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Aspects concerning the optimisation of a hydrogen fueled engine

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Abstract

Hydrogen fueled engines are known for several advantages, among which is the very low concentration of pollutants in the exhaust gases compared to internal combustion engines using traditional or other alternative fuels. Hydrogen driven vehicles thus reduce both local as well as global emissions. Furthermore, because of the wide flammability limits and the high flame propagation speed of hydrogen, a hydrogen fueled engine is capable of very lean combustion, allowing power regulation by varying the richness of the air–fuel mixture. Thus, better efficiency is reached because of the possibility to work without throttle valves. The Laboratory of Transport Technology (Ghent University) converted a GM/Crusader V8 SI engine for hydrogen use. A sequential timed multipoint injection system was implemented. The corresponding electronic management system was used to optimise the engine parameters (ignition timing, injection timing and duration) and to program several corrections in the case of changing working conditions (fuel pressure and temperature, inlet combustion air pressure and temperature, etc.). Finally, the goal of the development is discussed: the building-in of the engine in a city bus, with its conditions of sufficient power (90 kW) and torque output (300 N m), together with extreme low emission levels and backfire-safe operation.

Keywords: ICE; Bus; Optimisation; Ignition

1. Introduction

Several years ago, increasing interest arose in hydrogen as a fuel for transport application. In response to this, the Laboratory of Transport Technology (University of Ghent) has been and is conducting extended research on the use of hydrogen as a fuel in spark ignited internal combustion engines.

First, a naturally aspirated DI diesel engine (Valmet 420D) was converted to a spark ignited engine for the use of hydrogen. A multipoint timed injection system was implemented and several types of electromagnetic gas injectors were tested [1,2]. Several shortcomings of the injectors (leakage, unequal response time-opening delay, and low durability) as then available, have largely been solved nowadays due to the worldwide increased research on gaseous injection systems (natural gas, LPG, etc.).

After these tests, a second engine (GM/Crusader SI V8) was converted for hydrogen use. A gas carburettor was originally mounted, allowing testing with natural gas, hydrogen and mixtures of natural gas and hydrogen (hythane), the results of which are presented in [3]. The engine was then equipped with a sequential timed multipoint injection system. Such a system has well known advantages when applied to liquid fuels (gasoline, liquid LPG, etc.): the power output is increased, the air to fuel ratio of each cylinder can be tuned to a specified value and the cyclic variations are decreased. For gaseous fuels, an additional and important advantage is the better resistance to backfire (explosion of the air–fuel mixture in the inlet manifold). All these advantages have been discussed before [4–7]. A disadvantage of low pressure sequential gas injection is the low density of the gas. The injectors have to deliver a high volume of gas in a very short time, if applied to smaller engines running

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at high speeds (traction application). Other problems may arise with the durability of the injectors and possible leaks.

2. Description of the test rig

2.1. Engine

A GM 454 spark ignited engine (commonly known as the Chevrolet 'Big Block') is adapted to gaseous fuels.

The engine specifications are:

- eight cylinders in V,
- bore: 107.95 mm,
- stroke: 101.60 mm,
- swept volume: 7.4 l (454 in^3),
- compression ratio: 8.5 : 1,
- engine speed: 750–4000 rpm,
- ignition sequence: 18436572,
- EVO 93° ca. BBDC,
- EVC 62° ca. ATDC,
- IVO 42° ca. BTDC,
- IVC 95° ca. BBDC.

The engine is connected to a water (Froude) brake.

2.2. The fuel supply system

A multipoint sequential injection system was implemented to take advantage of its controlling possibilities. The fuel is supplied from steel bottles with compressed hydrogen at 200 bar. After a pressure reducing valve that expands the hydrogen to a pressure of about 3 bar, the hydrogen is admitted to a common rail system. From the common rail, eight tubes deliver the hydrogen to the eight individual injectors.

The injectors were originally developed for use with natural gas. Each cylinder has a short inlet pipe (no common inlet manifold), and the injector is located at 12 cm from the cylinder head under an angle of 45°. Fig. 1 gives a view of the installation of the injectors.

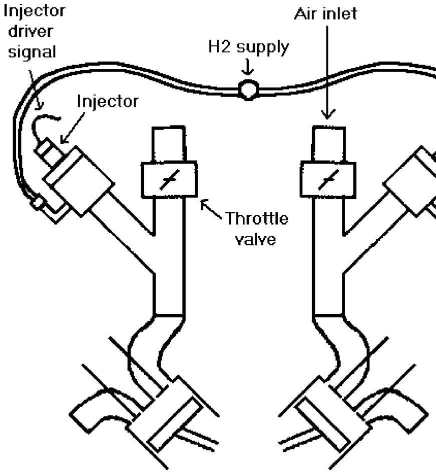

Fig. 1. View of the injection system.

