

Effects of Supercharging, EGR and Variable Valve Timing on Power and Emissions of Hydrogen Internal Combustion Engines

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ABSTRACT

Hydrogen-fueled internal combustion engines equipped with port fuel injection offer a cheap alternative to fuel cells and can be run in bi-fuel operation side-stepping the chicken and egg problem of availability of hydrogen fueling station versus hydrogen vehicle.

Hydrogen engines with external mixture formation have a significantly lower power output than gasoline engines. The main causes are the lower volumetric energy density of the externally formed hydrogen-air mixture and the occurrence of abnormal combustion phenomena (mainly backfire).

Two engine test benches were used to investigate different means of compensating for this power loss, while keeping oxides of nitrogen (NO_x) emissions limited. A single cylinder research engine was used to study the effects of supercharging, combined with exhaust gas recirculation (EGR). Supercharging the engine results in an increase in power output. The combination with EGR permits stoichiometric operation and thus low NO_x emissions because of the resulting high aftertreatment efficiency. Furthermore, the power output can be varied through the supercharging pressure and the EGR percentage, enabling throttle-less operation and thus higher engine efficiencies.

A four-cylinder production gasoline engine was converted to bi-fuel operation and was used to study the effects of continuously variable intake valve timing on power output, efficiency, emissions and the occurrence of backfire when operated on hydrogen. The engine efficiency on hydrogen is compared to gasoline operation.

INTRODUCTION

Greenhouse gas emission by the transport sector is a hot topic these days. There is a strong drive towards legislation limiting the fleet average CO_2 emissions [1].

The use of hydrogen as an energy carrier is one option with the potential of lowering CO_2 emissions investigated by the vehicle manufacturers. However, affordable fuel cell vehicles seem to be a long way off [2]. An interesting alternative is using hydrogen in internal combustion engines (ICEs). Next to being less expensive, hydrogen-fueled ICEs offer a number of other benefits of which the most practical one is the ability to run in bi-fuel or flex-fuel operation. These benefits, and experimental research on hydrogen-fueled ICEs is reviewed by the authors elsewhere [3].

Although hydrogen ICEs have shown remarkable progress in the last decade, some problems remain. First, even though measures can be taken to avoid abnormal combustion (glow ignition, backfire, knock), there is no given set of measures with guaranteed success. Backfire (the ignition of the hydrogen-air mixture during the intake process) can be particularly difficult to predict and control.

Second, hydrogen ICEs have a very strong power output versus NO_x emissions trade-off. At part load, the wide flammability limits of hydrogen-air mixtures allow lean mixtures and wide open throttle (WOT) operation, regulating power output through varying the equivalence ratio. This avoids throttle losses and increases engine efficiency. However, using this approach means richer mixtures (lean of stoichiometric) as the load increases, and correspondingly, increasing combustion temperatures. When going richer than some threshold equivalence ratio, peak cylinder temperatures exceed the NO_x formation temperature and NO_x emissions quickly rise, with maximum NO_x emissions higher than for gasoline operation, because of the higher adiabatic flame temperature and rapid combustion of hydrogen mixtures.

This threshold equivalence ratio depends on the engine and varies between about $\lambda = 1.8$ ($\phi = 0.56$) and $\lambda = 2.2$ ($\phi = 0.45$), with λ the air-to-fuel equivalence

ratio and ϕ the fuel to air equivalence ratio ($\phi = 1/\lambda$). This implies that the region between stoichiometric and the threshold equivalence ratio is to be avoided, as exhaust gas aftertreatment to reduce NO_x emissions is ineffective because of the excess of oxygen in the exhaust gas. For loads above the WOT threshold equivalence ratio condition, an approach using stoichiometric mixtures and throttling is required. Although engine efficiency suffers, exhaust gas aftertreatment is straightforward using a conventional three-way catalyst (TWC).

An alternative to the stoichiometric + throttling strategy is to regulate the power output using exhaust gas recirculation (EGR) and stoichiometric mixtures. Power output is then increased by decreasing the EGR percentage. This is possible because of the high EGR tolerance of hydrogen mixtures and increases efficiency compared to the stoichiometric + throttling strategy through decreased pumping losses [5]. However, the increasing combustion instability for high EGR percentages can be a practical limit [4].

Finding means to maximize engine efficiency is very important for H_2 ICEs considering the H_2 on-board storage challenge. This can lead to another trade-off, of efficiency versus maximum power output, as at full load H_2 ICEs lose the efficiency benefit over gasoline engines.

