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TITLE:

A HIGH SPEED SINGLE CYLINDER HYDROGEN FUELLED INTERNAL COMBUSTION ENGINE

Topic:

○ FUTURE AUTOMOTIVE TECHNOLOGY
○ INTELLIGENT TRANSPORTATION SYSTEMS
○ USER FRIENDLY AUTOMOBILE
○ ADVANCED PRODUCTION AND LOGISTICS
● VEHICLES & THE ENVIRONMENT

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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. Alternative gaseous fuels such as natural gas and hydrogen offer 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 author is conducting a study on a single cylinder research engine in order to critically assess the emission potential of alternative fuels. Hydrogen and methane are compared in terms of power production, fuel consumption and emissions. The engine parameters (ignition timing, injection start and duration) are optimised for each fuel.

Place / Date:

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INTRODUCTION

Pollutant emissions, greenhouse effect and uncertainty of energy supply… it is clear: hydrogen will be the fuel of the future. However, one has to keep in mind that hydrogen is not a real energy source, but an energy carrier. This means that hydrogen needs to be produced, preferably with renewable sources. In this way hydrogen has the potential to eliminate all carbon containing emissions from the well to wheel cycle. The only questions are when and at what expenses our cars will drive on hydrogen?

A lot of research is done on fuel cells, which yields very promising results. But there are still several drawbacks such as cost, bulkiness and low efficiency at high loads. Here the hydrogen fuelled internal combustion engine appears on the scene. At a fraction of the cost of fuel cells it is possible to propel cars with hydrogen in the very near future. The working principle of a combustion engine fuelled with hydrogen is the same as any spark ignition engine. Therefore it is possible to make an engine run on hydrogen as well as on gasoline, which is of great importance to the introduction of the hydrogen economy. The only harmful emission produced by the hydrogen IC-engine is NO_x.

The Department of Flow, Heat and Combustion Mechanics (Laboratory of Transporttechnology) at Ghent University has specialized in alternative fuels for more than 15 years. Natural gas, LPG, mixtures of methane and hydrogen, and hydrogen as fuel of internal combustion engines has been the subject of extended research (1-3). The focus in the laboratory is now on both hydrogen experimental and hydrogen simulation work. After testing a big GM V8 7.4l engine and a low speed CFR single cylinder engine a high speed single cylinder test rig is chosen. Power, safety, emissions, reliability … are a few features that need a lot of research.

THE USE OF HYDROGEN IN INTERNAL COMBUSTION ENGINES

Hydrogen-specific properties for combustion (4)

- The stoichiometric combustion of hydrogen is given as:

  $$2H_2 + O_2 \rightarrow 2H_2O$$

  The air/fuel ratio (A/F ratio) based on mass is 34.33 kg air/kg H_2 for a stoichiometric combustion. The volume percent of the combustion chamber occupied by hydrogen is then 29.6 %. This means that a significant part of the combustion chamber cannot be filled with air in contrast with gasoline that only displaces 1.8 % of the combustion chamber. Theoretically this means that the maximum amount of energy in a cylinder is less with hydrogen than with gasoline (about 15 %).

- Hydrogen has a very wide range of flammability in air (lower limit 4 %, upper limit 75 %). A significant advantage is that the engine can work with very lean mixtures, in other words, the air/fuel ratio can be very high (more than 120:1). The air to fuel ratio is frequently expressed as λ (lambda). λ is defined as the actual A/F ratio divided by the stoichiometric A/F ratio. Sometimes equivalence ratio ϕ ($=1/\lambda$) is used. Working with lean mixtures allows capturing load variations through variations in the richness of the hydrogen-air mixture, thus omitting a throttle valve (diesel principle). The greatest benefit is of course a better overall engine efficiency because of the absence of flow losses (pumping losses) and partly because of the better efficiency of the combustion at high λ-values.

