Effect of Ammonia Injection on Performance Characteristics of a Spark-ignition Engine

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***Abstract*:** The effects of direct injection of gaseous ammonia on the combustion characteristics and exhaust emissions of a spark-ignition engine were investigated. Ammonia can be burned directly in IC engines, however a combustion promoter is necessary to support combustion. As a matter of fact, the best (and carbon-free) promoter is hydrogen, which has very high combustion velocity and wide flammability range, whereas ammonia combustion is characterised by low flame speed and temperature, narrow flammability range and high ignition energy. Appropriate direct injection strategies were developed to allow ammonia to be used in spark-ignition engines without sacrifice of volumetric efficiency. The use of ammonia/hydrogen mixtures as an SI engine fuel was investigated in the same context.

Keywords: *Ammonia, Hydrogen, Spark-ignition engine, Carbon free fuel*

I. INTRODUCTION

With the increased world population comes increased demand for fuels for the transportation industry. The transportation industry depends on petroleum fuels, with a huge usage of 88.13 million barrels a day worldwide [1].

Although improvement in drilling technology will certainly help exploit fossil fuel reserves, however, fossil fuels don't seems to be a sustainable option as looking to the rate they are being consumed. So ammonia can be used as an alternate fuel.

A. Ammonia and hydrogen mixtures as SI-engine fuel

Through the years a lot of investigations on hydrogen as an engine fuel have been made. Many of these investigations have shown hydrogen as a suitable fuel for the spark ignited internal combustion engine. However, problems with abnormal combustion such as backfire have been widely reported. An overview of these experiences has been made by Verhelst et al. [2]. With ammonia the number of investigations is limited [3–7]. They show that it is possible to use ammonia as a fuel for SI-engines. With the decomposition of a small amount of ammonia equaling a hydrogen content of approximately 1% by mass (approximately 8 vol.%), the performance was satisfactory. An advantage of ammonia and hydrogen is that they do not contain carbon, eliminating emissions of carbon oxides from the engine. In Table 1 some fuel properties of ammonia, hydrogen and gasoline are given. The octane rating of both ammonia and hydrogen is higher than gasoline, making it preferable to run at a higher compression ratio (CR). The flame velocity and the min. ignition energy of ammonia and hydrogen are far apart. By mixing it was hoped that a suitable compromise could be gained. The ammonia to hydrogen ratio presents a new possible engine control parameter. Some fuel properties of ammonia, hydrogen and gasoline. Data from [8–10].

Table 1: Fuel Properties Comparison

		Ammonia	Hydrogen	Gasoline
Lower heating value	MJ/kg	18.8	120.0	44.5
Flammability limits, gas in air	vol.%	15–28	4.7–75	0.6–8
Laminar flame velocity	m/s	0.015	3.51	0.58
Auto ignition temperature	C	651	571	230
Absolute min. ignition energy	mJ	8.0	0.018	0.14
Octane rating, RON	–	>130	>100	90 – 98
Density,25 C, 1 atm	g/L	0.703	0.082	740

B. Properties of ammonia

Ammonia has arisen as a potential hydrogen carrier to solve the problem of on board storage. Although ammonia (NH_3) is not a pure hydrogen compound, it is easily stored in liquid state at a pressure of 10.3 bar. The ability to store ammonia in a liquid state gives ammonia an advantage in energy per unit volume when compared to pure hydrogen. In other words, for equivalent tanks more hydrogen is stored in ammonia (liquid) than in a tank of pure hydrogen (gaseous or liquid). Ammonia's storage capabilities demonstrate an advantage over hydrogen as an onboard fuel. Ammonia is also a very competitive fuel when compared to conventional fuels in terms of energy cost, i.e. ¢/MJ. Ammonia is less than one cent higher than gasoline at 3.38 ¢/MJ compared to gasoline and diesel at 2.94 and 2.81 ¢/MJ, respectively. Although ammonia storage has much less energy density than gasoline and diesel, ammonia exhibits significantly higher energy density than compressed natural gas (CNG), liquid hydrogen, and gaseous hydrogen. Ammonia also has a higher octane number than gasoline type fuels, which allows ammonia to be used in higher compression ratio engines. The ability to use ammonia with higher compression ratios allow for more efficient engine operation.

