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POTENTIAL OF A SUPERCHARGED PORT FUEL INJECTED HYDROGEN ENGINE

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ABSTRACT

In view of the ever more stringent exhaust gas regulations, attention is turned to new or improved engine technology and new fuels. An alternative gaseous fuel such as hydrogen offers the potential of very clean emissions. Even more interesting is the reduction of CO_2 emissions, widely held responsible for the global warming of the planet. The authors are conducting a study on a single cylinder research engine. The standard test engine is modified to provide reliable operation with hydrogen. The engine parameters (ignition timing, injection start and duration) are optimised for hydrogen operation.
In this paper, supercharging and a combination of supercharging and EGR is studied with the aim of increasing the power output of a hydrogen PFI engine with NOx emissions as a restriction.

KEYWORDS: hydrogen, powertrain, NO_X emissions

1 INTRODUCTION

Hydrogen can be used as an energy carrier, with the potential to lower greenhouse emissions, increase energy security and decrease or eliminate vehicle emissions.
Spark ignition engines can be relatively easily converted to hydrogen using port fuel injection (PFI). However, because of the lower volumetric energy density of a hydrogen-air mixture and the occurrence of abnormal combustion phenomena such as backfire, hydrogen-fueled PFI engines suffer from a power deficit in comparison with gasoline engines [1].
With a naturally aspirated, PFI hydrogen engine, the NOx emissions are a trade-off against the engine power output. At low loads, wide open throttle operation is possible, beneficial for the engine efficiency. As long as the air-to-fuel equivalence ratio remains above a value of around 2 (specific values depend on the type of engine), NOx emissions are near-zero. For richer mixtures the NOx emissions rise very steeply. For higher loads, it is thus required to throttle and to operate stoichiometric. With stoichiometric mixtures, after-

treatment of the exhaust gases is possible, using a three way catalyst (TWC). When using this strategy, higher power outputs are possible, while losing in efficiency [2].
Instead of throttling in order to have a stoichiometric mixture, exhaust gas recirculation (EGR) can be used. With EGR, a part of the exhaust gases is brought back into the cylinder, diluting the fresh charge. Therefore, the peak cylinder temperatures are lower, so NOx formation is reduced. After-treatment with a TWC is also possible. The power output is then determined by the amount of EGR. Because of the lower pumping losses, due to the WOT operation, efficiencies reach higher values [2].
For hydrogen PFI engines to achieve a similar power output as gasoline ICEs, supercharging can be used [3,4,5].
There are two options: either the air-fuel mixture has to be kept lean enough, so that NOx formation stays limited. The air to fuel ratio at which the NOx emissions reach a value of 100 ppm (the threshold value) depends on the supercharging pressure. By using this method, power output is increased by increasing the charging pressure.
The other option is a strategy that combines EGR and supercharging, so that the engine can run stoichiometric. Because of the diluting effect and the possibility to use a TWC, NOx emissions do not exceed the limit of 100 ppm. The EGR also diminishes the risk of abnormal combustion. Therefore, high output power and high efficiencies are achieved.

2 TEST RIG

2.1 Engine

An Audi-NSU diesel engine is adapted to the use of hydrogen. The specifications of the engine are:

- single cylinder
- bore: 77.02 mm
- stroke: 86.385 mm
- swept volume: 402.471 cm³
- number of valves: 2
- compression ratio: 11:1
- engine speed: 1500-4500 rpm
- EVO 75° ca. BBDC
- EVC 10° ca. ATDC
- IVO 23° ca. BTDC
- IVC 50° ca. ABDC

Because the engine was originally a direct injection diesel engine the injector could be replaced by a spark plug. The spark plug has a very low heat rate (cold type) in order to prevent hot spots (backfire danger) and has a silver electrode instead of the more commonly used platinum-tip spark plugs. Platinum is a catalyst, causing hydrogen to oxidize with air. The original compression ratio of 16:1 is reduced to 11:1.
The cooling water, which in turn is cooled by tap-water, is circulated by a Grundfos central heating pump. The temperature of the cooling water is chosen quite low (75°C) to avoid pre-ignition. This of course has a limited negative effect on the efficiency (more thermal losses). The engine is connected to an electric DC-motor. The engine is started up by the DC-motor. After increasing the fuel rate the engine will drive the DC-motor that will then work as a brake. A coil on plug ignition (direct ignition) is used, because this type enables higher ignition voltages (cf. lean mixtures) and considerably reduces the risks of electromagnetic disturbances.

