Design and test of an inexpensive hydrogen fueled single-cylinder four-stroke gasoline engine

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Abstract

Hydrogen has an interesting potential to become a future fuel. While hydrogen fuel cells are still expensive, cheap alternatives are needed. One alternative is a hydrogen powered internal combustion engine (H_2 - ICE) which powers a generator. This work focus on modifying an existing single-cylinder four-stroke gasoline engine. Main focus is on building an inexpensive engine-generator power supply while reaching an acceptable efficiency. Through a literature review different methods of hydrogen injection are discussed and a new carburetor is designed and tested. The engine is supplied with pressure and flow sensors at the air and hydrogen intake and a flow sensor at the exhaust. Current and voltage are measured at the generator load. Efficiency is calculated. Measurement on the engine shows a hydrogen leakage through the intake air pipe during the compression, combustion and exhaust stroke while the intake valve is closed. Furthermore exact measurement of hydrogen flow is difficult, due to the response time of sensors. Based on the experiments we suggest three modifications of the existing engine design.

Key words: Internal combustion engine; Premixed hydrogen injection

1. Introduction

The University of Aarhus - Institute of Business and Technology (AU-IBT) has specialized in renewable energy sources. Wind turbines and hydrogen are a part of the University's energy concept. A new project is to store surplus electricity from wind turbines as hydrogen by alkaline water electrolysis and subsequently convert hydrogen into electricity when wind is scarce (Fig 1).

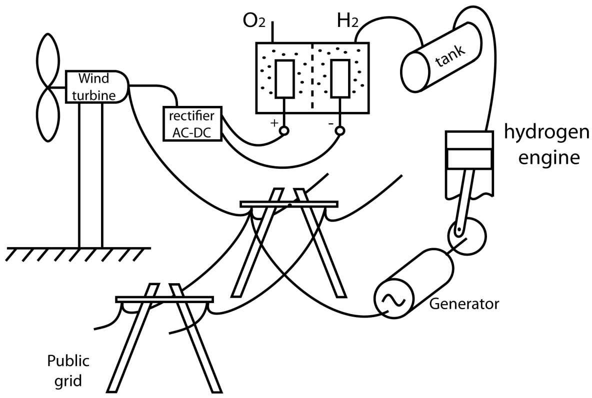

Fig 1. energy concept at AU-IBT

This work is a part of the project. The goal of this research is to modify a single-cylinder four-stroke spark ignited gasoline engine to run on hydrogen. This should be an inexpensive alternative to hydrogen fuel cells which are still expensive. ICEs which run on hydrogen have no CO_2 and HC gases in the exhaust fumes (Ganesh et al. [3]). Furthermore the amount of NO_x gases is reduced in lean operation

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Nomenclature

ICE	Internal Combustion Engine	slpm	standard liter per minute
η	brake thermal efficiency	HC	hydrocarbon
ϕ	fuel-air equivalent ratio	CO_2	carbon dioxide
rpm	revolutions per minute	NO_x	nitrogen oxides

mode. Advantages of ICEs are maturity of the technology and the low price. The price of a 2 kW gasoline engine AC-generator power supply is around 200€ compared 6 000€ for a 2 kW hydrogen fuel cell. This is the reason for developing a modified combustion engine running on hydrogen. We will review different mechanical setups in order to find a simple and cheap hydrogen fuel supply. This work has also an economical point of view in order to find a balance in between the price and efficiency of that engine.

2. Article Review

The idea of running an ICE on hydrogen is not new. Several groups of engineers have already modified an engine to run on hydrogen. Also most automobile manufactures are developing hydrogen powered engines. One of the famous projects is the BMW Hydrogen 7 [2], a rebuilt BMW 7.60 which passed the whole process of serial development. The used engine is a 6 liter V12 with a maximum torque of 390NM and 191 kW output power. Hydrogen is stored in liquid state in an insulated tank with a capacity of 7.8 kg, which allows a driving range over 200 km. The double VANOS technology allows a variable valve timing of inlet and outlet valves. This provides external mixing in stoichiometric relation without pre-ignition and combustion knock in full range of engine conditions.

