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Low-Cost, Hydrogen Monofuel Power Generation for Portable On-Site Energy Supply

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Introduction

The urgency attached to avoiding **climate change** implies that **cutting emission rates early is important** to reach the goals set by the Paris Agreement. Thus, not only the most common polluters need to reinvent themselves but also every sector has to take responsibility and rethink. In this spirit PlusZero, a company concentrating on making local generators for the events sector emission free, has launched a collaboration with Imperial College London and CMB.TECH to investigate a **hydrogen conversion of a carburetted, spark ignited gasoline fuelled engine.**

The engine conversion's foremost goal was not to maximise efficiency and power output but rather to find a **cost-effective** and **low-complexity** conversion approach to introduce clean fuels to existing carburetted engines. This would allow easy conversion of today's engines and the opportunity to build-up and profit on the experience gathered in combustion engines over the past decades.

The naturally aspirated **5 kW single-cylinder** Honda generator with a displacement volume of 389 cm³ and a **compression ratio of 8.1:1** is originally equipped with an electronic constant-speed throttle governor (ETG). Although electronic tuning was taken into consideration initially, we decided to implement, finally, **only physical changes to the intake and fuel system**.

Methodology

Carburettor Conversion Approach

We used a gaseous carburettor-conversion kit for the i-GX390, with a **zero-pressure controller (ZPC)** (Fig. 1), because of its low complexity and cost. The **dimensions** of the air and fuel **intake paths** were **changed** using a **comparative equation based on geometry as well as fluid- and thermodynamics**. The adjustments were executed on the OEM carburettor (Fig. 2) to retain the advantages of an ETG mechanism. To complete the hydrogen supply line, tubing was fitted onto the new riser leading to the ZPC together with a manually adjustable pressure valve.