2.2 Fuel and air supply

An injection system, placed in the inlet manifold close to the inlet valve, was implemented. The injector is a very compact GSI (gaseous sequential injection) injector from Teleflex Ltd. The fuel is supplied from a steel bottle with compressed hydrogen at 200 bar. The gas is expanded in two pressure reducing valves, placed in series, and then admitted to a reservoir. This reservoir damps the oscillating fuel flow, thus making a reliable measurement of the fuel flow rate possible. A Bronkhorst flow meter is placed upstream of the reservoir.
The air flows via an air filter, a flow meter (Bronkhorst) and a buffer vessel into the engine. The barrel is needed to damp the pulsations of the incoming air (cf. single cylinder), which is essential in order to measure the air flow rate.

2.3 Instrumentation

The engine is controlled by a MoTeC M4 Pro engine management system. The main function of the ECU is to appoint the correct injection duration, injection timing and ignition timing as a function of the primary parameters engine speed and load. These relations are stored in three dimensional mappings. Instead of regulating the power with a gas throttle, power can be regulated by changing the air-fuel ratio (cf. wide flammability limits). The desired load is dictated by a potentiometer that is connected to the MAP-sensor input. Secondary parameters like air temperature, fuel temperature, engine temperature, supply voltage… can correct the values selected from the mappings. It’s possible to change mappings on-line with a PC when running the engine.

Besides the usual sensors for measurement of coolant temperatures, exhaust gas temperature, torque, gas flow rates… a Bosch sensor (wide band λ-sensor) is installed. This sensor needed to be calibrated thoroughly because the normal working range of the sensor ($0.7<\lambda<2.2$) is exceeded during engine tests. The exhaust gas components are measured with the following methods of measurement: CO-CO2-NO-NO2 (non dispersive infra red); O2 (paramagnetic); HC (flame ionization); H2 (thermal conduction).

Safety is of course a very important issue when working with hydrogen. Therefore a hydrogen detection sensor is placed on the buffer vessel (air intake), preventing the formation of flammable mixtures. Several emergency switches are placed around the test rig. A blow-by meter from AVL is implemented. This sensor allows monitoring the condition of the engine continuously. If one of these measures gives a warning the hydrogen supply is shut down immediately. Previous tests show that there is a chance to form flammable mixtures in the crankcase because of the very small H2 molecule (higher blow-by volumes) and the broad flammability limits. Therefore crankcase gases are diluted by means of additional air, so that the maximum H2 concentration is always below 1 %.

3 RESULTS

3.1 Atmospheric conditions

First, some results at atmospheric conditions are shown to set a baseline for the supercharging experiments. A threshold equivalence ratio, defined as the equivalence ratio where NO_x emissions reach 100ppm, of $\lambda \sim 2$ was found for this engine. This threshold shifts to slightly richer mixtures at high engine speeds, as the time for NO_X formation decreases.