- Hydrogen has a laminar burning velocity that is about ten times higher at λ=1 than the burning velocity of a gasoline-air mixture. This results in a more isochoric, thus thermodynamically more favourable combustion. At leaner mixtures, the burning velocity decreases fairly rapidly, Fig. 1.

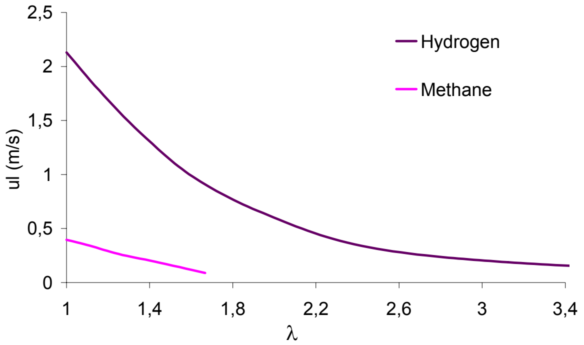

Figure 1. Burning velocities of H_2 and CH_4

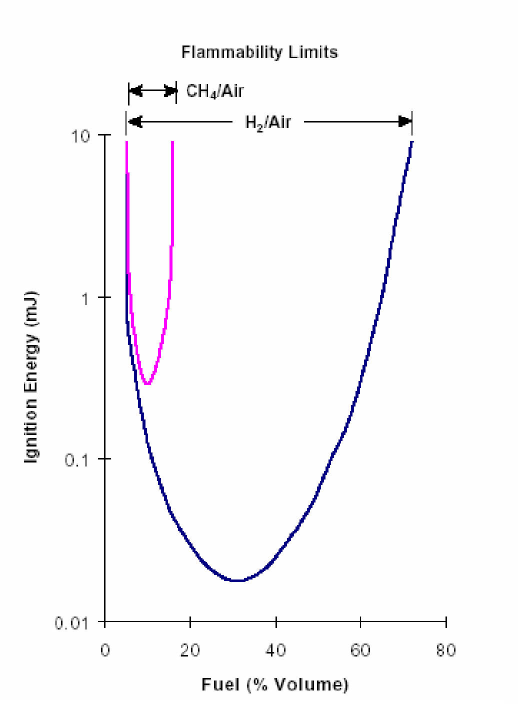

Figure 2. Ignition energy of H_2 and CH_4 (5)

- The necessary ignition energy of a hydrogen-air mixture is very low, especially at the stoichiometric condition, Fig. 2. This enables the ignition of very lean mixtures and ensures immediate ignition. However, contact with hot spots or residual gas, can cause the mixture to ignite spontaneously. This pre-ignition tendency results in backfire if the mixture ignites when the inlet valve is still open. The flame in the combustion chamber ignites the mixture in the inlet manifold through the inlet port, which causes a very loud bang and can result in severe engine damage. The backfire phenomenon is also called flashback or backflash and is one of the main issues of hydrogen fuelled internal combustion engines.

- Hydrogen has a higher autoignition temperature then gasoline. The autoignition temperature is an important parameter in view of choosing the maximum compression ratio without any danger of knocking. This means that a higher compression ratio is allowed than in a gasoline engine, which is of course beneficial for the thermodynamic efficiency of the engine.

- Hydrogen has a small quenching distance, about three times as small as gasoline. This implies that it can burn slowly in small and narrow clearances, like crevice regions. The burning in these small regions can continue up to and during the intake process. During the intake process, the hot burning gases can flow out of the crevice volumes and ignite the intake charge thus causing backfire.

- The ability to disperse in air is much greater than gasoline. This property makes it very easy to form a homogeneous fuel-air mixture. Another advantage of the high diffusivity, with a view to safety, is that the hydrogen disperses very rapidly in case of a hydrogen leak, avoiding high concentrations of hydrogen.