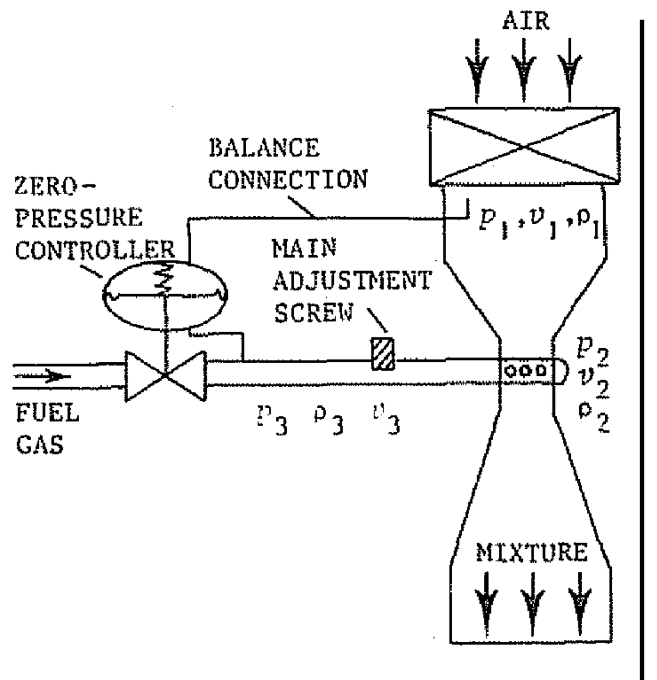


Fig. 1: Intake System

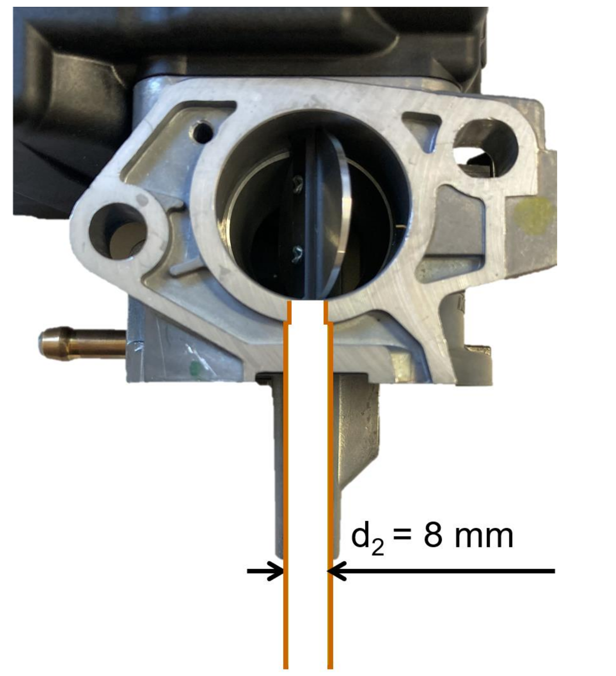


Fig. 2: Enlarged Fuel Riser

Test-Setup and Retrospective AFR-Determination

We tested three operating conditions: **steady-state operation** to explore the load limitations and examine steady-state stability; **load-step behaviour** to analyse stability under changing load conditions and to identify limiting parameters; and **emission measurements** to detect the present emission species.

The electrical load was imposed by a panel of conventional lightbulbs, with a resolution of 100 W. A **current sensor** monitored the attached electrical loads, a **differential pressure sensor** and manometer allowed the measurement of the pressure values at different access-points and a **potentiometer** mounted onto the throttle gear allowed the reading of the **throttle-valve position**. For the hydrogen flow an Alicat sensor was used: the emissions were measured with a MEXA-One analyser (HORIBA) for CO_2, CO, O_2, HC and NO_x and a Buveco ST650EX for unburned H_2.

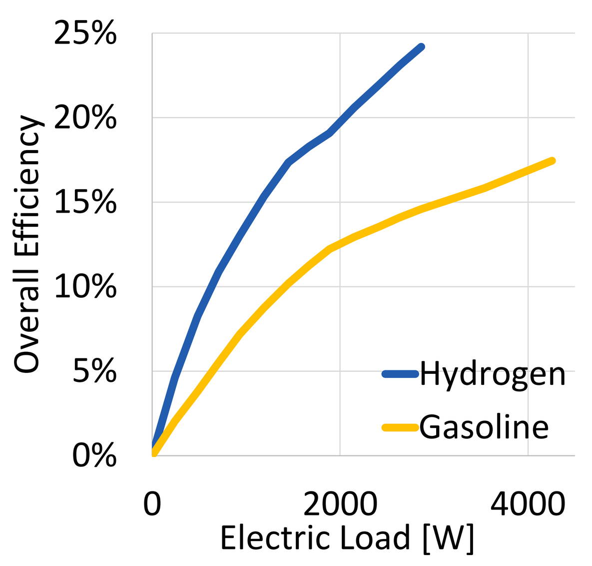
The air-to-fuel ratio was measured by both an adjusted oxygen balance according to ISO 8178-1 and a self-derived stoichiometric formula (more details in the reference: QR-Code):

$$\lambda = \frac{1 - [H_2]\cdot 10^{-4} - [O_2]\cdot 10^{-2}\cdot\left(1 - \left(3[H_2] + 2[NO_x]\right)\cdot 10^{-4}\right)}{1 - [O_2]\cdot 10^{-2}\cdot(1+\sigma)}$$