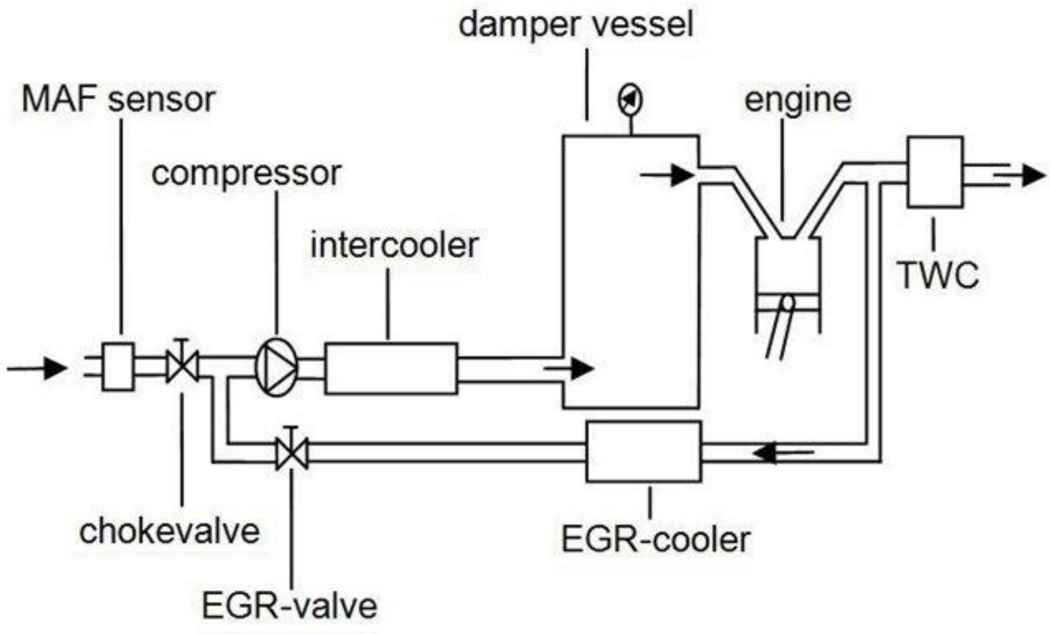

Figure 1. Single cylinder engine bench layout

The maximum brake mean effective pressure (bmep) at stoichiometric is only 6.5 bar. However, the volumetric efficiency for this engine is very low, due primarily to the air mass flow meter and extensive piping before and after the damper vessel (see Fig. 1).
When determining the optimal ignition timing (MBT, minimum spark advance for best torque), it was found that timings to reduce NO_X emissions also benefit backfire resistance: lowering the peak temperatures also leads to less hot spots in the engine. Stoichiometric operation was possible with late (after TDC) ignition.

Figure 2 shows the MBT ignition timing as a function of air to fuel equivalence ratio, for different engine speeds, at wide open throttle. The large range in equivalence ratio leads to a large range in burning velocities, with lean, slow burning mixtures requiring more spark advance. The effect of engine speed is most obvious for the lean mixtures, where more spark advance is needed when less time is available (higher engine speed) and burning velocities are relatively low. Near stoichiometric, the burning velocities of hydrogen are so high [6] that there is hardly any influence of the engine speed on MBT timing.

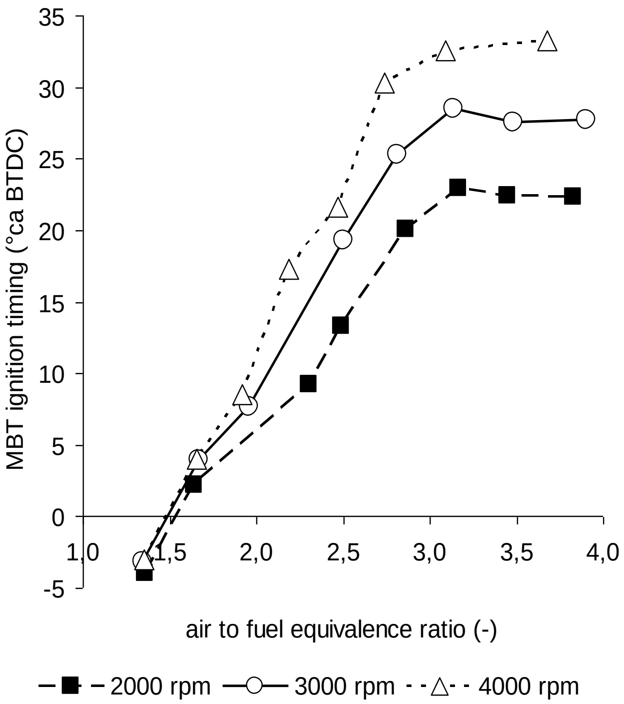

Figure 2. MBT ignition timing as a function of air to fuel equivalence ratio, for different engine speeds, WOT.

