A Short Review of Ammonia Compression Ignition Engines for an SOFC-ICE Power Plant for Shipping

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Abstract. Ammonia is considered one of the most promising hydrogen and energy carriers for decarbonizing deep-sea shipping and other remote heavy-duty applications. The AmmoniaDrive power plant concept uniquely combines Solid-Oxide Fuel Cell (SOFC) and Internal Combustion Engine (ICE) technology to address the issue of how to convert e-ammonia, produced from renewable resources, into useful on-board power safely and effectively, without the need for fossil fuels as combustion promotor. This paper introduces the AmmoniaDrive concept, outlines the challenging combustion properties of ammonia and ammonia-hydrogen mixtures and provides a short review of Compression Ignition ICE research for ammonia-fuelled engines. Three promising combustion concepts are introduced to give direction to further numerical and experimental research.

Keywords: Ammonia · Hydrogen · reciprocating Internal Combustion Engines · Compression Ignition · on-board Power · Propulsion and Energy Systems

1 Introduction

In the fast approaching hydrogen economy, many researchers and engineering professionals consider ammonia (NH_3) as a promising hydrogen (H_2) and energy carrier to decarbonize hard-to-electrify economic sectors. In deep-sea shipping and other remote heavy-duty applications, ammonia may be applied directly as a fuel in reciprocating Internal Combustion Engines (ICEs) combined with a promotor fuel. Several research initiatives therefore investigate and develop ammonia ICE technology ([1–4]). The promotor fuel in many research initiatives is a hydrocarbon fuel originating from crude oil, i.e. a fossil fuel. The next challenge is an ammonia-fuelled power plant concept that does not require fossil fuel. A novel concept is introduced here, which uniquely combines Solid-Oxide Fuel Cell (SOFC) and reciprocating ICE technology in a single-fuel, highly efficient power plant for ships and other heavy-duty applications. We refer to this concept as the AmmoniaDrive power plant.

The power plant concept utilizes ammonia as both hydrogen and energy carrier and is expected to have a relatively small, and thus acceptable, impact on the ship design.

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When the ammonia is produced from renewable resources, i.e. "green" ammonia or e-ammonia, the energy chain is zero-carbon.

1.1 AmmoniaDrive Power Plant Concept

The AmmoniaDrive power plant makes optimal use of the strengths of both energy converters (SOFC & ICE). Figure 1 depicts a schematic overview of the AmmoniaDrive power plant concept. The SOFC produces electric power and is fuelled by ammonia. The ICE produces mechanical power and is fuelled by ammonia and hydrogen. The hydrogen originates from the hydrogen-rich anode off gas of the SOFC. The hydrogen is used as a promotor fuel in the ICE, in theory without any hydrocarbon (fossil) fuel.

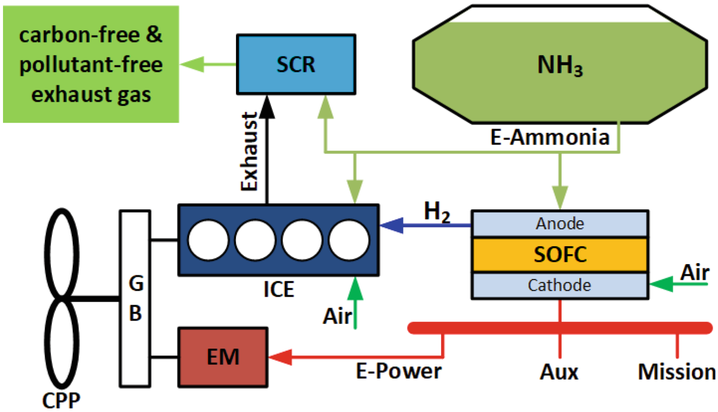

Fig. 1. The AmmoniaDrive SOFC-ICE on-board power plant concept.

The components in the AmmoniaDrive power plant concept are not yet commercially available, especially not at the industrial scale relevant for maritime applications. This also holds for the NH_3-H_2 ICE, whose fundamental working principles are influenced by technical details of the engine and the challenging combustion properties of ammonia. Further research into injection strategies, ignition mechanisms, and resulting combustion modes will be performed to better understand the principles and overcome the challenging combustion properties of ammonia.

