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Hydrogen Fuelled Ic Engine – An Overview

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Abstract: *For more than a century, hydrocarbon fuels have played a leading role in propulsion and power generation. Recent years, declining oil reserves and increased fuel prices have, together with increased awareness of the environmental impacts of burning hydrocarbon fuels, led to an interest in alternatives to fossil fuel based propulsion and power generation. One such alternative is to use hydrogen as an energy carrier and to extract energy using a fuel cell or a modified internal combustion engine. Hydrogen as a fuel in Internal Combustion engines is a solution for the near future to realize zero CO2 emissions for trafficapplications. This paper presents an overview of the internal combustion hydrogen fuelled engine.*
Keywords: *Hydrogen, Fuels, Combustion, Propulsion, Engine*

I. Introduction

For more than a century, hydrocarbon fuels have played a leading role in propulsion and power generation. Recent years, declining oil reserves and increased fuel prices have, together with increased awareness of the environmental impacts of burning hydrocarbon fuels, led to an interest in alternatives to fossil fuel based propulsion and power generation. One such alternative is to use hydrogen as an energy carrier and to extract energy using a fuel cell or a modified internal combustion engine. Some hydrogen production technologies are well known, mature and well-developed. Still, a number of concerns over the conversion technologies need to be addressed in relation to power to weight ratio, price, reliability, storage and transportation. The incentives for a hydrogen economy are the emissions, the potentially CO_2 -free use, the sustainability andthe energy security. In this paper the focus is on the use ofhydrogen in internal combustion engines (ICE), or moreprecisely, hydrogen fuelled spark ignition (SI) engines.

Hydrogen possesses some features that make it attractive for use as a fuel in internal combustion engines, enabling fast, close to constant volume combustion, high combustion efficiency and low emissions. Numerous authors have investigated the use of hydrogen in spark ignition (SI) engines, and the feasibility of hydrogen as a fuel in such engines is well established. An overview of the characteristics of hydrogen as a fuel for SI engines was presented by Karim [7]. The flame speed of hydrogen is higher and hydrogen allows operation at significantly higher excess air ratios than conventional hydrocarbon fuels. This enables extended lean burn operation of the engine, potentially leading to a drastic reduction of NO_x emissions. High diffusivity and low quenching distance avoids poor vaporisation problems. Emissions of carbon monoxide and unburnt hydrocarbons are practically eliminated with a hydrogen fuelled engine, as the only source of carbon will be the lubricating oil. For the same reason the engine does not emit carbon dioxide. The only non-trivial exhaust gas emissions will be nitrogen oxides, which result from the oxidation of atmospheric nitrogen under high temperatures. It will be shown below that with HCCI operation and a very lean mixture this pollutant can be reduced to near-zero levels. The ignition energy for hydrogen is low, however the temperature required for auto ignition is significantly higher than that of conventional hydrocarbon fuels. Therefore, CI engines using hydrogen fuel require high compression ratios and/or pre-heating of the inlet air to ensure autoignition. The latter was used in this study, and is discussed below. A comprehensive review of hydrogen-fuelled internal combustion engines was presented by White et al. [8].

II. Hydrogen Ic Engines – Fourgenerations

There are four generations in the development of hydrogen fuelled engines.

In the first generation a gas venturi is used. With a gas carburettor a large volume of combustible mixture is in the inlet manifold. To avoid backfire (an explosion in the inlet manifold before the inlet valve closes), the engine has to run lean ($\lambda \geq 2$) which results in a low power output.

For the second generation the same technologies are used as for gasoline SI engines: multipoint sequential (port) injection and electronic engine control. A possible strategy is then to use a late injection so that the admitted air will cool the inlet manifold and the combustion chamber before the injection of hydrogen. These injectors are now currently commercially on the market (after a delay of introduction due to the high volume of a low density gas to inject in a short time). Even with a late injection a stoichiometric mixture ($\lambda = 1$) is not always possible and the power output is lower than a corresponding gasoline engine, see e.g. Ford's results reported by Tang et al. (2002).

For the third generation, at high loads, the mixture is kept stoichiometric ($\lambda = 1$). To avoid backfire, exhaust gas

Recirculation (EGR) is used. At this stoichiometric mixture a three way catalyst (TWC) can be used to decrease the NOx emissions. And with turbo/supercharging and inter cooling the same or a higher power output is obtained as for a gasoline engine, as demonstrated by BMW obtaining an indicated mean effective pressure (imep) of 18 bar – Berckmüller et al. (2003), and Ford reaching gasoline engine torque outputs with a boost Pressure of 1.85 bar – Natkin et al. (2003).