with $\sigma = \frac{[N_2],[Ar],[CO_2],[\dots]}{[O_2]} = \frac{79.054}{20.946}$

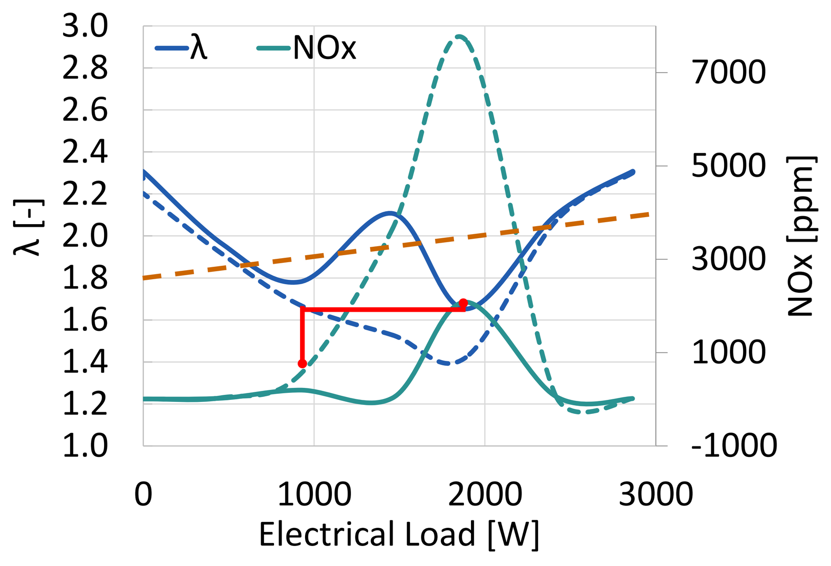
Results

Fig. 3: Overall Efficiency



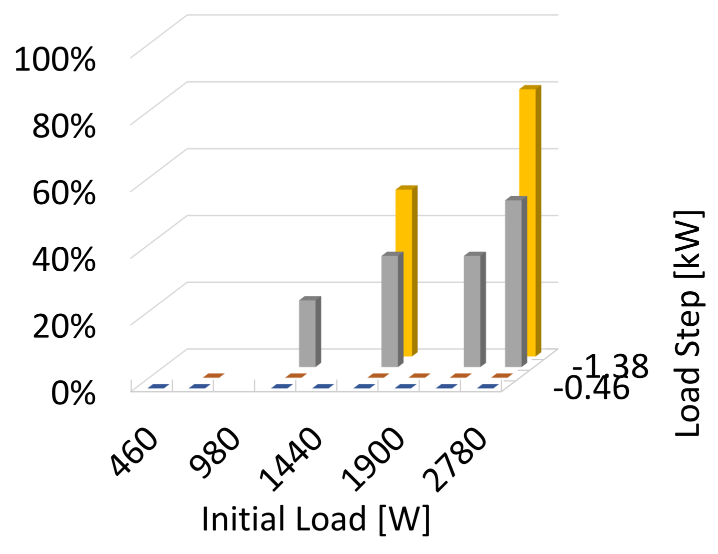
Comparing the gasoline and hydrogen mode overall efficiency (fuel input to electrical output) it becomes apparent that hydrogen reaches far better efficiency levels. The reason for that is mostly due to **rich running of the gasoline mode** ($\lambda = 0.9$), **lower pumping** losses due to wider open throttle in the case **of hydrogen** and **higher thermal efficiency** as the spark advance is fixed and the flame speed of hydrogen is higher.