As part of this research, the literature on Compression Ignition (CI) ICEs partly fuelled by ammonia has been collected and analyzed to identify knowledge gaps and research opportunities. The study [5] identified advanced CI combustion concepts like Reactivity Controlled Compression ignition (RCCI), Premixed Charge Compression ignition (PCCI), and Partially Premixed CI (PPCI) as potential candidates for operating NH_3-H_2 CI engines, Sects. 2 and 3 comprehensively provide the main results of this literature study. Section 4 discusses the three promising concepts mentioned above and provides an outlook to the experimental research that will be performed to enable the further development of the AmmoniaDrive concept.

2 Fuel Storage and Combustion Properties

The properties of ammonia and hydrogen differ from those of diesel-like fuels. This will have an impact on the ICE and on the fuel-related common practices in the heavy transport industry. An overview of the fuel properties is given in Table 1.

Table 1. Several properties of NH_3, H_2, and diesel ([1] [6], [2] [7], [3] [8], [4] [9])

Property	Unit	Ammonia	Hydrogen	Diesel
Storage method	–	Compr liquid[1]	Compr liquid/gas[1]	Liquid[1]
Storage pressure	MPa	1.03[1]	0.1/24.8[1]	0.1[1]
Storage temperature	K	298[1]	20/298[1]	298[1]
Energy density	MJ/m^3	11300[1]	8539[1]/2101[1]	36403[1,2]
Autoignition temperature	K	924[1]	884[1]	503[1]
Stoichiometric air/fuel ratio	–	6.05[3]	34.33[3]	14.5[2]–17.4[3]
Lower Heating Value	MJ/kg	18.5[2]	120[2]	42.5[2]
Latent heat of vaporization	kJ/kg	1370[2]	445.6[2]/-[2]	270[2]
Laminar burning velocity at $\varphi = 1$	m/s	0.07[4]	3.51[4]	0.86[4]

Storage-wise the large difference in energy density is of importance, especially for long-range / heavy-duty applications. With regard to combustion properties, note the large difference in the lower heating value (LHV), which has a direct relationship with the amount of fuel needed.

Another notable difference from diesel fuels is the high latent heat of vaporization of ammonia. This causes a large cooling effect where the fuel evaporates. This partly explains the lower NO_x emissions than often expected when using a nitrogen-based fuel. It may also result in a requirement to heat the ammonia supply in some experimental set-ups. Another important property for engines is the corrosivity of ammonia. Ammonia is corrosive to copper (alloys), nickels and plastics. This is important for the design of the ammonia supply system.

Ammonia is used in combination with other (promotor) fuels, because pure ammonia has unfavorable combustion properties in typical ICE conditions. Understanding the fuel mixture composition is essential to compare and interpret the results of experimental studies, as those in Sect. 3. The compositions are often defined by either energy percent ($\%_e$), volume percent ($\%_v$), or mass percent ($\%_m$), e.g. an ammonia/hydrogen mixture at 323K and 1 bar of 80/20$\%_v$ NH_3/H_2 equals 82/18$\%_e$ and 95/5$\%_m$ NH_3/H_2.

3 State-of-the-Art NH_3-Fuelled CI ICEs Experimental Results

Conventional dual-fuel (CDF) engines, which are now being developed by marine engine OEMs, can achieve up to 40–60$\%_e$ ammonia when it is combined with diesel. In these CDF engines, the ammonia is commonly injected in the inlet ports or directly at low pressure and the diesel is directly injected at high pressure when the piston is close to Top Dead Centre (TDC). Advanced compression ignition concepts are required to achieve higher ammonia energy fractions. Experimental research results of higher ammonia fractions using CI combustion is limited and this is even more so for the combination of ammonia and hydrogen. Promising experimental results have been achieved with homogeneous charge compression ignition (HCCI) in [10] and reactivity controlled compression ignition (RCCI) in [11].

The HCCI combustion concept was fuelled by an ammonia-hydrogen mixture and achieved up to 94$\%_v$ ammonia in [10]. However, it required an inlet temperature of 240°C and a compression ratio of 22. The limiting factor of this concept was the pressure rise rate.