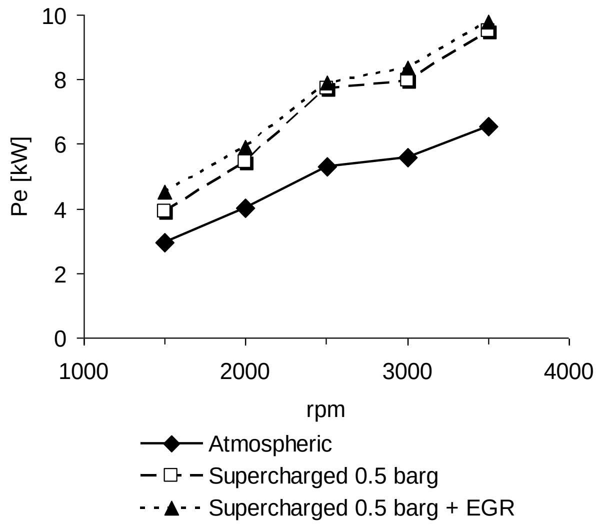

Figure 3. Brake power as a function of engine speed. WOT, atmospheric operation at stoichiometric; supercharged operation at backfire/pre-ignition limited equivalence ratio (λ=1.3-1.4); and supercharged operation with EGR at stoichiometric (λ=1).

3.2 Supercharging conditions

Supercharging is a straightforward way to increase the power output of PFI hydrogen engines. However, as in-cylinder mixture densities are increased the likelihood of hot spot formation also increases.

Initial experiments on the supercharged single cylinder engine were aimed at determining any power benefit. All measurements reported in this section were with a supercharging pressure of 0.5 barg (measured in the damper vessel). Figure 3 shows the resulting maximum power output as a function of engine speed. The net power output for the supercharging experiments (accounting for the power needed to drive the air blower) is compared to the power output for the atmospheric experiments. The dip at 3000 rpm is due to a drop in volumetric efficiency for this intake configuration.

Supercharging results in a net power increase of about 40%. This is somewhat less than what could be expected from the supercharging pressure (given that the intercooler is over dimensioned), but is easily explained as stoichiometric operation was no longer possible when supercharging. The air to fuel equivalence ratio λ was now limited to 1.3 to 1.4, because of backfire or pre-ignition. This essentially means that the power increase cannot be used because of the resulting high NO_X emissions in an oxygen-rich environment. Recycling part of the exhaust gases is a means to displace some of the intake air and enrich the mixture, so experiments with EGR were done to determine the possibility of running stoichiometric at supercharged conditions.

Figure 3 shows the (net) maximum power output as a function of engine speed when exhaust gas recirculation is used while supercharging. Stoichiometric operation is now possible without backfire or pre-ignition events, through increasing both the injected fuel quantity and the EGR rate. The high heat capacity of the recycled exhaust gases (with a high water vapor content) is the reason why the fueling rate can be increased without abnormal combustion phenomena. As a result, not only is stoichiometric operation now possible with efficient NO_X after treatment, but furthermore the power output can be seen to increase slightly. This results in a net power increase of almost 50%.

After these initial results, another supercharger was installed so that higher charging pressures could be reached. First, 'lean burn' experiments were conducted at an engine speed of 2000 rpm and WOT at charging pressures from 0 barg (atmospheric) to 1 barg. Measurements were taken with charging pressure steps of 0.2 barg. At these measuring points, the richness of the mixture at which the NO_X emissions remained just below the NO_X limit of 100 ppm was determined. For every charging pressure, the torque that corresponds with this λ, is the maximum torque that could be reached, with the NO_X limit as a restriction. The results of the experiments are shown in Fig. 4. All brake torque numbers given in this section are net values, accounting for the energy needed for the supercharging.

As can be seen in Fig. 4, the minimal richness of the mixture, to keep NO_X emissions below the threshold, decreases (λ increases) as the charging pressure increases. If the air-to-fuel equivalence ratio would not have been increased, the cylinder temperature would increase, accelerating NO_X formation, resulting in NO_X emissions higher than 100 ppm. Although the mixture richness decreases, brake torque increases with increasing charging pressure. A maximum brake torque of 23.9 Nm is reached at the maximum charging pressure (for the current tests) of 1 barg with λ = 2.5.

For atmospheric operation the torque output is 13.3 Nm with λ = 1.9. At lean operation, supercharging up to 1 barg thus results in a net torque increase of 80%.