Finally for the fourth generation, research is going on into direct injection of hydrogen in SI engines, e.g. by BMW – Gerbig et al. (2004), Rottengruber et al. (2004).

III. Experimental Research: Literaturereview

Here, an overview is given of the design features in which a dedicated hydrogen engine differs from traditionally fuelled engines, following Verhelst (2005).

A. Abnormal combustion

The suppression of abnormal combustion in hydrogen engines has proven to be quite a challenge and measures taken to avoid abnormal combustion have important implications for engine design, mixture formation and load control. For spark ignition engines, three regimes of abnormal combustion exist: knock (auto-ignition of the end gas region), pre-ignition (uncontrolled ignition induced by a hot spot, premature to the spark ignition) and backfire (also referred to as back flash, flashback and induction ignition, this is a premature ignition during the intake stroke, which could be seen as an early form of pre-ignition) Backfire has been a particularly tenacious obstacle to the development of hydrogen engines. The causes cited for backfire are:

- Hot spots in the combustion chamber: deposits and particulates - Bardon and Haycock (2002), MacCarley (1981); the spark plug – Das (2002), Lucas and Morris (1980); residual gas - Das (1996), Lucas and Morris
- (1980), Berckmüller et al. (2003); exhaust valves - Berckmüller et al. (2003) , Stockhausen et al. (2002), Swain et al. (1988), TÜV Rheinland (1990) ; etc.
- Residual energy in the ignition circuit - Lucas and Morris (1980), Kondo et al. (1997)
- Induction in the ignition cable - MacCarley (1981)
- Combustion in the piston top land persisting up to inlet valve opening time and igniting the fresh charge -
- Lucas and Morris (1980), Swain et al. (1996), Koyanagi et al. (1994), Lee et al. (2000)
- Pre-ignition - Tang et al. (2002), MacCarley (1981), Swain et al. (1988), Koyanagi et al. (1994), Lee et al.(1995)

All causes itemized above can result in backfire and the design of a hydrogen engine should try to avoid them, asengine conditions different from normal operation are always a possibility.

B. Air- Fuel Mixture formation

A range of mixture formation methods has been tested for hydrogen engines, mostly in the pursuit of backfire-free operation:

- External mixture formation with a gas carburettor - Lucas and Morris (1980), Jing-Ding et al. (1986)
- External mixture formation with `parallel induction', that is: some means of delaying the introduction ofhydrogen, e.g. a fuel line closed by a separate valve on top of the intake valve that only opens when the intakevalve has lifted enough – Olavson et al. (1984)
- External mixture formation with a gas carburettor and water injection - TÜV Rheinland (1990), Binder andWithalm (1982), sometimes with additional exhaust gas recirculation (EGR) – Davidson et al. (1986)
- External mixture formation with timed manifold or port fuel injection (PFI) - Tang et al. (2002), MacCarley (1981), Berckmüller et al. (2003), Swain et al. (1996), Lee et al. (1995), Natkin et al. (2003), Heffel et al. (1998), sometimes also with some means of 'parallel induction' – Heffel et al. (2001)
- Internal mixture formation through direct injection (DI) – Meier et al. (1994), Furuhama (1997), Guo et

al. (1999), Kim et al. (1995) during the last decade, only timed port injection and direct injection (during the compression stroke or later) have been used, as the other methods are less flexible and less controllable. External mixture formation by means of port fuel Injection has been demonstrated to result in higher engine efficiencies, extended lean operation, lower cyclic variation and lower NOx production compared to direct injection – Smith et al. (1995), Yi et al. (2000). An important advantage of DI over PFI is the impossibility of backfire. This too increases the maximum power output of DI compared to PFI as richer mixtures can be used without fear of backfire. Pre-ignition can still occur though, unless very late injection is used.