C. Combustion Characteristics of ammonia

As a fuel ammonia also presents many of the upsides of hydrogen. Like hydrogen, ammonia contains no carbon and therefore produces no CO or CO_2. However, unlike hydrogen water is not the only byproduct of ammonia combustion. When ammonia is burned in an unaltered state byproducts include nitric oxide (NO) and nitrogen dioxide (NO_2) both of which are considered harmful pollutants and as a combination (NOx) are regulated by the Environmental Protection Agency (EPA) [11]. The resultant NOx from ammonia combustion is primarily produced from fuel-bound nitrogen which is separated from the hydrogen and seeks to re-bond. The free nitrogen bonds primarily with free oxygen, thus producing NOx. NOx, however, can be converted to nitrogen (N_2) and water (H_2O) using selective catalytic Reduction (SCR). Use of an SCR can simultaneously reduce NOx and residual ammonia from incomplete combustion in the exhaust. As of current there are, however, no production SCR's available for small vehicle application. Therefore, further development of the industry is needed. Neverthe-less the technology does exist to transform ammonia combustion into an essentially nonpolluting event.

There are alternative options, however, to potentially enable clean ammonia combustion. Ammonia can be decomposed before combustion into hydrogen and nitrogen, which in effect results in hydrogen driven engine with byproducts returning to water. Several theoretical studies have been conducted to examine the potential efficiency of a hydrogen operated engine that utilizes onboard decomposition of ammonia [6] [2]. Zamfirescu *et al.* [6] suggested that if all parts of the fuel system were properly utilized the potential efficiency of the entire system could reach 65%. When compared to standard efficiencies of current systems we begin to see the vast potential (~30% and ~35% for gasoline and diesel, respectively). In order to achieve high efficiencies as suggested, a comprehensive engine fuel system must be used. A fully comprehensive system utilizes the cooling properties of ammonia to cool both the engine and the passenger cabin. The exhaust gas is utilized to heat the dissociation catalytic reaction. However, for some applications the exhaust temperature does not reach the necessary temperature (500^{o}C) to decompose ammonia. A solution that has been proposed is to oxidize a portion of the fuel in the exhaust line, which in turn provides the additional heat for the ammonia decomposition to occur [11]. These main implementations combined with the higher efficiency of hydrogen engines results in highly efficient machines [6]. Using ammonia in a comprehensive engine design fully utilizes the potential of storage capabilities combined with high efficiency combustion and zero pollution of hydrogen. These systems are ideal but are not the only manner for ammonia combustion.

Other studies suggest alternatives, such as using a catalyst to minimally crack or decompose the ammonia resulting in a mixture of ammonia with traces of hydrogen for ignition enhancement purposes. Frigo *et al* worked with a similar setup using both ammonia and hydrogen to simulate a dissociation catalyst. Using this model in a single cylinder spark ignition engine they were able to achieve engine break thermal efficiencies of nearly 26%. It is also believed that with increased compression ratio the thermal efficiency could be further improved. It should also be noted that this example did not include comprehensive fuel supply and thus did not utilize ammonia cooling or exhaust gas heat, both of which would increase the overall efficiency of the engine.

II. EXPERIMENTAL SETUP

For the experimental purpose a 505 cm^3 Lombardini twincylinder S.I. engine was chosen[12] (the main engine specifications are reported in Table 2) and located on the test bench maintaining the original (gasoline) mechanical configuration.

The only mechanical modification of the engine involved the intake manifold, where hydrogen and ammonia are injected in the gaseous phase by electro-injectors added to the original ones for gasoline. As a whole, six electro-injectors are located on the intake manifold (three for each duct). The injectors for ammonia and for hydrogen are conventional ones for LPG application with appropriate modification to inner parts. Fig. 1 shows a picture of the engine with ammonia and hydrogen injectors in evidence (on the left), together with a schematic drawing of the ammonia injectors and the rail (on the right).