2.3. Apparatus

The engine is fully equipped with the usual sensors. The measurement/control signals are read and controlled by a programmable logic controller (PLC) system. This system monitors engine speed, oil and coolant temperature, exhaust gas temperatures, etc. and shuts down the engine when necessary (by cutting off the hydrogen supply). All values are visible on a computer screen and can be stored in a Microsoft Excel worksheet.

The exhaust temperature and exhaust gas composition can be measured at the exhaust of each cylinder and at the end of each bank (V engine). Two oxygen sensors are installed at the common exhaust pipe of each bank, which allows an immediate reading of the air to fuel ratio of each bank. The oxygen sensors together with the exhaust temperatures provide the possibility of checking differences in mixture richness between the cylinders.

The exhaust gas components are measured with the following methods of measurement: CO–CO_2–NO–NO_2 (Multor 610, non-dispersive infra red); O_2 (Servomex model OA 1100, paramagnetic); HC (Signal model 3000, flame ionization); H_2 (Thermor 615, thermal conduction).

A high pressure transducer (type AVL QC32) is located in one cylinder head (mounted flush with the combustion chamber wall of cylinder 1) giving in-cylinder pressure measurements, used for the calculation of e.g. heat release analysis.

3. Optimisation of the engine parameters

The first results with the multipoint sequential injection system are already given in [8]. This paper now discusses the optimisation of the engine parameters.

One of the main problems when running a hydrogen fueled engine is backfire. In nearly all cases, backfire-safe operation implies a limitation of the operation region of the air–fuel mixture on the 'rich' side, thus for high load conditions. This restriction is decreased by the use of a multipoint sequential injection system. Direct injection in the combustion chamber, cryogenic storage (LH_2 tank) and pump is even better, but not technically available for mass production [9]. To avoid backfire, the engine is run with a lean mixture. Several tests have shown that with an air to fuel ratio λ of 2, backfire-safe operation is obtained [10]. But with such lean mixtures, the power output of the engine decreases [4]. As the engine has to be built in a city bus, a power output of 90 kW and a torque of 300 N m are the minimum conditions.

The main objective of the optimisation is thus to obtain maximum engine torque and power over the whole of the

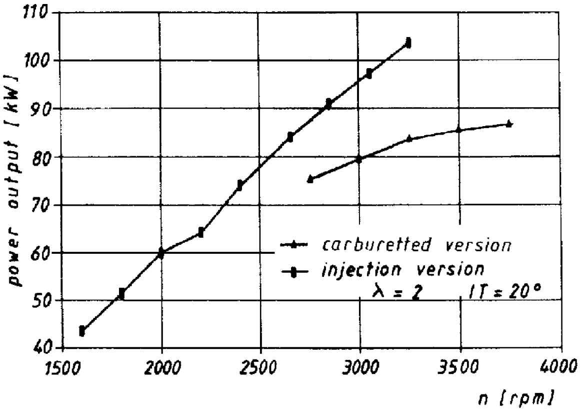

Fig. 2. Power output.

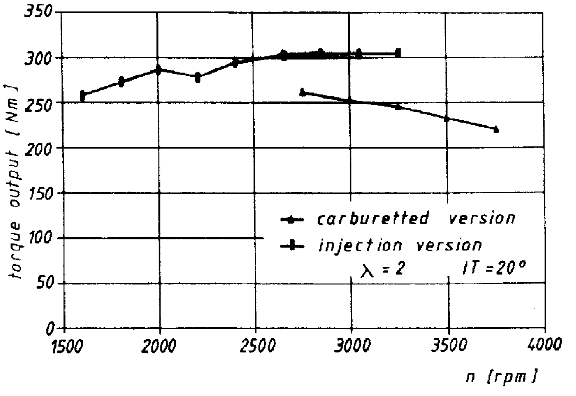

Fig. 3. Torque output.

speed range (750–4000 rpm). This optimisation is achieved with a fixed air to fuel ratio λ of 2. Figs. 2 and 3 show the power output (kW) and torque (N m) for the speed range with $\lambda = 2$ and the ignition timing (IT) set to 20° ca. BTDC. These are the initial and starting settings of the engine. For comparison, these figures also show the results with the carburetted fuel mixing system. The increase of the power output and torque for the injection version is mainly due to the better filling of the engine. These tests were performed with wide open throttle (WOT). For part load conditions the mixture is set leaner and leaner ($\lambda = 5$ is possible), as is done for diesel operation, except for idling conditions. This means that throttle valves are present, but they are only used to achieve a stable idle run. In all other conditions, there is no throttling (WOT), and the power is regulated by varying the air to fuel ratio.