The easiest way to introduce hydrogen ICEs is by converting a gasoline engine to bi-fuel operation, by mounting a hydrogen fuel system and gas injectors. Starting from a gasoline engine implies port fuel injection (PFI) of the hydrogen. Therefore, this paper concentrates on hydrogen PFI engines, although dedicated hydrogen engines would benefit greatly from direct injection [3].

A PFI hydrogen engine operating stoichiometric at WOT, has a theoretical power deficit of about 15% compared to a gasoline engine, due to the lower volumetric energy density. In practice, the power deficit can be even higher if the equivalence ratio has to be limited to avoid abnormal combustion. Variable valve timing has been used to enable hydrogen engines to run stoichiometric without backfire [5], through better scavenging of hot exhaust gases. Supercharging is a means to further increase the power output, to gasoline levels or higher.

Natkin et al. at Ford [6] report work on a supercharged 2.3 liter PFI engine. Using a standard (air to air) intercooler and a fixed equivalence ratio of $\lambda = 2$ ($\phi = 0.5$) so that aftertreatment is not necessary, resulted in a torque deficit of 28% compared to the base (naturally aspirated) gasoline engine. Going richer (the exact equivalence ratio was not specified) and adding an extra air-conditioning to air intercooler was necessary to restore the torque level to that of the gasoline engine. What this did to the NO_x emissions was not given in the paper. In the recently

introduced Ford E-450 H_2 ICE vehicles, a 6.8 liter supercharged PFI engine is used at a lean equivalence ratio (not specified) eliminating the need for aftertreatment [7]. The engine has a maximum power output of 173 kW and maximum torque of 420 Nm.

Berckmüller et al. at BMW [5] report work on a supercharged stoichiometric H_2 engine, reaching peak power outputs of about one third above that of an atmospheric gasoline engine. Compared to the naturally aspirated case, they had to lower the compression ratio from 12 to 11:1 when charging to 0.85 barg to enable stoichiometric operation without the occurrence of pre-ignition. The cylinder head coolant flow and the valve timing were optimized to minimize pre-ignition tendencies.

White et al. [8] present a review of H_2 ICEs in which they discuss work on boosted H_2 ICEs, concluding that such engines are a compelling alternative to fuel cells when used in a series hybrid vehicle, at lean equivalence ratios so that very low emissions are reached without any aftertreatment.

At Ghent University, two PFI hydrogen engines were supercharged in an effort to increase the power output. For one of the engines (Valmet 4.4 liter four cylinder) this was unsuccessful as the occurrence of backfire necessitated leaner mixtures, effectively resulting in the same power output as the atmospheric engine [9]. For the other engine (GM 7.4 liter V8), maximum torque output could be increased by 60% compared to the atmospheric case. The increase in power output was less substantial as leaner mixtures were necessary at the higher engine speeds to avoid backfire [10].

Other work at Ghent University on a CFR type engine was focused on NO_x reduction by using a three-way catalyst at stoichiometric operation and regulating load by varying the amount of recycled exhaust gas. Results are reported in ref. [4]. For an efficient NO_x reduction, mixtures slightly rich of stoichiometric should be used so that the small amount of excess hydrogen can act as a reducing agent in the TWC.

The current paper reports measurements on two hydrogen engines. On one engine, supercharging and EGR are combined to increase power output while limiting NO_x emissions, on the other engine the effects of intake valve timing on backfire and internal EGR is investigated. In the following, the test set-ups are described and experimental results are presented.

EXPERIMENTAL

SINGLE CYLINDER ENGINE – The single cylinder two valve engine used in this study is based on a Audi-NSU research engine. It has a swept volume of 400cc. The compression ratio was set at 11:1 by machining a DI diesel piston. The engine is coupled to a DC motor and

is operated between 1500 and 4500 rpm. Two Teleflex GSI gas injectors are used for port fuel injection of gaseous fuels. Fuel (hydrogen) is supplied at 2 barg. Fuel mass flow is measured using a Bronkhorst Hi-Tec sensor.

A large damper vessel (600 liter) is used between the air inlet and the engine, to allow intake air mass flow measurements (strongly pulsating flow) with a second Bronkhorst Hi-Tec sensor.

The test bench is equipped with a Zepher air blower driven by an electric motor which is fed by an inverter, allowing supercharging the engine up to 0.5 barg (independent of engine speed and load). The blower is placed between the air intake and the damper vessel. Additionally, an intercooler is placed between the air blower and the damper vessel.