White et al. [8] reviewed different concepts for hydrogen injection in hydrogen fueled ICE's and stated that in general external mixed hydrogen-air fueled engines have lower engine output power than gasoline engines due to three reasons:

- Hydrogen has a lower volumetric heating value of 10.7 kJ/liter at 1 bar and 298°K compared to 33 600 kJ/liter for gasoline.
- Premixed hydrogen-air engines suffer from a loss in volumetric efficiency due to the high volume of hydrogen, which reduces the possible amount of air. The stoichiometric mixture (ϕ=1) is 30% hydrogen and 70% air by volume [1], whereas the stoichiometric mixture is 2% gasoline and 98% air by volume.
- The hydrogen-air mixture must be lean to prevent pre-ignition. The low minimum ignition energy around 0.02 mJ for hydrogen compared to 0.24 mJ for gasoline predispose hydrogen to pre-ignite especially when the hydrogen-air ratio is above ϕ=0.5.

The article suggest turbo charging the engine with compressed air to raise engine output power.

Al-Garni [1] suggests direct injection of hydrogen into the combustion chamber at pressures around 10-100 bar eliminating external mixing in a carburetor. The article states that direct hydrogen injection "improves efficiency, increases power output, and significantly helps to eliminate abnormal combustion phenomena, such as pre-ignition and combustion knock". Direct hydrogen injection at the hot cylinder head creates a potential risk for self-ignition. Direct injection demands an intervention in the cylinder head design to make room for an injection valve. Typically the injection valve is driven by a rocker arm and a cam connected to a hydrogen intake puppet valve or through a solenoid valve consisting of an electromagnetic coil connected to a spring loaded valve. In the latter case hydrogen flow is controlled by increasing the hydrogen pressure or the injection time at constant hydrogen pressure. Garni split his valve into a hydrogen injection controller and a hydrogen injector (Fig 2). The hydrogen injection controller consists of a rod connected to a cam and the rod slides between two portholes thus effectively opening and closing for hydrogen. The hydrogen injector consists of a check valve that closes under combustion and opens under suction and contains injection holes for mixing hydrogen with air inside the cylinder. Hydrogen is injected during the second half of the compression

[1] Stoichiometric ratio of hydrogen-oxygen is 2:1. Since air contains only 20% oxygen the stoichiometric hydrogen-air ratio becomes 2:5 or (2/7)*100% = 29% by volume

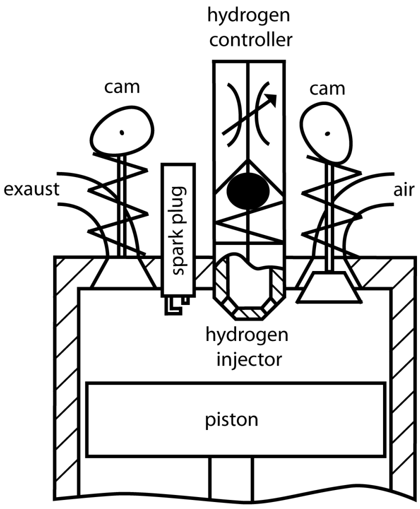


Fig 2. direct injection

stroke at 40 to 100 bar. The air-hydrogen ratio was controlled by throttling the hydrogen flow rate at constant pressure and keeping the air flow constant.

Verhelst and Sierens [7] converted a V8 gasoline engine to run on hydrogen using an electromagnetic gas injector and spark ignition. The engine was feed from a 200 bar hydrogen bottle reduced to 3 bar by a pressure reducing valve. An oxygen sensor in the exhaust measured the air-to-hydrogen ratio. To avoid backfire the engine was run on a lean air/hydrogen mixture of ϕ=0.5. The authors found that hydrogen under pressure is an isolator and hence reduced the spark plug gab from 0.9 mm to 0.4 mm to get a higher ignition voltage. Hydrogen leaked to the crankcase and deteriorated the lubricating oil thus calling for a ventilation of the crankcase. The engine speed was regulated by the hydrogen/air ratio, exploiting the flammability limits of hydrogen in air with a lower limit of 4% and an upper limit of 75%.

Saravanan et al. [5] examined both external mixing in a carburetor and direct hydrogen injection to the cylinder, finding the later more efficient and with a lower NO_x emission. The external carburetor mixing was less efficient due to hydrogen leak through the air intake. They used a four stroke single cylinder direct injection diesel engine coupled to an electrical dynamo meter with a resistance load to measure output power. Hydrogen was supplied from a 150 bar cylinder and reduced to 1.4 bar using a pressure regulator. Hydrogen flow was regulated by a valve and passed through a flame trap (hydrogen bubbling through water) and connected to either a carburetor or a direct injection valve.