Another possible optimisation strategy is towards minimum exhaust gas pollution. Although a hydrogen engine naturally is a very low emission engine, problems arose with the amount of unburned hydrogen in the exhaust gases during idle run. The possible optimisation of this emission is currently being researched.

The main engine parameters suitable for optimisation are the ignition timing, the injection timing and the injection duration. The control scheme of the motor management system is given in Fig. 4. The various parts are examined in the following paragraphs.

3.1. Ignition timing

The ignition advance is normally set to the minimum value for best torque (MBT timing). For lean mixtures (low loads and speeds), the optimum ignition timing is early, up to 50° ca. BTDC (power cycle). The engine load is the main influence. For high loads and speeds (maximum power output) the optimum ignition timing is about 20° BTDC. This is shown in Fig. 5, with the pre-ignition along the Z-axis, as a function of engine load (Y site, with the engine load proportional to the reading of a simulated MAP sensor by means of a function generator. This generator produces a square wave with adjustable frequence, as produced by an MAP sensor) and engine speed (X site).

As can be seen, the range of ignition timings is wide. One would suspect a narrow range because of the high flame speed of hydrogen. However, one must keep in mind that the engine is operated with a very wide range for the air to fuel ratio ($\lambda = 2 - 5$). The wide range of applied mixture richness is the reason for the wide range of ignition timings. It is also clear from Fig. 5, that there are only very small changes of the ignition timing over the range of engine speeds (X site) for a fixed load (Y site). Fig. 5 clearly shows that the influence of the load (thus, the mixture richness) is much more important than the engine speed.

The efficiency of a hydrogen fueled engine is very dependent on an optimally adjusted ignition timing as a function of the richness of the mixture. Even with this MBT timing the exhaust gases are very clean. The only noxious exhaust emission to consider for a hydrogen engine is NO_x. The maximum NO_x emission over the whole speed-load region was found to be about 750 ppm, occurring at a low speed, high load setting (1000 rpm, 256 N m), this is a setting with a rich mixture (high load), and a long time available for NO_x formation (low speed).

3.2. Injection duration

The engine is operated as a diesel engine: it is a spark-ignited engine but load variations are captured through variations in the richness of the hydrogen–air mixture. As a consequence, the injection duration (in degrees crank angle) is proportional to the engine load. Thus, in idling conditions, injection durations of about 3 ms are applied, corresponding to 13.5° ca. with an engine speed of 750 rpm. Under high load conditions, injection durations of up to 14 ms and more are applied, corresponding to 315° ca. with an engine speed of 3750 rpm. For comparison: the inlet valve opening time is 317° ca. A more stable idle run is reached by programming a longer injection duration

