HCCI Engine Powered By Hydrogen And Ammonia Coming From Power-To-Fuel Storage Systems

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Abstract

As the proportion of renewable electricity is rising, the need for mid- and long-term storage becomes unavoidable. To that end the production of hydrogen and ammonia from excess electricity shows great potential. An Homogeneous-Charge Compression-Ignition (HCCI) engine is studied to use both storage fuels for heat and power production. The experiments were performed on a 15.3:1 compression ratio HCCI engine that successfully operated from pure hydrogen up to 60 %vol. in ammonia. The limited test bench intake conditions did not allow for higher ammonia concentrations. Ammonia was effective in reducing the heat release rate of hydrogen. Exhaust gas recirculation effectively limited the fuel-NO_x emissions.

Introduction

This study focuses on hydrogen and ammonia storage fuels given that their production and use can be fully decentralized and sustainable: they only require water and nitrogen to be produced from electricity and their combustion products in ideal conditions are water and nitrogen. Hydrogen is obtained from the electrolysis of water with an efficiency of about 70% based on its Lower Heating Value (LHV) for commercialized alkaline electrolysers. Yet hydrogen is not convenient for storage given its very low energetic density of about $10\,\mathrm{kJ\,L^{-1}}$ in normal conditions. To improve its storage density, many solutions exist and are recapitulated in Table 1. However the energetic density of compression storage is rather low; the liquefaction storage has a low efficiency; organic liquid and metal hydrides are expensive and require a specific process to set hydrogen free. Therefore compressed hydrogen is still preferred, but only up to mid-term storage.

Table 1: Comparison of various hydrogen storage technologies

Storage technology	State	Energy density (GJ/m^3)	Overall efficiency (LHV)
Compressed [1, 2]	700 bar - 293K	4.5	59%
Liquefied [3, 2]	1 bar - 20K	8.5	49%
Organic Liquids [2]	1 bar - 293K	10	47%
Metal Hydrides [4]	1-3 bar - >293K	15	-
Liquid Ammonia [5, 6, 7]	9 bar - 293K	13	50%

In the case of long-term storage (months to seasons) or in the case of high quantity of electricity storage, a higher density storage solution is preferable. In that regard, ammonia shows very

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interesting features (see Table 1). Obtained from hydrogen and nitrogen through the Haber-Bosch process, ammonia is a fuel convenient for storage since it is liquid under 9 bar of pressure and at ambient temperature. Liquid ammonia production can reach an LHV efficiency of 50% for processes combining conventional electrolysers, air separation units and Haber-Bosch systems [5, 6, 7]. We see that, by looking at the storage efficiencies, ammonia is energetically competitive to other hydrogen storage technologies. Moreover, taking into account the liquid state, non-leaking, energetic density and clean properties of ammonia we must acknowledge its high potential as a long-term storage fuel and future energy vector [8].

To meet the goal of a clean and highly efficient ammonia-hydrogen-CHP system, the authors decided to experimentally investigate the use of HCCI combustion. HCCI combustion allows for high compression ratios together with low in-cylinder temperatures (no thermal-NOx) while being inherently multifuel.

Still the ammonia molecule contains nitrogen and therefore fuel-NO_x can arise as soon as ammonia combustion starts. To avoid the production of fuel-NO_x from ammonia we need to reduce the oxygen availability [9, 10]. When ammonia was first experimented in SI engines, no increase in NO_x emissions was observed. SI engines being operated at stoichiometry, this shows that the available oxygen preferably combines with the ammonia molecules and their radicals instead of the freely moving nitrogen atoms. In the case of a HCCI engine, for which the fuel quantity is limited, one might think of replacing excess intake air by recirculating the exhaust gases to achieve stoichiometric conditions.

Finally hydrogen and ammonia are very different regarding auto-ignition: the ignition delay of ammonia is two orders of magnitude longer than hydrogen. On the other hand hydrogen leads to an intense combustion which limits the practicable equivalence ratio to avoid ringing. Consequently, to have an engine able to use both fuels efficiently, a trade-off between a high compression ratio to promote ammonia combustion and a limited compression ratio to prevent hydrogen from ringing is needed.