Ammonia is stored in the liquid phase at room temperature and 9 bars. A heated vaporizer with a pressure regulatoris placed before the electro-injectors. Stainless steel was employed for the ammonia tank and piping in addition to special coating made up of Nickel for some components (as the injectors). A further study should be completed trying out the effectiveness of a thinner coating than the one used (>10 mm) in the exposed zones to gaseous NH3 and, vice versa, increasing the thickness in the zones subject to shaving friction or connections with interference.

Because of the toxicity of gaseous ammonia, a suitable monitoring system was developed in view to be integrated into the final hybrid vehicle. It is based on a modular architecture, which allows the integration of several sensors in a scalable plug-and-play structure and provides data preelaboration. Three ammonia sensors are planned to be located in different places of the vehicle: one inside the cockpit, for the safety of the driver; another near both the ammonia tank and the catalytic reactor, to monitor possible ammonia leakages, and the last one at the exit of the tailpipe to detect the presence of ammonia slip in the exhaust gas. For engine testing only this last sensor was used, with the alarm settled at 100 ppm.

Particular attention was dedicated to the hydrogen ammonia feeding line to avoid leakages and partial ammonia condensation before the injectors. The original ECU was replaced with a fully-programmable one (MoTeC model M800) and set to drive the ignition system and the six electro-injectors for hydrogen, ammonia and gasoline (this last option, i.e. the use of gasoline, was kept in the prospective of a more flexible hybrid vehicle).

Thermal flow meters were adopted to measure hydrogen and ammonia consumption. Piezoresistive pressure sensors gauge the intake and the exhaust pipes, while a special spark plug with integrated piezoelectric sensor gauges cylinder pressure. Pressuresensorswere placed in the ammonia and in the hydrogen feeding lines. Thermocouples were located in the intake and exhaust pipes, as well as in the cooling and in the lubrication circuits. To measure fuel-air ratio (l) a proportional O_2 (UEGO) sensor was placed in the exhaust pipe, while a chemiluminescence NO_x analyser gauges the exhaust emissions. An optical encoder was placed on the frontal side of the crankshaft, while an AVL Indicom system performs data acquisition and processing. The intake air flow rate is controlled by the original motorized throttle valve.a schematic of the experimental apparatus is reported on Fig. 2.

Table 2:- Engine Specification

Experimental engine specifications.	
Model	Lombardini *LGW 523 MPI*
Displacement	505 cm^3
Stroke	62 mm
Compression Ratio	10.7:1
Cooling system	Water cooled
Valves	2 per cylinder
Max power (gasoline)	21 kW @ 6000 rpm
Max torque (gasoline)	39 Nm @ 2200 rpm
Engine velocity at idle	1100 rpm

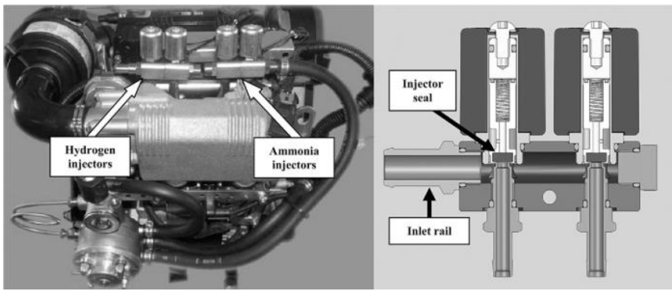

Fig. 1 The experimental engine with ammonia and hydrogen injectors in evidence (left), together with a schematic drawing of the ammonia injectors and the rail (right)