Szwaja et al. [6] examined combustion knock in a spark ignited hydrogen fueled combustion engine. They defined knocking as the spontaneous ignition of a portion of the end gas mixture in the combustion chamber ahead of the propagating flame causing high pressure waves and resulting resonance frequency noise. They found that knocking appears at hydrogen/air ratios near stoichiometric relation. Hydrogen's low ignition energy, high flame speed and low energy density per unit volume increase the knocking while hydrogen's broad flammability range and high auto-ignition temperature decrease the knocking.

Mohammadi et al. [4] examined a direct hydrogen injection, spark-ignited engine. They state that external mixing of hydrogen and air causes backfire and knock at higher engine loads. Instead they examined internal mixing where hydrogen was directly injected into a single-cylinder four-stroke engine at the later stage of the compression stroke using a 80 bar high-pressure electromagnetic actuated gas injector (Westport Innovation Inc.) and found that backfiring was eliminated and higher output power was obtained. The hydrogen flow rate was measured by a mass flow controller (Oval, F-123S). The gas injector had seven hole nozzles with a hole diameter of 0.52 mm. Injection timing and duration was controlled electronically (Fig 2.)

Yvon and Lorenzoni [9, 10] rebuild a commercial sold lawn mower to run on hydrogen. They modified the original carburetor to mix hydrogen and air externally. Hydrogen is stored in a metal hydride tank. Output pressure is about 3-25 bar. Engine speed is regulated by hydrogen flow trough a needle valve and air flow is controlled by carburetor choke. Maximum output power decreases approximately by a factor of 20% compared to gasoline operation. No tendency of backfireing was observed. Additionally they found that engine noise is reduced about 2 dB to 70 dB. The second article reports that these engine was running for 14 years without any problems or abnormal wearout.

3. Methodology

We use an inductive - deductive approach where we through literature review (scientific articles and textbooks) and expert interviews formulate a suggested design and subsequently conduct and experiment to verify or discard the design.

4. Carburetor design and experimental setup

From the article review it can be concluded that direct injection raise engine output power and efficiency. But direct injection of hydrogen requires a substantial modification of the engine involving a new cylinder head and synchronization of injection timing with the crank angle. That is why our research is focusing on modifying an external mixing engine with a carburetor. We want to examine the modification of an external mixing engine, while keeping cost low and reach an acceptable efficiency. Furthermore we want to show the possibility of rebuilding any gasoline engine without changing engine parameters like valve- and ignition timing.

4.1. *Test engine*

The engine used in this research is a QUIN AC-generator with a single-cylinder four-stroke spark ignited gasoline engine. Generator specifications are listed in Table 1. These engine was bought in a hardware shop in Herning/Denmark (price $\sim$ 200€).

QUIN Gasoline Generator Model AG-HA-2500	
general details	single cylinder, vertical, four stroke, spark ignition, air cooled
displacement	165 cm^3
bore	68 mm
stroke	45.5 mm
rated output	2 kW at 3000 rpm

Table 1. engine specifications

4.2. *Engine setup*

The simplest way to introduce hydrogen to an engine is by external passive mixing in a carburetor. Fig 3 shows a schematic drawing of the engine setup. Passive mixing means hydrogen flow is regulated manually by a needle valve.

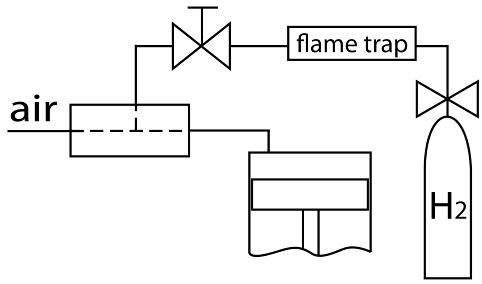


Fig 3. passiv external mixing

Hydrogen is supplied by a 20 liter norm-volume gas cylinder with a maximum pressure of 200 bar. A pressure regulator on top of the bottle reduces pressure to 1-10 bar overpressure. A flame trap is used as a safety device to ensure that flashbacks can not access the hydrogen cylinder. Hydrogen flow is controlled by a Festo needle valve. A second valve is used to cut hydrogen supply off.

4.3. *Carburetor design*

Research started with experiments on a Briggs&Stratton single-cylinder four-stroke lawn mower engine and various carburetor designs leading to the final design. Fig 4 shows a technical drawing of the final carburetor design without intake pipe (15cm). The pipe is used to advance engine running conditions. Hydrogen intake is under an angle of 25° to prevent pressure drops inside the carburetor. To avoid oxidation and for easier prototype modeling the carburetor is build out of plastic. Carburetor dimensions are the same as the original gasoline carburetor. So it can be easy replaced without any changes on the engine itself.