- Hydrogen is the lightest gas on earth. This implies that a large volume is necessary to store a reasonable quantity of energy. A lot of companies and institutes take up the challenge to develop a relatively light, compact, affordable and safe storage system for hydrogen. Hydrogen can be stored under different conditions: pressurized, liquified, on metal hydrides, in glass microspheres… As seen before hydrogen takes up a lot of space in the combustion chamber which limits the power output of the engine. Direct injection under high pressure or liquid injection can overcome this drawback. An overview of the properties of hydrogen compared with methane and gasoline is given in Table 1.

Property	Hydrogen	Methane	Gasoline
Limits of flammability in air (vol %)	4-75	5,3-15	1-7,6
Laminar burning velocity in air* (cm/s)	200-230	37-43	37-43
Minimum energy for ignition in air (mJ)	0,02	0,29	0,24
Autoignition temperature (K)	858	813	501-744
Quenching gap in air* (mm)	0,64	2,03	2
Diffusion coefficients in air* (cm^2/s)	0,61	0,16	0,05
Density* (kg/m^3)	0,0838	0,7174	700-750
Flame temperature in air at $\lambda=1$* (K)	2318	2148	2470
Lower heating value (MJ/kg)	120	53	44
Research octane number	>130	>120	90-100
Normal boiling point (K)	20,3	111,6	310-478

*273K 1013hPa

Table 1. Properties of hydrogen, methane and gasoline (5, 6)

Pre-ignition, backfire and some solutions (7-10)

Pre-ignition is a problem much more serious in hydrogen engines then in other internal combustion engines because of the lower ignition energy, the wider range of flammability and the smaller quenching distance of hydrogen. The appearance of backfire is difficult to predict. Generally speaking backfire arises at high thermal loads. Several studies have investigated the cause or causes of pre-ignition in hydrogen engines. The precise causes are not known with certainty, but the following are put forward:

- hot spots like spark plugs, exhaust valves, carbon deposits…
- residual gas
- pyrolysis of oil
- back flow of burning gases during intake process (crevices)
- catalytic effects

Possible adaptations to prevent backfire are:

- The use of cold-rated spark plugs, in order to have low surface temperatures on the tip. A waste spark ignition system has to be avoided. Using an ignition coil with grounding will avoid residual voltage on the spark plug.
- The use of cooled exhaust valves (e.g. sodium cooled exhaust valves)
- A cooling system designed to provide uniform coolant flow rates.

- The use of thermal dilution techniques like cooled exhaust gas recirculation (EGR) and water injection. Cooled EGR lowers the combustion temperature, cools the hot spots and can extinguish the flames in crevices. Water absorbs evaporating heat and increases the necessary ignition energy. Both techniques also decrease the formation of NO_x as a consequence of the lower burning temperature.
- Injection of the hydrogen as late as possible (requires sequential injection). Hot spots and residual gases are cooled by fresh air before the inflammable hydrogen-air mixture is sucked into the cylinder. Direct injection can of course exclude backfire but not pre-ignition.
- Oil control to avoid oil entering the combustion chamber.
- A high compression ratio, which implies a high efficiency and therefore lower residual gas temperatures. On the other hand, the charge will be more heated because of the higher compression, but bearing in mind the high autoignition temperature, this is not a problem. Different studies contradict each other. Ford has experienced that a possible power loss due to the earlier occurrence of backfire (leaner mixture) is compensated by the higher efficiency of the engine in the case of a high compression ratio.

TEST RIG (7, 8)

Engine

An Audi-NSU diesel engine is adapted to the use of hydrogen and methane, Fig. 3. 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.

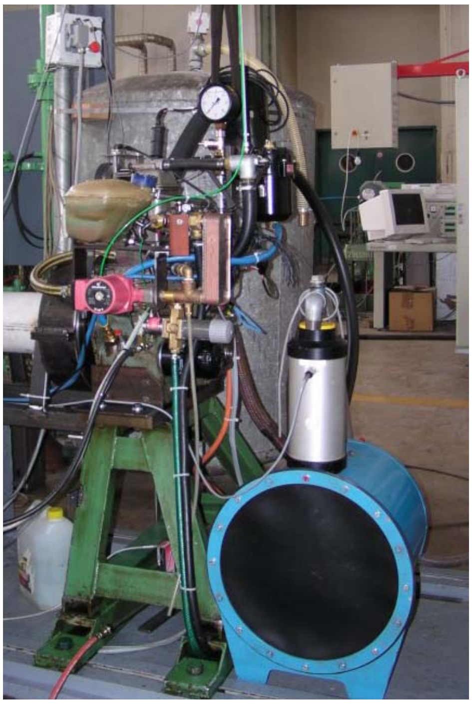

Figure 3. The test rig

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.