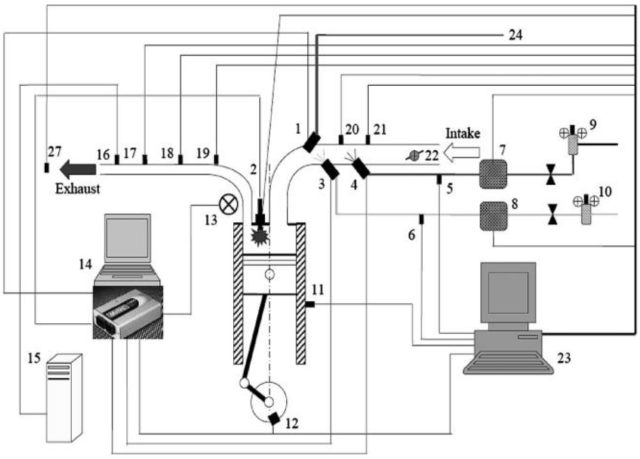

Fig. 2: Schematic of the experimental apparatus

1) Original gasoline injector; 2) Spark plug with integrated cylinder pressure sensor; 3) Ammonia injector; 4) Hydrogen injector; 5) Hydrogen pressure sensor; 6) Ammonia pressure sensor; 7) Hydrogen thermal flow meter; 8) Ammonia thermal flow meter; 9) Hydrogen feeding line pressure regulator; 10) Ammonia feeding line pressure regulator; 11) Water and oil temperature sensors; 12) Optical encoder; 13) Magnetic sensor for the correct phasing of the injection and ignition events; 14) ECU for injection and ignition calibration; 15) Chemiluminescence NO_x analyser; 16) Exhaust gas probe, 17) Exhaust gas oxygen sensor (UEGO); 18) Exhaust pipe pressure transducer; 19) Exhaust gas temperature sensor; 20) Intake air temperature sensor; 21) Intake pipe pressure sensor; 22) Motorized throttle valve; 23) Data acquisition and processing system; 24) Gasoline feeding line; 25) Hydrogen feeding line; 26) Ammonia feeding line; 27) Ammonia threshold sensor.

III. RESULTS

The experimentation produced evidence that the HAER mainly depends on load and less on engine speed, as Fig. 3 shows, where practical minimum HAER is plotted vs. engine speed.

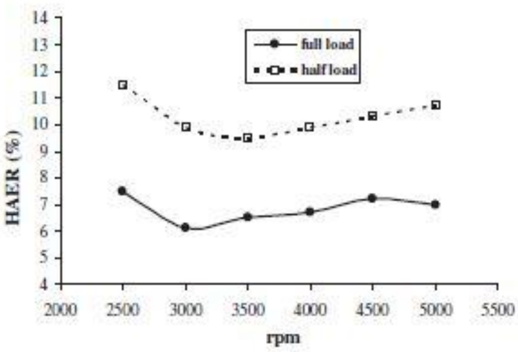

Fig. 3: Practical minimum HAER vs. engine speed at full and half load

Fig. 4 displays brake power vs. engine speed with gasoline and with ammonia plus hydrogen at practical minimum HAER which shows that in the second case power is roughly 15% less at low engine speed and 30% less at high engine speed.

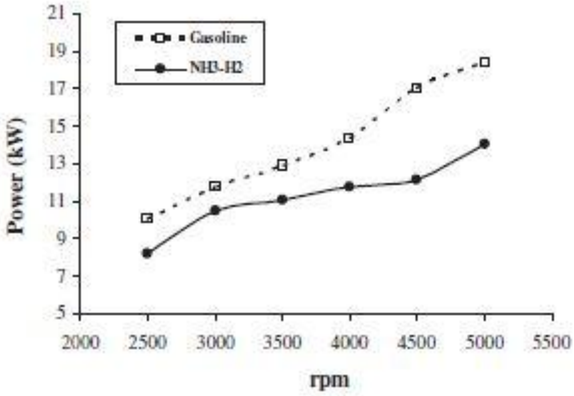

Fig. 4 Brake power vs. engine speed with gasoline and with ammonia plus hydrogen at full load

Fig. 5 shows NOx emission vs. engine speed with ammonia and hydrogen at minimum HAER at full and half load. NOx maximum emission is 1700 ppm at 3000 rpm at full load. Due to the lower combustion temperatures, NOx emission is always lower at half load,with a maximum of 1500 ppm, still located at about 3000 rpm.

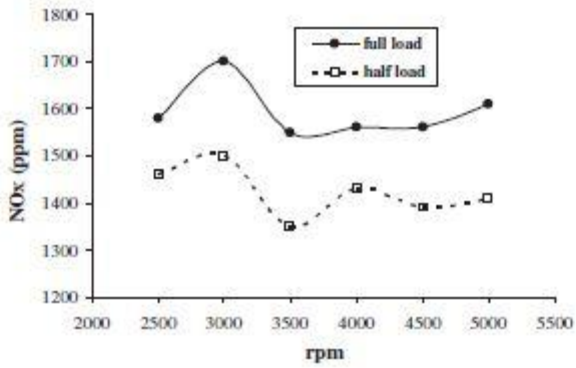

Fig.5 NOx vs. engine speed with ammonia plus hydrogen at full and half load

The thermal energy necessary for the catalytic reaction is obtained from the exhaust gasses whose temperature, at full and half load, were measured as shown in Fig 6.