4.4. *Experimental setup*

Hydrogen flow is measured by an AIRF 20 slpm N_2 sensor form Sensortechnics. Hydrogen pressure inside the supply pipe is measured by a Freescale MPX 5700 sensor. Air intake pressure is sensed by a MPX5050 while air flow is sensed by an AIRF 200 slpm. Sensor signals are recorded by an Agilent MSO6054A digital storage oscilloscope. Measurement data is transfered to a computer for further analysis. Fig 5 shows a schematic drawing of

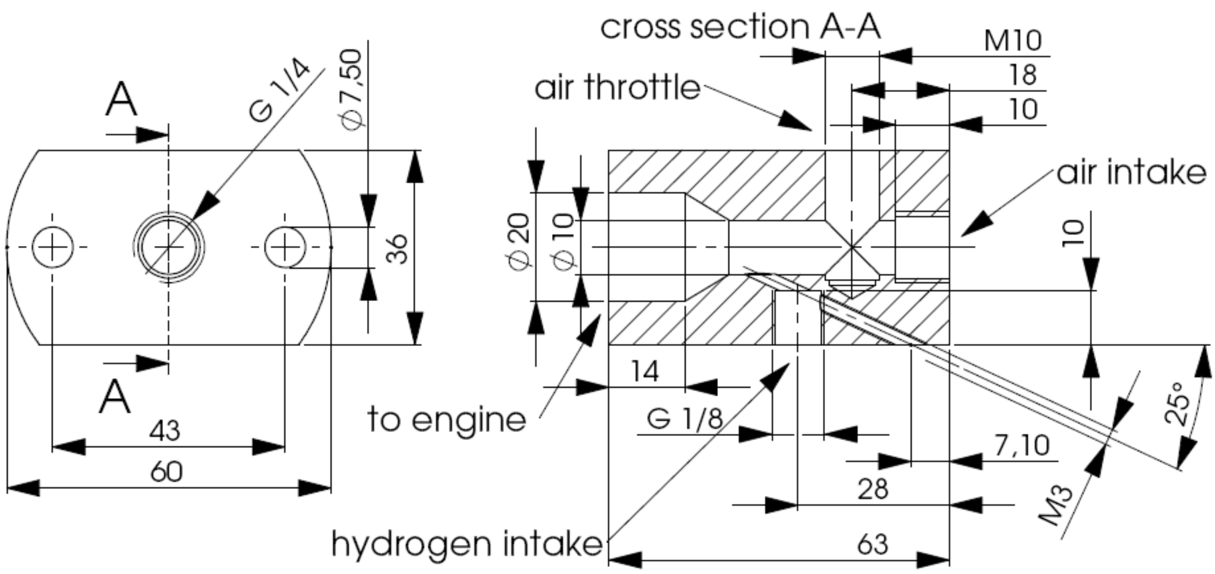


Fig 4. technical drawing carburetor final design

the experimental setup. To vary output load contin-

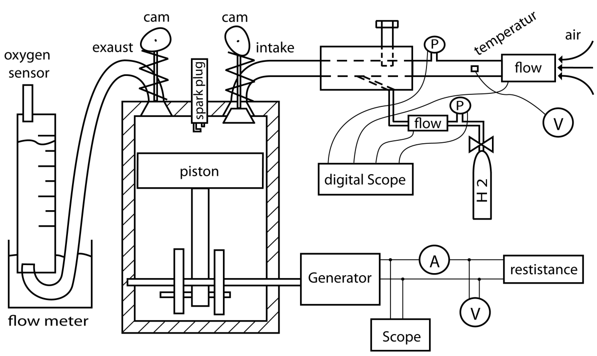


Fig 5. schematic drawing experimental setup

uously a regulating transformer with an electric radiator as resistance is connected to one of the power output plugs of the generator. Output voltage and current are measured by Branford Digital Multimeters 2286. In addition intake air temperature is measured with a LM35 sensor by National Semiconductors and a Branford Multimeter 2286. Engine revolutions are detected by an analog oscilloscope which is also connected to the generator output plug. Experiments on the spark plug showed that generator output frequency follows the ignition frequency. All sensors are supplied by a Bang&Olufsen SN16A power supply with 2 separate variable outputs.