Therefore an HCCI engine will be experimented to assess ammonia resistance to auto-ignition and hydrogen promotion effect on ammonia. Moreover hydrogen-ammonia blends influence on the combustion intensity will be investigated. Then the performances will be analyzed and finally high Exhaust Gas Recirculation (EGR) rates will be performed to evaluate the oxygen availability impact on the fuel-NO_x formation.

Methodology

Table 2 gives the specifications of the experimental engine. It is a PSA DW10 engine retrofitted to a single-cylinder operated under HCCI conditions at a fixed rotational speed of 1500 rpm.

Table 2: Engine specifications

Engine model	PSA DW10
Displacement volume, V_c	499 cc/cyl.
Stroke/Bore/Conrod length	88/85/145 mm
Geometric/effective comp. ratio	16:1 / 15.3:1
Intake Valve Closing (CAD)	157 BTDC

To ensure homogeneous intake conditions, the mixture is first admitted into a 10L intake plenum before entering the engine. To allow the use of ammonia, high temperature and/or pressure are necessary. Pressurized intake air was supplied by a compressor up to 1.5 bar. Two heaters allow the intake temperature to reach 475 K. In-cylinder pressure is measured by a piezo-electric pressure sensor Kistler 6043A having an accuracy of +/- 2% and recorded every 0.1 CAD. NOx, HC and CO emissions were measured by an Horiba MEXA 7000.

We define the EGR rate as the percentage of excess intake air (compared to stoichiometry) that is replaced by exhaust gases. This will be done experimentally by inserting the correct amount of nitrogen and steam before the intake manifold.

Results and Discussion

Naturally aspirated conditions with an intake temperature of 428 K were sufficient to efficiently operate full hydrogen. Yet the maximal intake conditions of 1.5 bar and 475 K could not allow for more than 60%vol. ammonia in the mixture. This depicts ammonia high resistance to auto-ignition as well as the promoting effect of hydrogen on ammonia.

Regarding combustion efficiency, Figure 1 shows that ammonia tends to burn less efficiently than hydrogen. Still ammonia combustion can be as efficient as the one of hydrogen provided that the equivalence ratio, ϕ, is high enough to create high temperatures, therefore speeding up ammonia kinetics.

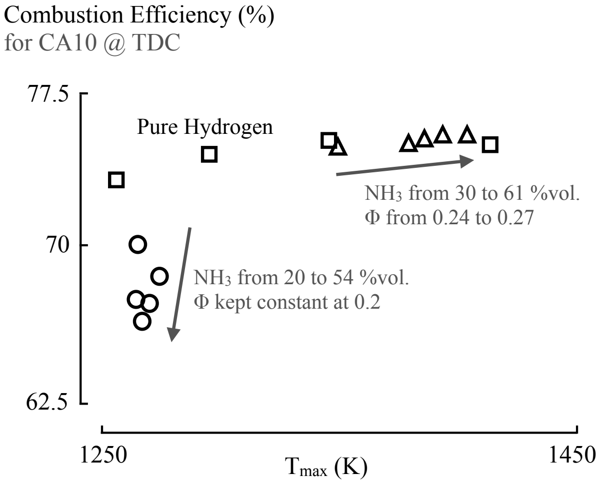

Figure 1: Combustion efficiency as a function of the maximal in-cylinder temperature. Staying higher than 1300 K ensures a good combustion efficiency for ammonia. The overall low combustion efficiency is due to the Diesel piston shape having a high squish volume.

A global combustion duration reduction, and consequently combustion intensity reduction, was observed when adding ammonia, even when increasing the equivalence ratio, see Figure 2. Therefore higher equivalence ratios can be reached with ammonia without producing ringing. This proves that using higher equivalence ratios for better combustion efficiency can be a safe operation with ammonia HCCI engines.