The RCCI concept was fuelled by an ammonia-diesel mixture and achieved up to 81$\%_v$ of ammonia in [11]. However, it still required 19$\%_v$ diesel. The limiting factor of this experimental set-up was the limitation of their turbocharger.

Based on the experimental engine results, five objectives are identified to improve the feasibility of CI combustion of ammonia. These are:

1. To lower the required compression ratio w.r.t. the CR of 22 required for the HCCI combustion concept.
2. To lower the intake temperature w.r.t. the required inlet temperature for the HCCI combustion concept.
3. To reduce the pressure rise rate compared to the HCCI concept
4. To reduce the amount of carbon-based fuel compared to the RCCI concept.
5. Minimizing the formation of pollutants

In order to minimize the required amount of carbon-based fuel, the choice of fuel is also relevant. Hernandez et al. [12] has investigated the autoignition of mixtures of sustainable hydrogen carriers and carbon-based fuels. Their results show that Hydrotreated Vegetable Oil (HVO) has better results with ammonia than (bio)diesel.

4 Promising NH_3-H_2 CI Combustion Concepts

Three CI combustion concepts have been created by combining the identified objectives mentioned above, available literature and the possibilities created by the AmmoniaDrive concept. The three concepts are shown in Fig. 2.

Concept 1, the RCCI concept, is based on controlling the reactivity by changing the mixture composition of ammonia, hydrogen, air, and HVO. There are two modifications compared to the RCCI combustion concept of Chiera et al. [11], the addition of hydrogen and replacing diesel by HVO. Both modifications are aimed at minimizing the required amount of carbon-based fuel by improving the combustion of ammonia. Hydrogen has been shown to be a combustion accelerant for ammonia [13].

Concept 2, the PCCI stratification concept, is based on controlling the combustion by varying the stratification in the combustion chamber. The stratification is intended to decrease the pressure rise rate. Achieving the desired in-cylinder stratification and adapting it to operational conditions, would require a sophisticated injection system.

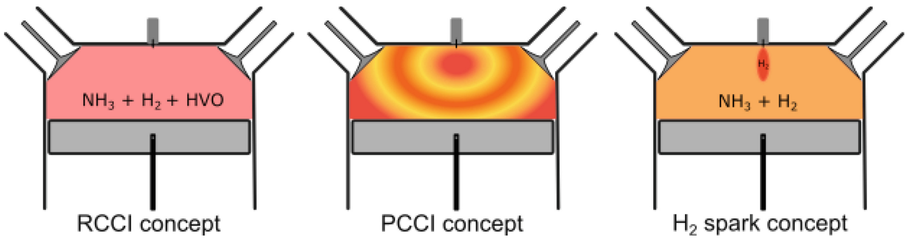

Fig. 2. Three combustion concepts for CI combustion of ammonia and hydrogen.

Concept 3, the hydrogen spark concept, is a combination of a homogeneous charge and dual hydrogen injection and may be regarded as a PPCI concept. The ammonia and early hydrogen injection form a homogeneous mixture leading to a higher flame speed of the mixture compared to pure ammonia operation. The second hydrogen injection causes a local hydrogen-rich region. This region should auto-ignite resulting in two options; 1) a propagating flame ignites the homogeneous NH_3-H_2 mixture, 2) an increase in cylinder temperature, due to the combustion of the second hydrogen injection, causes the homogeneous NH_3-H_2 mixture to auto-ignite.

These advanced compression ignition combustion concepts and/or combinations of them will be investigated to improve the feasibility of ammonia as a CI ICE fuel.

5 Conclusions

The growing interest in ammonia as a maritime fuel is promising and underlines the need for research and development of ammonia-fuelled shipboard power plants to prepare for the fast-approaching hydrogen economy. The AmmoniaDrive project is looking to eliminate fossil-fuel dependency and corresponding harmful emissions altogether by utilizing an innovative SOFC-ICE combined cycle. One of the objectives of this project is to improve the feasibility of ammonia as an ICE fuel. To do so, the maximum attainable ammonia energy fraction has to be increased, compared to available experimental engine results, whilst staying within engine limits, emission requirements, and maintaining good engine performance. More research towards advanced combustion mechanisms utilising the Compression Ignition principle is required to achieve this.

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