5. Analysis and results

Preliminary test showed that the engine speed can be regulated either by throttling the hydrogen needle valve or by changing the hydrogen supply pressure. Changes in the air flow showed just small influence of engine performance. Further experiments were conducted at wide open throttle condition.

The used engine is constructed to run constantly at 3000 rpm which is equal to 50 Hz frequency in electrical output. Engine momentum seems to be optimized to that point. If the engine is decelerated due to a higher electrical output load without raising hydrogen flow, engine revolutions fall rapidly down to approximately 2000 rpm. At output loads higher than 500 W the engine is going to run unsmoothly. A fast drop in engine revolution at these conditions force the engine to stop, most times with backfire through the air intake.

The maximum measured output power was 650 W.

5.1. *Analysis*

Fig 6 shows schematic curves of the flow and pressure sensors. Intake air pressure drops during intake stroke to a maximum vacuum of 450 mbar. At the same time airflow raise to a maximum.

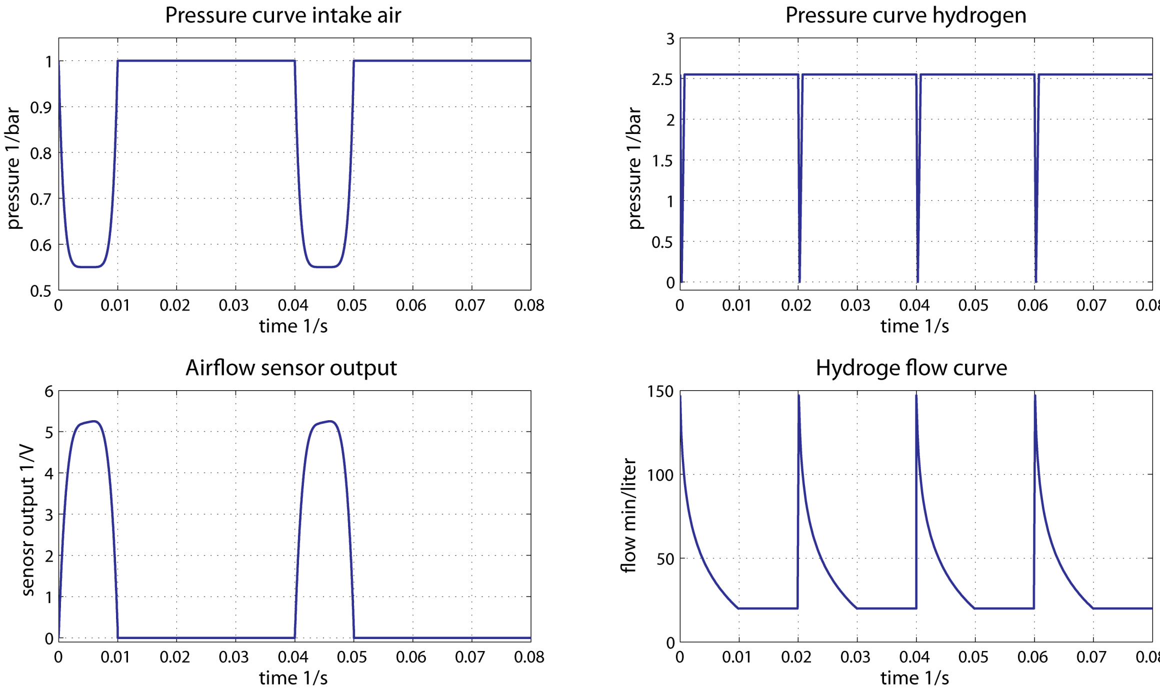


Fig 6. schematic curves of hydrogen and air pressure and flow during four full engine revolutions

Exact measurement failed due to the physical limit of 200 slpm of the flow sensor. Experimental measurement of the amount of exhaust fumes showed an average flow of $\approx 112\frac{l}{min}$. While the air intake valve is only opened for one quarter of four strokes the maximum airflow raise to $\approx 448\frac{l}{min}$.

Furthermore these figures show hydrogen pressure and flow. Peaks in hydrogen pressure can be explained by a fast pressure drop during the intake stroke in the intake pipe. The hydrogen regulations valve compensates that immediately. Hydrogen pressure can be seen as constant. Hydrogen flow could not be measured properly. The response time of the used sensor is 60 ms. It is not capable to follow the fast changing conditions. The constant hydrogen pressure indicates that there is a hydrogen flow through the intake pipe when intake valve is closed. That will causes an efficiency loss.