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 Koltec-Necam (recently taken over by Teleflex Ltd.). The injector, originally developed for use with LPG, has a working pressure of 1 to 2 barg. The fuel is supplied from a steel bottle with compressed hydrogen or methane 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 large barrel 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.

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 is 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 NTK UEGO 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-CO_2-NO-NO_2 (non dispersive infra red); O_2 (paramagnetic); HC (flame ionization); H_2 (thermal conduction).

Safety is of course a very important issue when working with hydrogen. Therefore a hydrogen detection sensor is placed on top of the large barrel (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 crank-case because of the very small H_2 molecule (higher blow-by volumes) and the broad flammability limits. Therefore crank-case gases are diluted by means of additional air, so that the maximum H_2 concentration is always below 1 %.

INITIAL TEST RESULTS (7)

The first experiments were conducted in order to find a good initial mapping (injection duration and ignition timing) to run the engine properly. With a view to postponing the occurrence of backfire/pre-ignition as long as possible the end of injection is set very late (45°ca ABDC with IVC at 50°ca ABDC). As discussed, fresh air will cool the combustion chamber before hydrogen is added. The engine was operated over the entire load and speed range. At every operating point the MBT ignition timing was searched for. MBT stands for Minimum advance for Best Torque, so giving also the best efficiency. Load is adjusted by adding more or less fuel until a certain lambda value is reached, bearing in mind that power is regulated by changing the air-fuel ratio, Fig. 4.

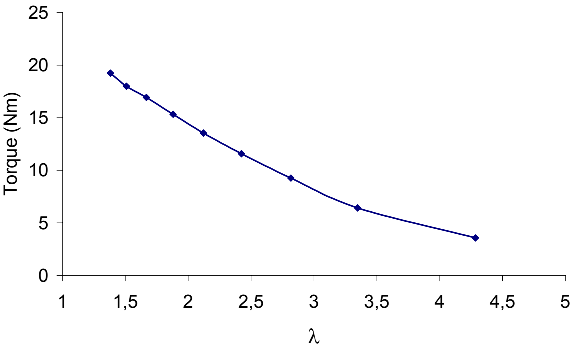

Figure 4. Torque-λ relation

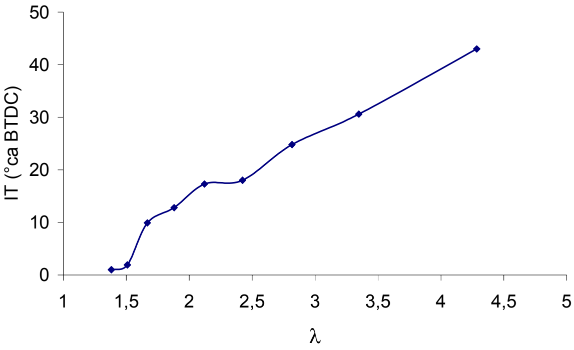

Figure 5. Ignition timing (2800 rpm)

Figure 5 clearly shows that the MBT timing is very dependent on the load. However, when searching the maximum power output, the ignition timing was set fixed at 1° ca BTDC, which gives good results (cf. fast burning speed at low air-fuel ratios). The power is limited by the occurrence of pre-ignition. At moderate speeds the minimum lambda value achieved without pre-ignition was about 1.25. This lambda value has a tendency to be higher at both low speeds and high speeds (λ>1.4) and is also dependent on the ignition timing. So pre-ignition is the main cause of limited torque in the hydrogen fuelled engine. In the fuel mapping the injection duration when pre-ignition occurs is set as the 100% load for that speed.