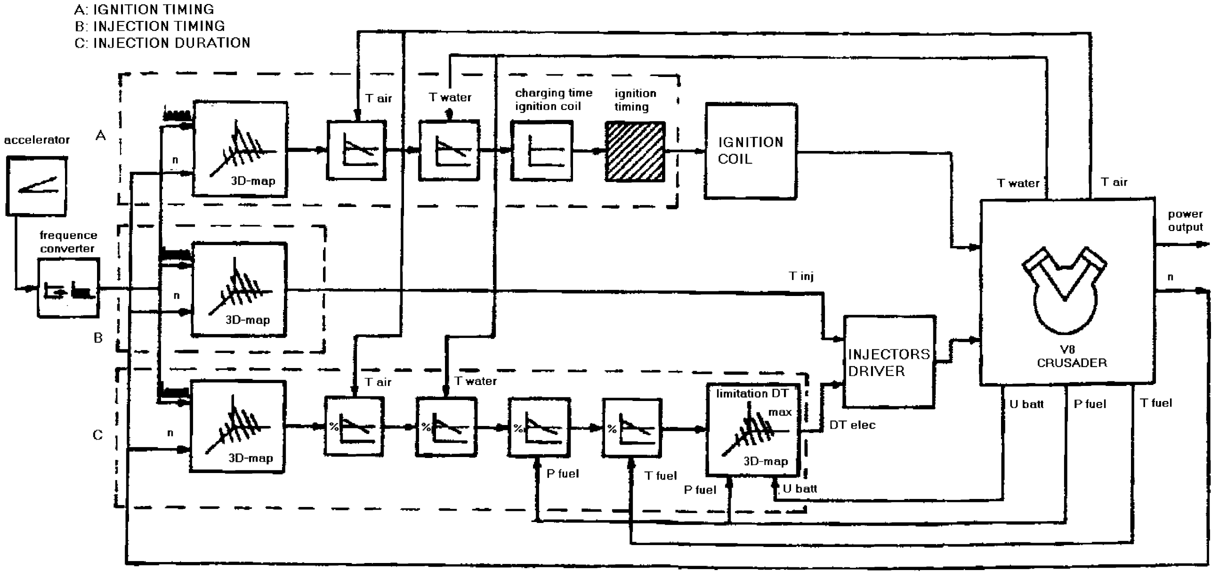

Fig. 4. Control scheme of the engine management system.

when the engine speed drops below the idle speed (which allows the engine to speed up to the idle speed again).

3.3. Injection timing

This parameter has a great impact in the lower range of engine loads and speeds. In this region, differences in power output, by varying the injection timing, of up to 20% are no exception. All optimum injections start at or before TDC (gas exchange), and should be advanced with speed increase. For example, during idling conditions the injection starts at TDC and in high speed conditions the injection timing is advanced up to 105° ca. BTDC (thus before the inlet valve opens, because of the time needed for the fuel to travel from the injector to the inlet valve, as a consequence the injection ends well before the inlet valve closes). In the higher range of engine loads and speeds, the differences in power output are still noticeable, but minimal. All injections should end before the inlet valve closes (95° ca. after BDC). 3D plots as shown in Fig. 5 are available for the injection duration and timing [11]. The injection timing can be used to avoid backfire, when the injection starts only after a period during which the inlet air can cool the combustion chamber.

3.4. Trims

The motor management system allows corrections on the values for ignition timing and, injection timing and duration as fixed in the 3D maps when the environment conditions change. Thus, changes in fuel pressure and temperature, inlet air temperature and cooling water temperature can be automatically compensated for. The calculation of the changes in density of the hydrogen fuel as a function of the fuel's temperature and pressure is taken into account in order to apply the correct injection duration. A correction of the injection duration as a function of the combustion air inlet temperature is also done.

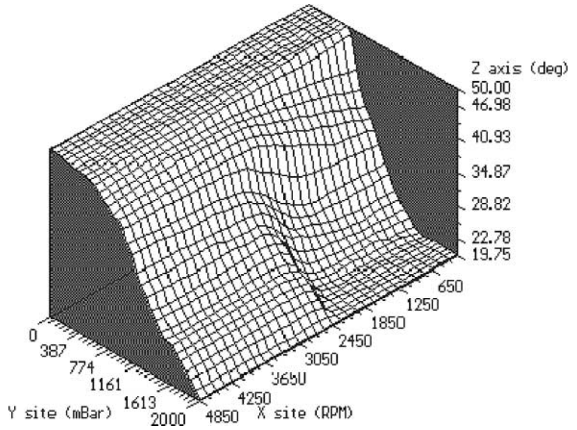

Fig. 5. Ignition timing map.

The corrected values can differ from the programmed values by a maximum of ±50%.

Other possibilities include changes in the ignition timing when the combustion air inlet temperature or cooling water temperature change. The motor management also allows the regulation of a stoichiometric mixture, but it is clear that this is not an option for a hydrogen fueled engine.

The positions in the control scheme where the trims are applied can easily be seen in Fig. 4.

4. Conclusions

- A V-8 spark ignited engine was adapted for gaseous fuels. The first tests were done with an external mixture formation system for natural gas, hydrogen and hythane.
- With a sequential timed multipoint injection of hydrogen and the corresponding electronic management system, the power output of the engine is increased without danger of backfire.
- The optimisation of the engine parameters is discussed. The ignition timing has a strong influence on the efficiency of the engine, it should be adjusted adequately as a function of the mixture richness. As a consequence of the wide range of applied mixture richness, the range of ignition timings is also wide. The injection timing has the most influence in the low load and speed region, it is not very critical in the high load and speed region. An adequate injection timing can be used to avoid backfire. The necessary corrections to the engine parameters as a function of varying working conditions are programmed in a number of trims.

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