5.2. *Carburetor calculations*

Based on the carburetor design and experimental data some theoretical calculations and suggestions can be made. Given numbers from carburetor design or measurement data.

$$\begin{array}{ll} \text{Air flow:} & Q_{max} \approx 448\frac{l}{min} \\ \text{air intake pipe diameter:} & D = 8,5mm \\ \text{kinematic viscosity:} & \nu_{air} = 15 \cdot 10^{-6}\frac{m^2}{s} \\ \text{equivalent roughness:} & \epsilon = 0,8mm \end{array}$$

$$\begin{aligned} Re &= \frac{Q \cdot D}{A \cdot \nu} \\ &= \frac{4 \cdot 448 \cdot 10^{-3}\ \frac{m^3}{s} \cdot 0,0085m}{60\pi \cdot (0,0085m)^2 \cdot 15 \cdot 10^{-6}\ \frac{m^2}{s}} \\ &= 74\ 563 \end{aligned}$$

Formular 1. Reynolds number

Flows above $Re = 4000$ indicate a full turbulent flow. Calculated Reynolds number of 74 563 shows intake air flow is highly turbulent.

$$\Delta p = \frac{1}{2} \cdot \lambda \cdot \frac{L}{D} \cdot \rho_{air} \cdot \left(\frac{Q}{A}\right)^2$$

Δp = pressure difference; λ = darcy friction factor; L = pipe length; D = pipe diameter; ρ = density; Q = flow; A = pipe cross section;

Formular 2. pressure drop in a horizontal pipe

λ can be calculated iterative by solving the colebrook equation.

$$\frac{1}{\sqrt{\lambda}} = -2 \cdot \log\left(\frac{\epsilon}{D \cdot 3,7} + \frac{2,51}{Re\sqrt{\lambda}}\right)$$

ϵ = equivalent roughness; D = hydraulic diameter

Formular 3. Colebrook equation

λ was calculated to ≈ 0.1. With this additional information it is possible to recalculate the volume flow of air through the intake pipe which cause the measured maximum pressure drop of 450 mbar.

$$\Rightarrow Q = \frac{\pi \cdot D^2}{4} \sqrt{\frac{2 \cdot \Delta p \cdot D}{L \cdot \rho_{air} \cdot \lambda}} = 734 \frac{l}{min}$$

Formular 4. volume flow in intake pipe

These calculated flow is about 60% bigger than the experimental measured.

5.3. *Efficiency calculation*

5.3.1. *by volume flow*

Due to the missing number of hydrogen flow, we suggest to calculate the engine efficiency by the assumption of a full stoichiometric mixture ratio of $\phi = 1$. This is a worst case calculation. According to the reviewed articles an equivalent ratio of one causes heavy engine knock. Our engine was running smooth and without any knock or pre-ignition. That leads to the second assumption of an equivalent ratio of $\phi = 0.5$ for a lean combustion.

$$\begin{aligned}
Q_{\overline{tot}} &\approx 112 \frac{l}{min} \\
\phi &= 1 \quad \rightarrow 30\% \quad H_2 \\
\phi &= 0.5 \quad \rightarrow 16.6\% \ H_2 \\
H_{H_2} &= 10.7 \frac{kJ}{l} \\
H_{gasoline} &= 33.6 \frac{MJ}{l}
\end{aligned}$$

$$\begin{aligned}
Q_{\overline{H_2}} &= Q_{\overline{tot}} * 30\% \\
&= \frac{112 \frac{l}{min} \cdot 0.3}{60s} \qquad = 0.56 \frac{l}{s}
\end{aligned}$$

$$\begin{aligned}
P_{in} &= H \cdot Q \\
&= 11\ 000 \frac{J}{l} \cdot 0.56 \frac{l}{s} = 6\ 160W
\end{aligned}$$

$$\begin{aligned}
\eta &= \frac{P_{out}}{P_{in}} \\
\eta_{\phi=1} &= \frac{650W}{6\ 160W} \qquad = 10.6\% \\
\eta_{\phi=0.5} &= \frac{650W}{3\ 410W} \qquad = 19.1\%
\end{aligned}$$