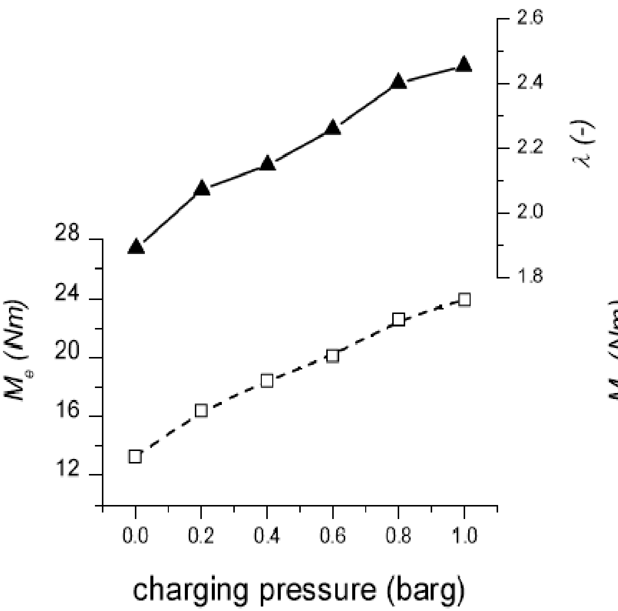

Figure 4. Supercharging at the NO_X threshold, using the WOT lean burn strategy: brake torque and air-to-fuel equivalence ratio as a function of the charging pressure.

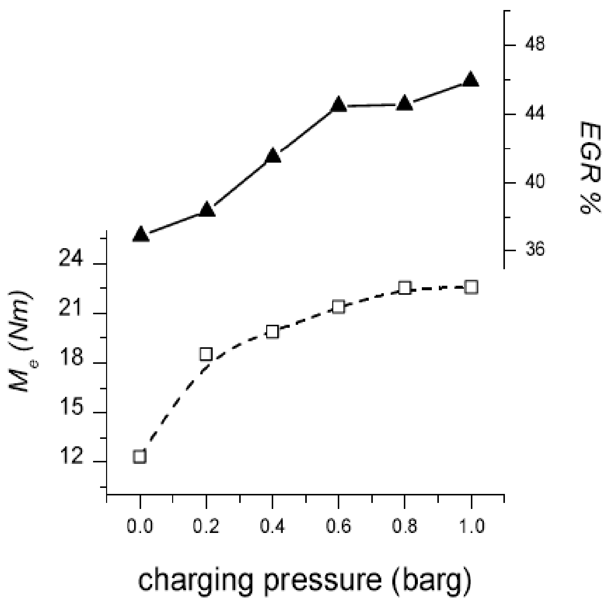

Figure 5. Supercharging at the NO_X threshold, using the stoichiometric + EGR strategy: brake torque and EGR percentage as a function of the charging pressure (λ = 1).

As stated above, when combining supercharging with EGR, stoichiometric operation becomes possible. This is due to the diluting effect of the exhaust gases, as a result of which NO_X formation is reduced. Stoichiometric operation allows for the use of a TWC. However, with this engine configuration, it was not possible to run at λ = 1 with

supercharging and without EGR. Because of safety reasons (buffer vessel and low pressure EGR loop, and the safety system reacting too slow), the air-fuel mixture was set slightly lean, with λ ~ 1.07, so that recirculation of unburned hydrogen is avoided. As with lean operation, measurements were taken at an engine speed of 2000 rpm with charging pressures varying from 0 to 1 barg. For this range of charging pressure, the amount of EGR was set so that NO_X emissions after conversion (i.e. after the TWC) remained just below the NO_X limit. Thus, with NO_X emissions as a restriction, the corresponding brake torque is maximal at this EGR percentage for a particular charging pressure.
Figure 5 shows the brake torque and EGR percentage as a function of the charging pressure.
In order to keep the cylinder peak temperature and NO_X formation limited, the EGR percentage increases with increasing charging pressure, with a maximum of nearly 46% at a charging pressure of 1 barg. Similar to the lean operation, the brake torque increases when increasing the charging pressure. At atmospheric operation, the brake torque is 12.3 Nm, with an EGR rate of about 37%. At 1 barg a maximum torque of 22.6 Nm is reached. Supercharging in combination with EGR, results in a power increase over atmospheric operation (λ = 1) of nearly 85%.