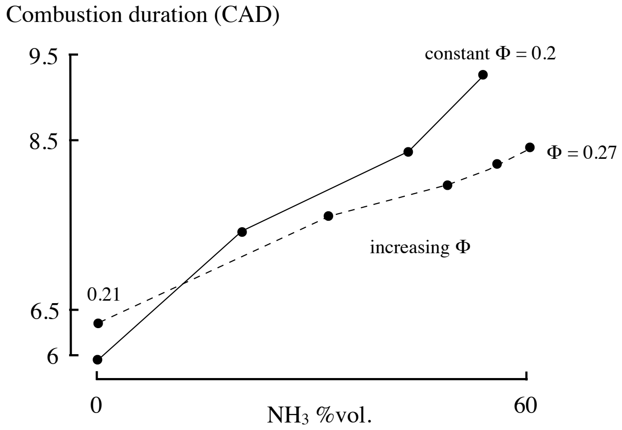

Figure 2: Increasing ammonia content induces longer combustions, even with increasing equivalence ratio.

Regarding emissions, as soon as some ammonia was added in the mixture, a surge of NOx emissions above several thousands ppm was observed, whereas the global in-cylinder temperature did not increase. Therefore these emissions are not linked to the thermal route but they find their origins in the nitrogen contained in ammonia, which is set free as soon as the combustion starts. In that perspective, EGR can be used to reduce the oxygen excess. The maximum EGR rate allowed by the experimental setup, i.e. 60%, pushed the effective equivalence ratio from 0.3 to 0.4, which reduced the NO_x emissions from 3300 ppm to 2300 ppm, with a 20%vol. ammonia mixture. The decreasing trend of NOx emissions with an increase in EGR rate is therefore significant. Simulations show that stoichiometric conditions obtained by 100% EGR would bring down NO_x emissions to 89 ppm.

Conclusion

A 15.3:1 effective compression ratio HCCI engine has been used to burn various mixtures of hydrogen and ammonia. Using the maximal intake pressure (1.5 bar) and the maximal intake temperature (480 K) possible, the engine was able to operate efficiently with an ammonia content up to 60 %vol. Hydrogen and ammonia were found to be complementary fuels as hydrogen promotes ammonia and ammonia damps hydrogen combustion to avoid ringing at higher loads, which highlights the interest of such a dual storage fuel concept. Finally, the fuel-NO_x emissions induced by ammonia could be effectively reduced through the use of EGR to reduce the oxygen availability. Further experiments are needed to experimentally verify full EGR operations and assess ammonia maximal ringing reducer potential.

Acknowledgments

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References

[1] M. Gardiner, “Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs,” tech. rep., DOE Department OF Energy, 2009.

[2] H. Wang, X. Zhou, and M. Ouyang, “Efficiency analysis of novel Liquid Organic Hydrogen Carrier technology and comparison with high pressure storage pathway,” *International Journal of Hydrogen Energy*, vol. 41, pp. 18062–18071, 2016.

[3] D. Teichmann, W. Arlt, and P. Wasserscheid, “Liquid Organic Hydrogen Carriers as an efficient vector for the transport and storage of renewable energy,” *International Journal of Hydrogen Energy*, vol. 37, no. 23, pp. 18118–18132, 2012.

[4] R. Aslam, K. Müller, M. Müller, M. Koch, P. Wasserscheid, and W. Arlt, “Measurement of Hydrogen Solubility in Potential Liquid Organic Hydrogen Carriers,” *Journal of chemical engineering data*, vol. 61, pp. 643–649, 2015.

[5] E. R. Morgan, “Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind,” tech. rep., University of Massachusetts, dissertation, 2013.

[6] European Commission, “Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals - Ammonia, Acids and Fertilisers,” Tech. Rep. August, European Commission - Integrated Pollution Prevention and Control, 2007.

[7] J. Fuhrmann, M. Hülsebrock, and U. Krewer, *Transition to Renewable Energy Systems - Energy Storage Based on Electrochemical Conversion of Ammonia.* Wiley-VCH Verlag GmbH Co. KGaA, 1st ed., 2013.

[8] W. L. Ahlgren, “TheDual-Fuel Strategy: An Energy Transition Plan The,” *Proceedings of the IEEE*, vol. 100, no. November 11, 2012.

[9] C. Duynslaegher, *Experimental and numerical study of ammonia combustion.* PhD thesis, Université Catholique de Louvain, 2011.

[10] C. Zamfirescu and I. Dincer, “Using ammonia as a sustainable fuel,” *Journal of Power Sources*, vol. 185, no. 1, pp. 459–465, 2008.