Brake thermal efficiency (BTE) is the highest at high loads and clearly starts to decrease at λ values higher than two, Fig. 6. Reasons are the not proportional decrease of mechanical losses with lower loads, the slower combustion and the appearance of misfires. As a result unburned hydrogen concentrations in the exhaust gasses are quite high (up to 1 %) at those low loads (λ>3). Therefore it is advantageous to use a throttle that only works at very low loads (especially at idling), holding the air-fuel ratio at about 2-2.5, and is fully open at higher loads (11). For this reason and also for controlling the load when using methane a throttle valve was implemented recently.

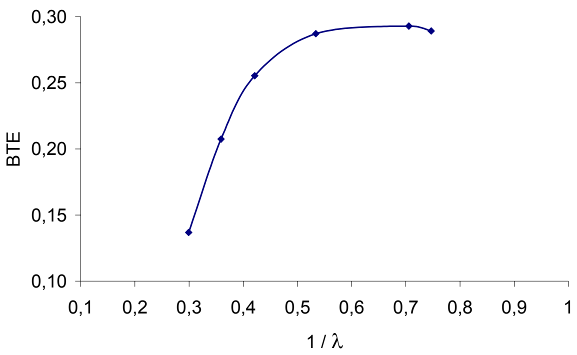

Figure 6. Efficiency (average taken over speed range)

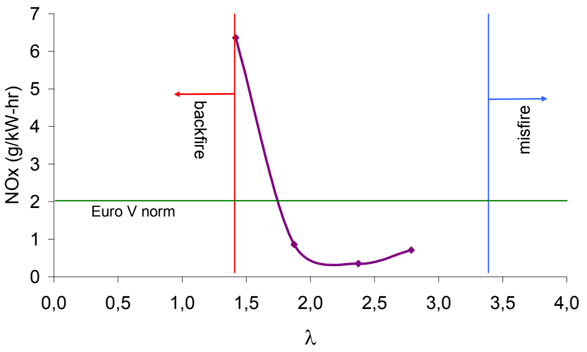

Figure 7. NO_x emissions

Hydrogen is a very clean fuel because of the absence of carbon atoms. Apart from the minimal amount of CO, CO_2 and HC's in the exhaust gas because of the burning of lube-oil, the only real pollutant is NO and NO_2, thus NO_x. The NO_x concentration is primarily a function of the air-fuel ratio and reaches a maximum at about $\lambda=1.2$. This maximum is even higher than when operating the engine with gasoline. However these NO_x concentrations decrease extremely rapidly when the air-fuel mixture gets leaner, Fig. 7. Lambda values higher than 2 results in NO_x concentrations below 100 ppm. It's useful to calculate the brake specific NO_x emissions (g/kW-hr). Comparing the emissions of the test engine with the Euro V emission limits for heavy duty vehicles (2 g NO_x/kW-hr), the engine needs to work with a mixture leaner than $\lambda=1.75$ (without any catalyst). These lean mixtures of course put a strain on the power output of the engine. Therefore measures are to be taken to restore power without increasing NO_x emissions too much.

Some experiments were conducted with methane on the same engine in order to compare the results of the measurements with the hydrogen results, especially at full load. In Table 2 the comparison is made between hydrogen operation at the pre-ignition limit (full power) and methane with the throttle fully open. The given quantities in the table are the averages taken over the entire speed range (2000-4000 rpm). The efficiency is a bit less for hydrogen, but this changes at part load. For example, delivering a torque of 10 Nm (2400 rpm) using hydrogen ($\lambda=2.32$) or methane the efficiencies are respectively 26 % and 21 %. This illustrates the advantage of regulating the power with the air-fuel ratio and not with a throttle.