C. Load control strategies

Hydrogen is a very versatile fuel when it comes to load control. The high flame speeds of hydrogen mixtures and its wide flammability limits permit very lean operation and substantial dilution. The engine efficiency and the emission of NOx are the two main parameters used to decide the load control strategy. Constant equivalence ratio throttled operation has been used but mainly for demonstration purposes – Olavson et al. (1984), Davidson et al. (1986), as it is fairly easy to run a lean burn throttled hydrogen engine (accepting the severe power output penalty). Where possible, wide open throttle (WOT) operation is used to take advantage of the associated increase in engine efficiency – Heffel et al. (2001), Smith et al.(1995), so regulating load with mixture richness (qualitative control) instead of volumetric efficiency (quantitative control) and thus avoiding pumping losses.

Across the load range of the engine, different strategies, which try to make as much advantage as possible of the properties of the hydrogen-air mixture, can be used. It is important to know that NOx production is very dependent on the mixture richness, the air-to-fuel equivalence ratio λ, as this is the major parameter controlling the maximum combustion temperature. At lean mixtures NOx production is very low until a certain λ is reached, the so-called 'NOx formation limit'. A mixture richer than this limit, which is normally around $\lambda = 2$ will produce high levels of NOx and a maximum will be reached at about $\lambda = 1.3$. So, for loads below this 'NOx formation limit', a quality-based mixture control will be used. For idling and very low loads the mixture has to be very leanwith WOT ($\lambda > 4$). At these lean mixtures the coefficient of variation for imep (COV) is high due to the lower combustion velocity and combustion stability. Therefore throttle control, in order to enrich the mixture, is used at these loads. High efficiencies of more than 40% are reported in this operating range – Berckmüller et al. (2003). Depending on the mixture formation, different methods can be used to control the engine at high loads. Beyond the NOx formation limit throttled stoichiometric operation with a reduction catalyst can be used, as demonstrated by BMW – Rottengruber et al. (2004). This catalyst for NOx reduction can be used with great efficiency (> 99.5%), because H2, which is present in the exhaust feed gas at $\lambda = 1$, is a highly efficient reducing agent. For higher efficiency, EGR (0 – 50%) instead of throttling can be used in this load range to control the amount of fresh air in the engine, this has been reported by Ford – Natkin et al. (2003).

Efficiencies of 35% and 40% are reported for respectively throttle and EGR control in this load range. If the engine is charged, for loads above the naturally aspirated full load limit, control is possible by regulating the charge pressure while keeping a stoichiometric mixture. Another strategy proposed by BMW is to use the common port injection for low and part load, and direct injection for high loads – Rottengruber et al. (2004). External mixture formation is advantageous because of the better mixture preparation (mixing) and less throttling requirements due to the lower volumetric efficiency NOx emissions of less than 1 ppm are reported with the use of a normal three way catalyst in stoichiometric operation – Natkin et al. (2003). If a hydrogen engine is designed for single speed/power operation, e.g. for stationary power generation or for a series hybrid vehicle, very clean and highly efficient operation is possible without any after treatment (of which the effectiveness could deteriorate with time). NOx emissions below 10 ppm or even 1 ppm, with indicated efficiencies of perhaps 50 % are possible - Smith et al. (1995), Van Blarigan (1996), Aceves and Smith (1997). Hydrogen is the only fuel with which this is possible (with hydrocarbons, decreasing NOx emission with lean burn implies increased unburned hydrocarbon emissions).

D. Hydrogen SI engines

Here, an attempt is made to provide a comprehensive overview of engine design features that make the most of hydrogen's advantages and counter its disadvantages.

- Spark plugs: use cold rated spark plugs to avoid spark plug electrode temperatures exceeding the autoignitionlimit and causing backfire – Das (2002), Kondo et al. (1997).
- Ignition system: avoid uncontrolled ignition due toresidual ignition energy by properly grounding theignition system or changing the ignition cable's electrical resistance - TÜV Rheinland (1990), Kondoet al. (1997).
- Injection system: provide a timed injection, either using port injection and programming the injectiontiming such that an initial air cooling period is created in the initial phase of the intake stroke and the end ofinjection is such that all hydrogen is inducted, leaving no hydrogen in the manifold when the intake valve closes; or using direct injection during the compression stroke.
- Hot spots: avoid hot spots in the combustion chamberthat could initiate pre-ignition or backfire, use cooledexhaust valves; use multi-valve engine heads to further lower the exhaust valve temperature – Stockhausen et al. (2002), Swain et al. (1988), TÜV Rheinland (1990).
- Piston rings and crevice volumes: decrease the piston top land clearance to prevent hydrogen flames frompropagating into the top land.