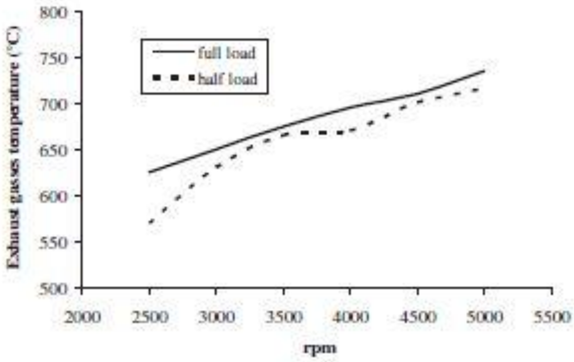

Fig. 6 Exhaust gasses temperature vs. engine speed at full and half load, with the minimum HAER.

CONCLUSION

Ammonia represents a hydrogen carrier and can be effectively utilized as fuel in IC engines, provided that a small percentage of other fuels is added as combustion promoter. Among them, the best one is hydrogen, which can be obtained directly from ammonia on board the vehicle by means of a catalytic reformer. In this experimental activity a simple electronic fuel injection system, that injects ammonia and hydrogen in the gaseous phase, was designed and implemented on a 505 cm^3 twin-cylinder SI engine that was mechanically modified only as concerns the intake manifold, to host the electro-injectors for ammonia and hydrogen. The experimental results confirm the need to speed combustion up by adding hydrogen to air-ammonia mixture, with ratios that mainly depend on load and less on engine speed. Exhaust pollutant emission (only NO_x) is low, with a maximum of 1700 ppm at full load and 3000 rpm. Ammonia presence in the exhaust pipe was monitored by a threshold sensor. So by analyzing results it has been concluded that Ammonia/hydrogen mixtures constitute a very suitable fuel for SI engines.

References

[1] Central Intelligence Agency. The World Factbook. US Government Printing Office,;2013.

[2] Verhelst S, Verstraeten S, Sierens R. A comprehensive overview of hydrogen engine design features. Proce Inst Mech Eng, Part D: J Automob Eng

[3] Pearsall J, Garabedian C. Combustion of anhydrous ammonia in diesel engines. Society of Automotive Engineers – Papers (670947).

[4] Sawyer R, Starkman E, Muzio L, Schmidt W. Oxides of nitrogen in combustion products of ammonia fueled reciprocating engine. Society of Automotive Engineers – Papers (680401).

[5] Starkman E, Newhall H, Sutton R, Maguire T, Farbar L. Ammonia as spark ignition engine fuel – theory and application. Society of Automotive Engineers – Papers (660155).

[6] Starkman E, James G, Newhall H. Ammonia as diesel engine fuel – theory and application. Society of Automotive Engineers – Papers (670946).

[7] Gray Jr J, Dimitroff E, Meckel N, Quillian Jr R. Ammonia fuel – engine compatibility and combustion. Society of Automotive Engineers – Papers (660156).

[8] Saika T. Study of an ammonia fueled engine as a clean energy system. Nihon Enerugi Gakkaishi/J Jpn Inst Energy 2000;79(6):530–9.

[9] Ferguson CR, Kirkpatrick AT. Internal combustion engines, applied thermosciences. second ed. John Wiley & Sons; 2001.

[10] Hodgson JW. Alternate fuels for transportation - part 3: ammonia for the automobile. Mech Eng 1974;96(7):22–5.

[11] Emission Standards Reference Guide,United States Environmental Protection Agency, 18 December 2012. [Online]. Available: http://www.epa.gov/otaq/standards/index.htm. [Accessed 5 Febraury 2013].

[12] Analysis of the behavior of a 4 stroke Si engine fulled with ammonia and hydrogen-Intrenational Paper by Stefano Frigo,Roberto Gentili.