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► **To cite this version:**

Charles Lhuillier, Pierre Brequigny, Francesco Contino, Christine Mounaïm-Rousselle. EXPERIMENTAL STUDY ON THE PERFORMANCE AND EMISSIONS OF AN AMMONIA/HYDROGEN FUELED SI ENGINE. 25th "Journées D'étude" Belgian Section of the Combustion Institute, May 2018, Mons, Belgium. hal-01934848

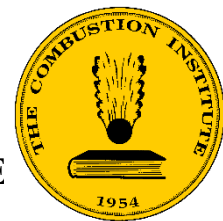
HAL Id: hal-01934848

<https://hal.science/hal-01934848v1>

Submitted on 26 Nov 2018

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EXPERIMENTAL STUDY ON THE PERFORMANCE AND EMISSIONS OF AN AMMONIA/HYDROGEN FUELED SI ENGINE

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Introduction

As the concerns regarding climate change are gaining high awareness throughout our societies, a majority of governments has agreed on common objectives to try mitigating this phenomenon [1]. Consequently, several scenarios have been proposed by national and international organizations, such as the International Energy Agency, aiming at reducing the global carbon-based greenhouse gas (GHG) emissions. These imply a transition from a carbon-dominated energy mix towards a sustainable carbon-free mix based on Renewable Energy Sources (RES), whose implementation has already started. The share of RES in the world energy balance should reach up to 40% by 2040 [2].

A major challenge of the use of electricity produced from intermittent RES, such as wind or solar PV is the difficulty to store surplus electrical energy during production peaks in order to meet demand and maintain a sufficient power supply during inevitable periods of production deficit. Current storage technologies, such as pumped hydropower or batteries present several limitations [3]. Thus, several alternative solutions are currently being investigated by academia and industry in order to increase the energy density of and mitigate the dependence on particular energy storage technologies [3]. Power-to-Gas (PtG) and Power-to-Fuel (PtF) are promising options to store and carry surplus electricity, based on hydrogen as an energy carrier obtained by water electrolysis. These solutions present a high energy density, are not limited in time (seasonal or long-term storage) and ease the penetration of RES into other sectors than electricity production, such as heating or mobility. The direct use of hydrogen, however, is considerably limited by the need of a tailored infrastructure and the associated cost and safety issues.

Ammonia (NH₃) has received recent interest as an alternative hydrogen carrier [4]–[6]. Its carbon-free nature and relatively high energy density make it a promising competitor to hydrogen and carbon-based hydrogen carriers. Ammonia is stored in liquid form under 9 bar at standard temperature and safe transportation and storage processes are already provided. Furthermore, it can be easily produced from water and air using electrolysis and several research efforts are being conducted in order to improve this process [7]. This would allow

decentralized NH₃ production close to the renewable power plants or fields, a safe transportation to the point of storage or use, and a CO₂-free conversion into electrical power, heat or work for mobility by means of direct or indirect fuel cells [8], or combustion in gas turbines or internal combustion engines. The higher corrosiveness and toxicity of ammonia when compared to other fuels should however lead to additional safety considerations, especially when final users are exposed.

Following these considerations, several teams have studied ammonia combustion [9]–[11]. One main drawback of NH₃ as a fuel is its very low combustion intensity, as illustrated by its laminar burning velocity, which is one order of magnitude smaller than the one of methane in atmospheric conditions [9]. Thus, some researches have considered enhancing the combustion by associating ammonia with another fuel, such as hydrogen [10] or methane [11]. These studies have different focus regarding the final application of ammonia combustion. They all show promising results regarding the fuel efficiency and power output. However, they draw some limitations in the actual state of engine technology, noticeably substantial NO_x emissions, and the need of tailored injection and ignition strategies.

Nevertheless, a lack of extensive studies on ammonia combustion in SI engines can be noted. Thus, this work focusses on fueling premixed hydrogen-enriched ammonia/air gaseous mixtures to a modified commercial SI engine. The performance, NO_x and unburned NH₃ emissions of a single-cylinder SI engine are experimentally studied and first results will be presented.

Experimental Setup

Experiments are carried out in a commercial four-cylinder four-stroke SI engine modified to a single-cylinder engine by fueling only one out of four cylinders. It is characterized by a four-valve pent-roof chamber with a displacement volume of 399.5 cm³ and a compression ratio of 10.5. The engine is driven by an electric motor at a fixed engine speed of 1500 rpm. A water-cooled AVL quartz pressure transducer with a 0.1 Crank Angle Degree (CAD) resolution provides in-cylinder pressure measurements. All gaseous flows are measured and controlled using Brooks thermal mass flowmeters, premixed in an intake plenum and preheated to the intake

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temperature of 50°C. Additional details on the experimental setup can be found in [12]. The exhaust gases are analyzed using a Fourier Transform Infrared (FTIR) spectrometer, allowing to track the NO_x and NH₃ emissions. No exhaust H₂ measurement is considered here. The ranges of operating conditions and mixture composition was [0.6 – 1.2] bar for the intake pressure, [0.6 – 1.2] for the global fuel equivalence ratio and [0 – 60] vol. % for the hydrogen content in the NH₃/H₂ blend. The spark ignition timing is set at Maximum Brake Torque (MBT) to ensure the maximum Indicated Mean Effective Pressure (IMEP), a quantification of the work provided by the combustion in the absence of direct torque measurements. The friction losses caused by the three deactivated pistons make the latter irrelevant.

First results and conclusions

First analysis of cylinder pressure data for preliminary experiments show stable engine operation characterized by a COV IMEP lesser than 5% over a wide range of operating conditions. Most notably, engine operation is perfectly stable at high intake pressures for a stoichiometric ammonia/air mixture. Decreasing the intake pressure and varying the equivalence ratio reduces the combustion stability, thus making hydrogen enrichment a necessity. The volumetric enrichment with H₂ does not have a significant effect on the IMEP, since the low molar mass of H₂ compensates the low Lower Heating Value of NH₃. The obtained IMEP levels are comparable with those obtained with conventional fuels, e.g. 7 bar for 1 bar of intake pressure and a stoichiometric mixture with 10 vol. % of H₂ in the fuel.

However, the spark timing has to be dramatically advanced with increasing ammonia content in the fuel due to the low burning velocity of ammonia. In addition, the initial phase of the combustion seems to be decisive. For high ammonia contents in the fuel, the initiation phase is longer than the rest of the combustion. Hydrogen enrichment seems to accelerate the combustion primarily in these early stages.

The NO_x and NH₃ emission profiles exhibit quite significant values over the entire operating range, reaching orders of magnitude of several thousands of ppm. Blends with high hydrogen content demonstrate higher NO_x and lower NH₃ concentrations in the exhaust gases due to increased flame temperatures and improved combustion efficiency coupled with smaller NH₃ content in the reactive mixture respectively. Maximum NO_x concentrations are found for slightly fuel-lean mixtures as expected and decrease for leaner or rich mixtures, towards very low values in the latest case. By contrast, the concentration of unburned ammonia finds a minimum at near-stoichiometric lean conditions and increases when the equivalence ratio raises. In future technical applications, a trade-off between NO_x and NH₃ emissions will most likely be necessary in order to mitigate both negative impacts on the environment. After-treatment systems such as Selective Non Catalytic Reduction could also be implemented on future SI engines.

Acknowledgements

The investigations presented in this paper have been obtained with the support of the French LabEx CAPRYSES and the Vrije Universiteit Brussel.

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