- Valve seats and injectors: the very low lubricity of hydrogen has to be taken into account, suitable valveseat materials have to be chosen – Stockhausen et al. (2002), TÜV Rheinland (1990), and the design of theinjectors should take this into account.
- Lubrication: an engine lubrication oil compatible with increased water concentration in the crankcase has tobe chosen.
- Crankcase ventilation: positive crankcase ventilation is generally recommended due to unthrottled operation(high manifold air pressures) and to decrease hydrogen concentrations (from blow by) in the crankcase - Stockhausen et al. (2002), Strebig and Waytulonis (1987).
- Compression ratio: this should be chosen as high as possible to increase engine efficiency, with the limitgiven by increased heat losses or appearance of abnormal combustion (in the case of hydrogenprimarily pre-ignition).
- In-cylinder turbulence: because of the high flame speeds of hydrogen, low turbulence combustion chambers (pancake or disk chamber and axially aligned symmetric intake port) can be used which are beneficial for the engine efficiency – Swain et al. (1988), Swain et al. (1996), Van Blarigan (1996).
- Electronic throttle: as stated above, hydrogen engines should be operated at wide open throttle whereverpossible, but throttling is needed at very low loads to maintain combustion stability and limit unburned.
- Hydrogen emissions. At medium to high loads, throttling might be necessary to limit NOx emissions. This can only be realized with a drive-by-wire system

Advantages Of Hydrogen For Sparkignition Engines

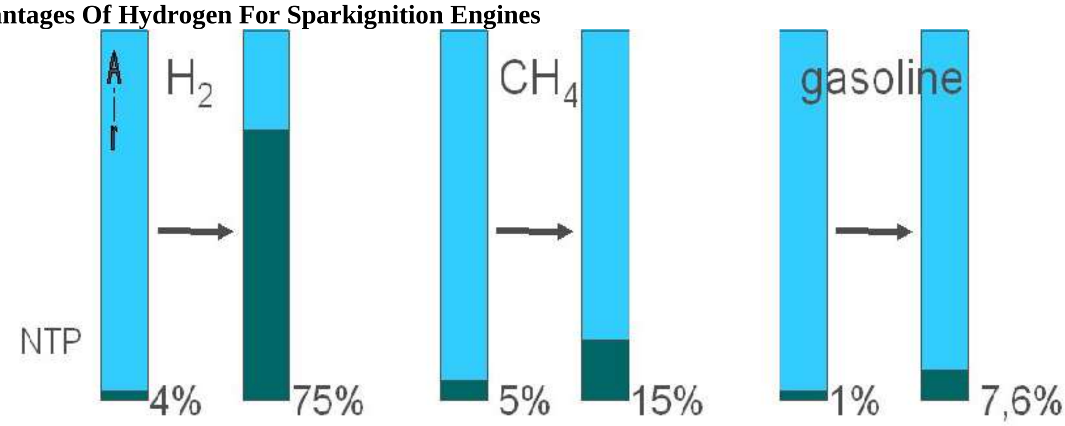

Fig 1: Flammability limits for air with hydrogen (H2), air with natural gas (CH4) and air with gasoline

Fig. 1 gives the flammability limits for different fuels at normal temperature and pressure. A scan be seen the flammability limits (= possible mixture compositions for ignition and flame propagation) are very wide for hydrogen (between 4 and 75% hydrogen in the mixture) compared to gasoline (between 1 and 7.6%). This means that the load of the engine can be controlled by the air to fuel ratio, as for diesel engines. Nearly all the time the engine can be run with a wide open throttle, resulting in a higher efficiency.

The second advantage of hydrogen for SI engines is the high burning velocity. For near stoichiometric mixtures (near $\lambda = 1/ \varphi = 1$) the combustion is almost a constant-volume combustion, which increases the (thermodynamic) efficiency. Also the properties of lean hydrogen flames will cause flame acceleration due to cellularity and no turbulence enhancing methods have to be used (swirl ports, etc.). Again this increases the efficiency of the engine. Furthermore, hydrogen has a high octane number and the compression ratio of the engine can be increased. This, of course, increases the efficiency. Finally the emissions of a hydrogen engine are very clean, only the noxious component NOx is emitted.