Figure 6 shows the brake torque (see also Figs. 4 and 5) and efficiency for both methods. For the whole pressure range, the efficiency of the lean burn strategy exceeds the efficiency of the λ = 1 (actually 1.07) + EGR operation. This is due to the higher power needed for supercharging of the mixture of EGR and fresh charge at EGR operation, as a result of the higher temperature at the inlet of the compressor. The brake torque that could be achieved is similar for both methods. At 1 barg, where the maximum torque for both methods is reached, the torque at lean operation exceeds the torque at EGR operation.

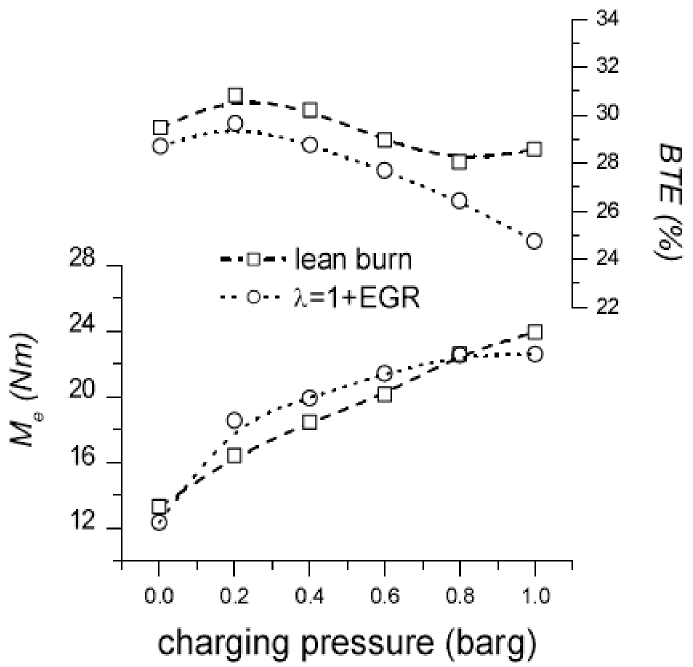

Figure 6: Comparison of brake torque and efficiency as a function of supercharging, between lean burn operation and stoichiometric+EGR operation, at the NO_X threshold.

When deviating from stoichiometric operation, as done here for safety reasons, the conversion efficiency of the TWC decreases drastically. Therefore, when taking the 100 ppm tailpipe limit into account, the raw NO_X emissions (before conversion) had to be limited. This severely restricts the maximum torque. Taking into account the non-optimized TWC location, low conversion efficiencies were to be expected. When assuming a more realistic (conservative) conversion efficiency of 95% for the TWC, the restriction on the engine-out NO_X emissions are less severe (2000 ppm). As a consequence, the necessary EGR percentage decreases while brake torque and efficiency increase. At a charging pressure of 1 barg, the brake torque reaches a maximum value of 34.8 Nm. This means an increase of 46% in comparison with the maximum torque at lean operation. This brake torque of 34.8 Nm exceeds the torque of a comparable gasoline engine with almost 30%. The brake thermal efficiency is 27.9%, which is similar to the efficiency at lean burn. These results emphasize the importance of a correct λ-control.

4 CONCLUSION

The goal of this paper was to study the potential of supercharging to increase the power output of a port fuel injection hydrogen engine, while limiting NO_X emissions and maximizing efficiency.

A single cylinder research engine was supercharged, increasing the power output substantially compared to the atmospheric case. However, to avoid backfire and pre-ignition, the air to fuel equivalence ratio λ was limited to a minimum of 1.3, which would lead to unacceptable NO_X emissions. Recycling part of the exhaust gases (EGR) allowed stoichiometric supercharged operation, increasing the maximum power output to gasoline levels and higher, while still enabling efficient after treatment.

When supercharging at equivalence ratios lean of the NO_X threshold (so that after treatment is not necessary), the maximum power output at the currently used maximum supercharging pressure of 1 barg exceeded that of stoichiometric atmospheric operation. Supercharging stoichiometric mixtures, and using exhaust gas recirculation, resulted in power outputs of up to 30% higher compared to gasoline (assuming a conservative 95% TWC conversion efficiency).

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