Formular 5. efficiency by stoichiometric relation

Engine efficiency with gasoline as fuel can be calculated as follows. Maximum tank volume = 15liter (duration ca. 13 hours)

$$Q_{gasoline} = \frac{15liter}{13hours} = 3.205 \cdot 10^{-4} \frac{liter}{s}$$

$$\begin{aligned}
P_{in} &= H \cdot Q = 33.6 \frac{MJ}{l} \cdot 3.205 \cdot 10^{-4} \frac{l}{s} \\
&= 10\ 769W
\end{aligned}$$

$$\eta = \frac{2\,000W}{10\,769W} = 18.6\%$$

Formular 6. efficiency with gasoline as fuel

This calculation shows that with an assumption of equivalent ratio $\phi = 0.5$ in hydrogen mode engine efficiency reaches the same level as in gasoline mode.

5.3.2. *by oxygen concentration*
Another possibility is to measure the chemical composition of exhaust fumes and the total amount of exhaust fumes flow. Formular 7 shows the chemical composition of the mixed gas. The relation in between x and y defines the equivalent ratio ϕ.

$$\underbrace{2x \cdot H_2 + x \cdot O_2}_{2x \cdot H_2 0} + \underbrace{y \cdot O_2 + 4(x+y)N_2}_{exhaust\ gases} \hat{=} 100\%$$

Formular 7. chemical composition of mixed fuel

We assume a measurement where the exhaust fumes bubbles through a water bath where all water vapor condenses. There is only unburned oxygen and nitrogen left in the exhaust fumes. By measuring the percentage amount of oxygen it can be recalculated how much oxygen got burned inside the engine. The relation of oxygen to nitrogen in air is 1/4. The amount of incoming and outgoing nitrogen is constant. Formular 8 shows the equation to calculated the percentage amount of burned oxygen. N_2 and O_2 have to be substituted by measured volume percentages (N_2 = 100% - O_2). Together with the total flow of exhaust fumes the hydrogen flow can be calculated as follows.

$$\Delta O_2 = \frac{1}{4} \cdot N_2 - O_2$$

$$\Rightarrow Q_{H_2} = 2 \cdot \Delta O_2 \cdot Q_{tot}$$

Formular 8. oxygen concentration based flow calculation

Formular 9 shows an example calculation with an oxygen concentration of 15% by volume, which was measured in the exhasut fumes while the engine was running without any load.

$$\Delta O_2 = \frac{1}{4} \cdot (100\% - 15\%) - 15\% \quad = 6.25\%$$

$$\Rightarrow Q_{H_2} = 2 \cdot 0.0625 \cdot 112 \frac{l}{min} \quad = 14 \frac{l}{min} = 0.23 \frac{l}{s}$$

Formular 9. oxygen concentration based flow calculation

The equivalent ratio ϕ can be calculated by Formular 10. All values are in percent.

$$\phi = \frac{H_2}{(O_{2\,exhaust} + O_{2\,burned}) \cdot 2}$$

$$\phi = \frac{12.5\%}{(15\% + 6.25\%) \cdot 2} \quad = 0.29$$

Formular 10. equivalent ratio

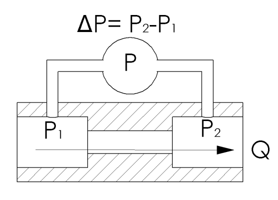
These calculations show that the equivalent ratio is below ϕ= 0.5 which indicates that our assumption above are true. The efficiency can not be calculated due to a missing output load.

A hydrogen sensor in the exhaust can be used to make sure that all incoming hydrogen got burned into water.

6. Suggestions for further work

To calculate engine efficiency properly further research is needed. Therefore different principles of flow measurement can be used. One possibility is to construct a flow sensor based on a differential pressure sensor. Due to a geometrical change in a pipe the pressure is dropping proportional to the flow (Formular 11).

$$Q = c\sqrt{\frac{\Delta p}{\rho}}$$



Formular 11. volume flow by pressure drop

Furthermore the measurement of exhaust composition needs exact measurement to show that the made assumptions are correct.

To prevent hydrogen flow during the time inlet valve is closed a check valve inside the air intake could be used to reduce the losses of hydrogen and ensure constant mixing conditions.

To regulate hydrogen flow for variable loads a mechanical or electrical proportional valve could be used. This will stabilize the output frequency and raise the efficiency in a bigger range of output loads Fig 7. While using an electrical actuated valve it is also possible to regulate engine speed and output power by injection duration.

