddy current breakdown is still achieved for flame anchoring purposes.

3.2. Ammonia-Hydrogen Blended Combustion and Emissions

Ammonia and hydrogen doping complement the combustion performance, ammonia helps hydrogen to improve combustion stability, and hydrogen accelerates the burning rate of ammonia. Ammonia-hydrogen doping combustion significantly improves the laminar combustion rate of mixed fuels. Hydrogen addition enriches O/H radicals and accelerates the NH_3 and NH_2 consumption. The ammonia-hydrogen engine combustion process tends to produce unburned ammonia gas and NO_x . Hydrogen doping volume fraction of 20% maintains the flame combustion and improves the better power density output and NO_x . Ammonia releases ammonia molecules during combustion and

produces fuel type NO_x compounds [14]. The effect of temperature, equivalence ratio, and hydrogen doping ratio on the emission of NO_x is plotted in Fig. 3.

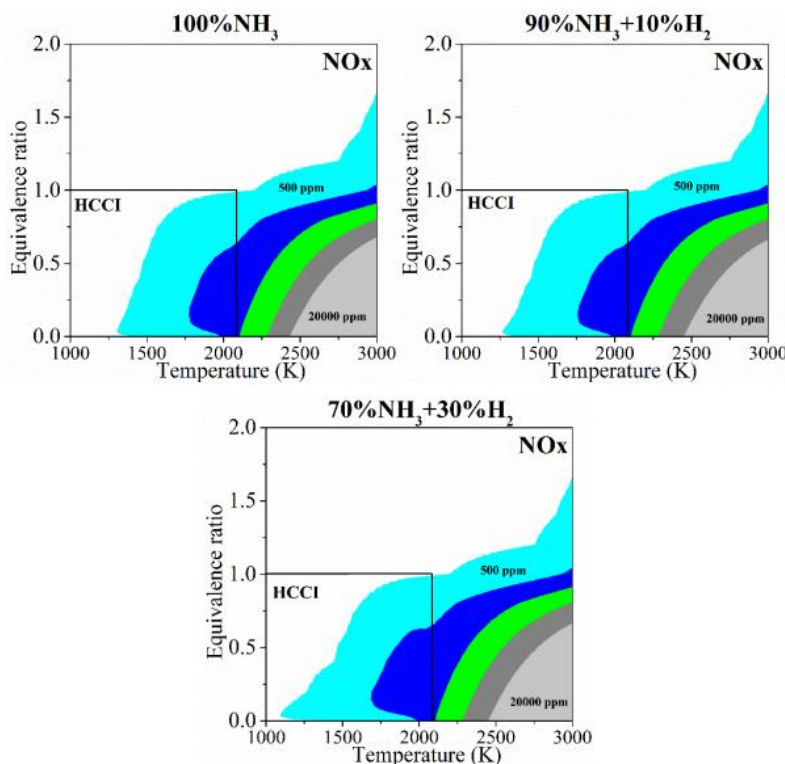


Figure 3. NO_x emission at different temperatures, equivalence ratios and hydrogen doping ratios [14]

The effect of different hydrogen addition ratios on the formation of NO_x is small, and the starting point of NO_x formation (500ppm) tends to migrate to lower temperatures (1000K) as the hydrogen doping ratio increases. Ammonia-hydrogen blending ratio, airflow organization and fuel injection strategy have some effects on flame propagation, combustion rate and pollutant generation of ammonia-hydrogen blended fuels [15].

4. Conclusion

This paper explores the combustion characteristics of engines fueled with ammonia blends, focusing on the operating conditions and emission profiles of these engines. Given the combustion properties of ammonia, it was concluded that ammonia alone is insufficient for efficient combustion in engines. Consequently, the study emphasizes the benefits of using ammonia in combination with other fuels, particularly hydrocarbons and diesel. The paper also provides an analysis of the structural and operational aspects of engines running on these blended fuels, highlighting the advantages of incorporating hydrocarbons and diesel into the combustion process. Finally, the emissions from the combustion of ammonia-hydrogen and ammonia-diesel engines are analyzed and the factors that can affect the emissions are described. Ammonia doping can dilute NO_x emissions. Ammonia doping combustion is a promising technology. However, with the addition of ammonia, the emission of NO_x from the discharge gas increases, so how to control the emission of the gas can be the focus of future research.

Ammonia-doped engines currently have problems with combustion performance and emission pollution, and further research is needed in the future on how to control the hydrogen doping ratio and how to reduce greenhouse gas emissions. The development of ammonia-fueled vessels has accelerated markedly after 2019, with several demonstration projects and conceptual vessel designs being announced and technology validation and safety assessments have been conducted. These efforts have focused not only on retrofitting the ship's power system, but also on building the entire

supply chain, how to cost-effectively produce green ammonia (synthesized from hydrogen and nitrogen generated by renewable energy sources), the and the establishment of the corresponding refueling infrastructure. Once these issues are resolved, ammonia-doped engines can be applied to automobile engines or ship engines, etc. Their low carbon emissions will effectively mitigate the global greenhouse effect and environmental pollution and will become a major application in the future.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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