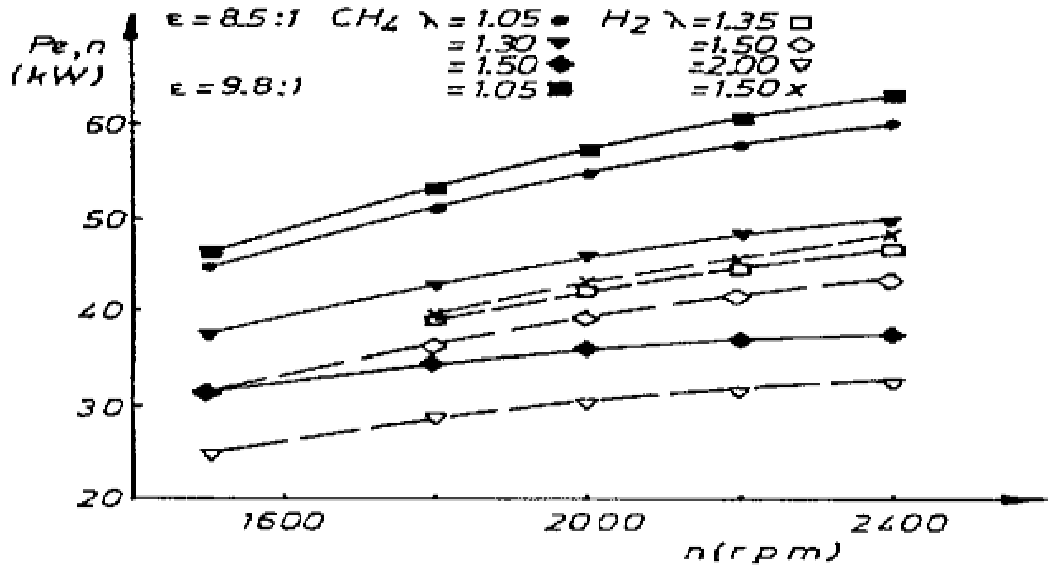

Fig 2: Power output of the Valmet engine fuelled with natural gas or hydrogen

It is clear that the Valmet engine with the gas carburettor is of the first generation. These tests have proved that it is not difficult to run an engine on hydrogen (under lean conditions). But it has shown at the same time that special attention is necessary for the power output, the NOx emissions and the backfire problem. The original Valmet diesel engine has a power output of 64 kW, which can be reached also with natural gas (CH4) but not at all with hydrogen (due to the lean conditions to avoid backfire), see Fig. 2 – Sierens (1992, 1993). Figure 3 shows the NOx emissions again for natural gas and hydrogen – Sierens (1992, 1993).

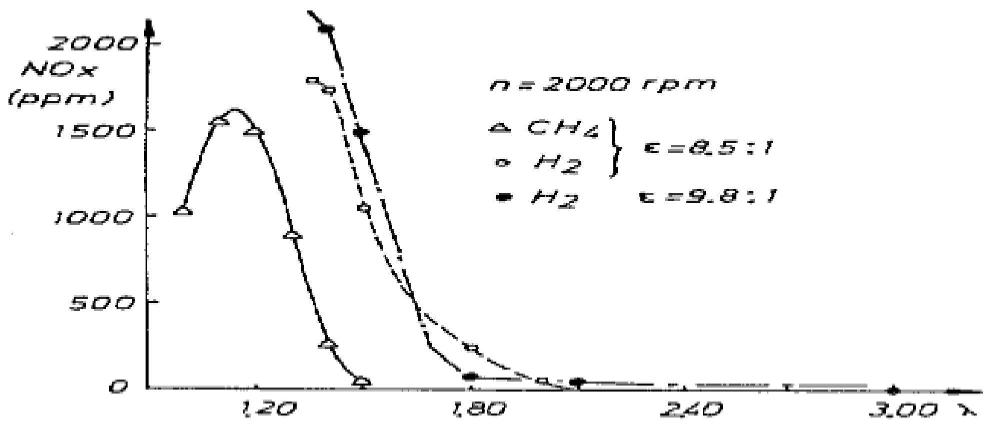

Fig 3: NOx emissions of the Valmet engine

IV. Conclusions

This paper has indicated the advantages of hydrogen as a fuel for spark ignited internal combustion engines and has shown that the hydrogen engine is growing up. An overview is given of the development by car manufacturers and also of the research at the laboratory of Transport Technology, Ghent University. Finally an extended overview is given of the design features in which a dedicated hydrogen engine differs from traditionally fuelled engines.

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