	Hydrogen	Methane
lambda	1,331	1,014
Torque (Nm)	17,8	25,76
BTE (%)	28,6	30,4
NO_x (ppm)	3482	3041
CO (vol%)	/	0,46
CO_2 (vol%)	/	10,88
H_2 (vol%)	0	0,3
O_2 (vol%)	6,18	0,74

Table 2. Comparison H_2-CH_4

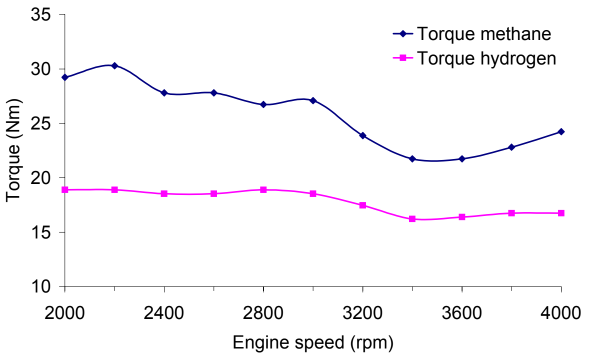

Figure 8. Maximum torque H_2 and CH_4

Figure 8 shows the maximum torque curves of the test engine fuelled with hydrogen and methane. With hydrogen the torque output is on average 31 % less compared to methane as a result of the leaner mixture and the lower density of hydrogen. If a stoichiometric mixture ($\lambda=1$) would be reached, theoretically there still would be a torque deficit of about 17.5 %. So trying to run on a stoichiometric mixture without the danger of pre-ignition will not solve the power issue completely. The case of indirect injection is discussed. Using direct injection (liquid or gaseous under high pressure) can eliminate this drawback and is theoretically even capable of delivering about 20 % more torque than the gasoline fuelled baseline engine. However costs and complexity will increase and problems are expected with mixture formation and NO_x emissions.

CONCLUSIONS AND FUTURE WORK

It is proven that the internal combustion engine, particularly the spark ignition engine, is very suitable for the use of hydrogen as a fuel. One has to take into account the hydrogen-specific combustion properties. Some of these properties are advantageous like the wide flammability range (omitting throttle), high burning velocity (efficiency), high autoignition temperature (compression ratio) and high diffusivity (mixture formation and safety). Other properties involve some difficulties like low ignition energy (pre-ignition and backfire), small quenching distance (idem) and density (power loss and storage problems). The purpose is to make the most of the 'good' properties and to conquer the drawbacks caused by the undesirable characteristics of hydrogen. Particularly, measures are to be taken to prevent the early occurrence of pre-ignition or backfire.

The fully equipped test rig is reliable and safe, thus ready for further research on hydrogen combustion. Recently a piezoelectric pressure sensor for measurements in the combustion chamber is installed, making a more profound study of the combustion possible. Initial testing revealed two main problems: a torque deficit of about 30 % compared with methane and the high emission levels of NO_x at high loads ($\lambda<1.7$). By choosing a single cylinder test engine modifications with a view to further experiments can be made relatively simple.

Several possibilities are put forward to solve power and NO_x problems. Boosting the inlet charge is a manner to restore the torque output. It is very important to cool the boosted air, keeping in mind the effect of heating the inlet charge on the occurrence of pre-ignition. It will be necessary to run on lean mixtures (e.g. $\lambda=2$). Although using boosting, NO_x emissions are expected to decrease because lean mixtures are used, so NO_x-power trade-off will be better (12). Another solution is Exhaust Gas Recirculation or EGR, cooled EGR in particular. EGR brings down the combustion temperature which has a strong positive effect on the NO_x emissions. As a consequence of the cooler combustion chamber the occurrence of pre-ignition will be postponed. It is possible to run on a stoichiometric mixture when a sufficient amount of EGR is used. Ford reported that the NO_x concentration can be reduced to less than 1 ppm when using a three way catalyst and running stoichiometric (13). However EGR results in a slight loss of power and efficiency. Therefore the combination of both boosting and EGR seems the most promising solution.

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