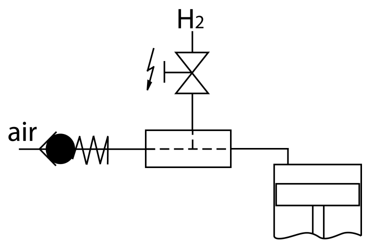


Fig 7. active external mixing

Turbo charging of intake air can help to raise engine output power and efficiency. Fig 8 shows a schematic drawing.

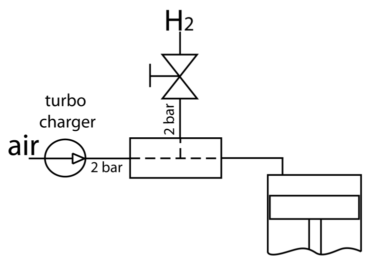


Fig 8. turbo charging

Fig 9 shows our preferred engine design. Hydrogen flow is throttled with an electric proportional valve which is regulated by a micro controller. The check valve inside the intake pipe prevents hydrogen leakage through the intake.

7. Conclusion

Research shows that a gasoline engine with a carburetor can be modified very easily to work on hydrogen. However some development is needed to find the correct conditions for start setup. After setup is found once it is a reproducible process.

Very simple carburetor designs can be used. It is also possible to modify the original carburetor, while replacing the gasoline fuel supply by hydrogen. However we recommend a special designed carburetor to improve power output and efficiency.

Efficiency calculations show that the modified engine reaches approximately the same level than the original engine.

8. Acknowledgment

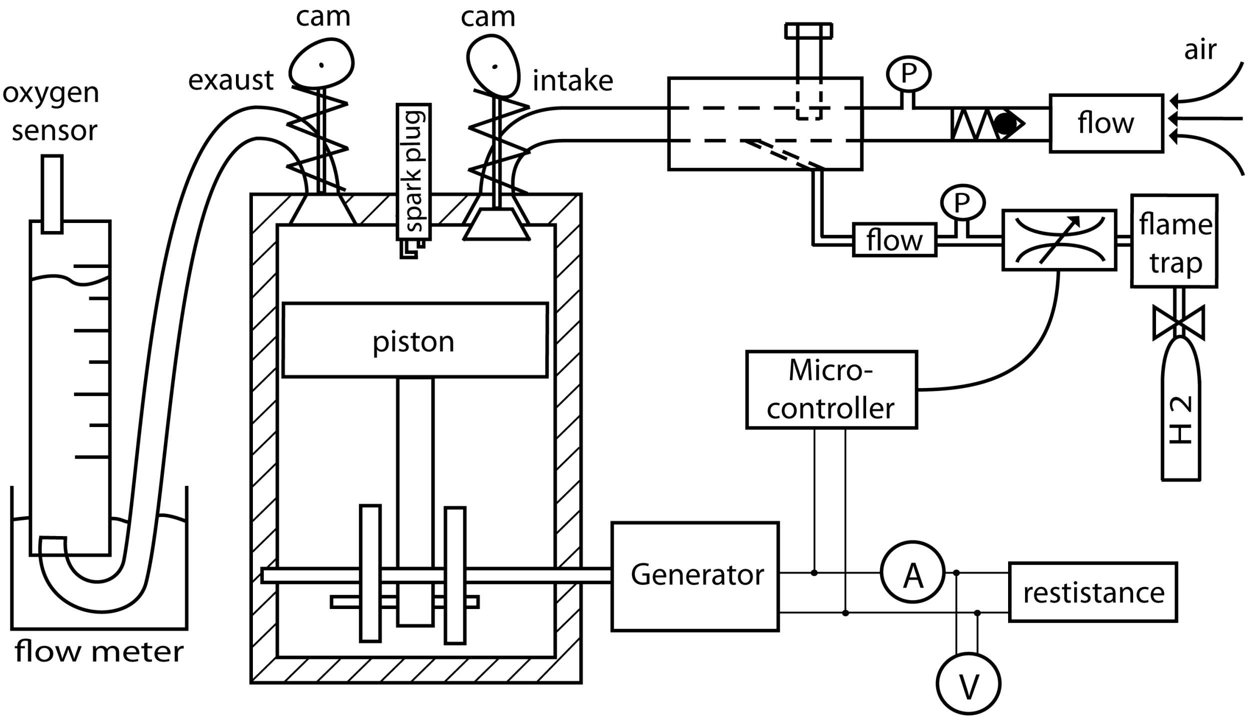


Fig 9. suggested design

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Biography:

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