Exhaust gas can be recirculated (EGR) from the exhaust to the intake of the blower. Although this is probably detrimental to the air blower's life expectancy because of the water vapour content of the exhaust gases, this set-up was chosen to avoid the complexity of high pressure loop EGR (supercharging+EGR combination).

A MoTeC M4Pro engine control unit is used to control ignition timing, start of injection and injection duration. A cold rated spark plug with a silver central electrode was used to minimize spark plug hot spots and catalytic reactions.

FOUR CYLINDER ENGINE - A Volvo four cylinder sixteen valve gasoline engine with a total swept volume of 1783cc and a compression ratio of 10.3:1 was converted to bi-fuel operation by mounting an additional fuel rail supplying gaseous fuel to 8 (2 per cylinder) Teleflex GSI gas injectors, mounted on the intake manifold. The intake manifold was modified to avoid any damage if backfire would occur during the hydrogen measurements: a T-type branch pipe was mounted on the intake manifold with the 'straight ahead' branch closed by a foam plug and the other branch leading to the air filter – mass air flow (MAF) sensor – throttle valve assembly, see Fig. 1. Any pressure rise in the intake manifold due to the occurrence of backfire results in the foam plug being blown out instead of damaging other components such as the MAF sensor.

The engine has continuously variable valve timing (CVVT) on the intake camshaft, allowing up to 40 degrees crank angle ($^{\circ}\text{ca}$) advance of the intake valve opening and closing time.

A MoTeC M800 engine control unit is used to control ignition timing, start of injection, injection duration and intake valve timing.

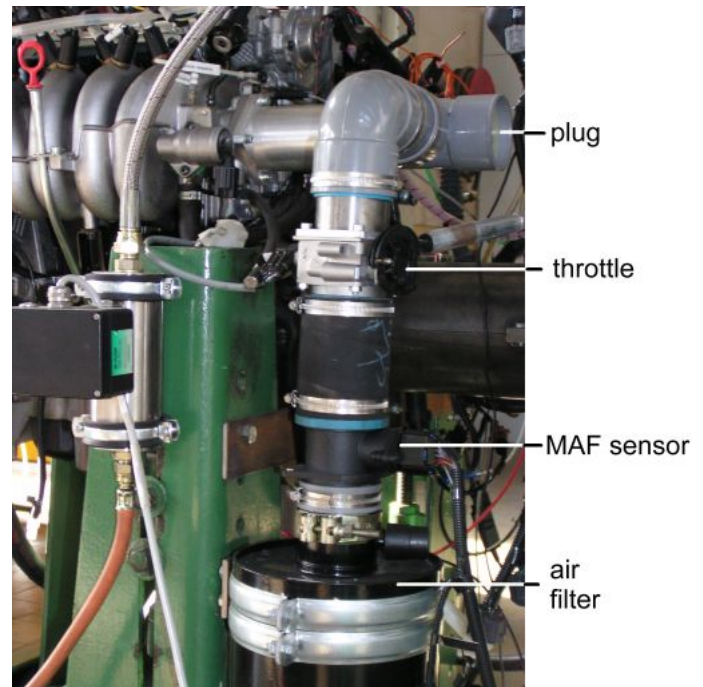


Figure 1. Modified intake of four cylinder engine

EMISSIONS - The exhaust gas components O_2 , CO , CO_2 , NO , NO_x and H_2 are measured. A direct reading of the air to fuel equivalence ratio λ is given by a Bosch wide band sensor and digital air/fuel ratio meter with calibrations for hydrogen and gasoline.

PRESSURE MEASUREMENTS - In-cylinder pressure measurements are recorded using a Kistler type 6125B piezoelectric sensor on the single cylinder engine and a Kistler type 6117BFG16 spark plug with integrated piezoelectric sensor on the four cylinder engine. A piezoresistive pressure sensor, Kistler type 4075A20, mounted as close to the intake valve as possible, is used for pressure referencing.

SAFETY - Both test benches have a tapered roof with a Buveco Bucom ST600EX hydrogen sensor located at the highest point. As an additional safety measure for the supercharging experiments, a small controlled flow is taken from the damper vessel (less than 0.5% of the intake flow) through a flow controller and pressure reduction valve to another ST600EX hydrogen sensor. This set-up is necessary as most commercial hydrogen sensors can not handle strong pressure fluctuations or overpressure. The monitoring of hydrogen concentration in the (large) damper vessel precludes any build-up of a combustible mixture in the supercharged vessel.