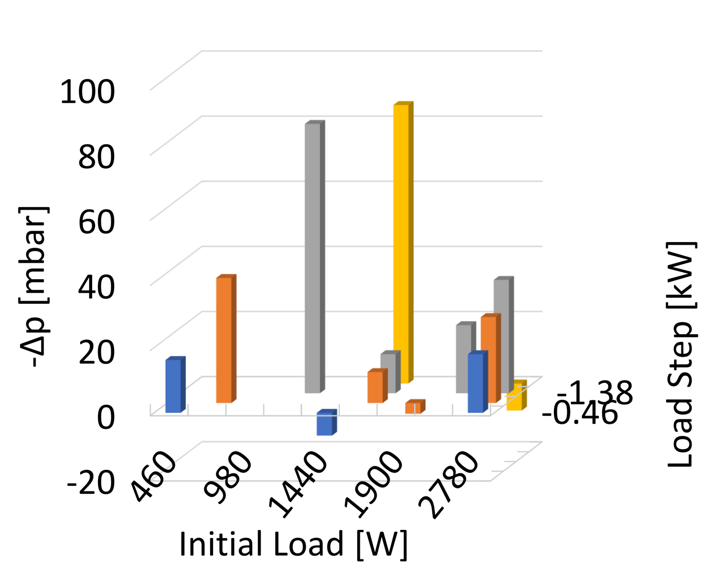
Fig. 4: NO_x levels vs. λ



The load-sweep up (solid lines) to an electrical load of 2800 W shows **strong correlation** between the lambda and NOx emission. For some reason, the grid supply had hysteresis upon down-sweeps which may originate in the multiple pressure regulators set in series. Whereas a **stable hydrogen supply pressure** allowed low $\mathbf{NO_x}$ (≤ 75 ppm), the unstable down sweep had much higher emissions with the **NOx-critical AFR level rising with increasing load** (brown dashed line). The red line connecting two equal levels of lambda at different load levels shows that the NO_x concentration at the higher load is also much greater.

Fig. 5: Flashback events, Fig. 6: pressure drop on load-step

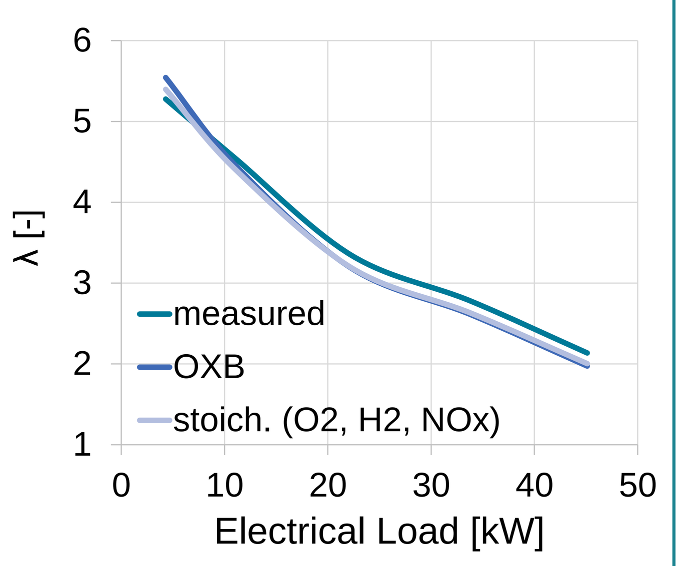




Discrete load steps from different starting points proved that **increases in load**, up to 2 kW at once, to be **unproblematic**. **Large negative steps**, however, often resulted in a single **flashbacks**. Fig. 5 shows that negative steps of size bigger than 1 kW (y-axis) occurred more often (z-axis) starting from initial loads above 1.5 kW (x-axis).

As higher loads lead to potentially more, and hotter, engine **hot-spots** which are more likely to **ignite fresh, incoming mixture**. Further, a denser charge inside the cylinder at high load increases the flame speed and heat release, both increasing the chance of a flame escaping through the closing intake valve. The latter was investigated with the help of an additional pressure measurement between the throttle and the intake valve (intake manifold). Fig. 6 shows that upon **closing** of the **throttle** the **pressure** in the intake manifold briefly **drops** below the steady state pressure ($-\Delta p$) at the new throttle position after the step. This leads to the assumption that for a short moment the pressure drop is large enough to pull back hot exhaust from within the cylinder igniting fresh mixture in the manifold.

Fig. 7: Validation of λ-model



The mentioned lambda calculation approaches were validated with engine data originating from one of CMB.TECH's test cells, where not only the hydrogen but also the air in-flow was measured. The **average relative offset**, over the whole sweep, for the **oxygen balance** (OXB) calculation was **−5.1%** and that for the **stoichiometric's** was **−4.3%**. Especially the latter proved to be an astonishingly simple to use but precise model to derive lambda from the species in the exhaust gases.

Summary

At the conclusion of this project, a determined set of parameter settings allowed the generator to run stably throughout for electrical loads corresponding to up to 57% of the initially rated power while keeping NO_x levels to a minimum and without tuning any inputs after starting-up the engine. The main challenges remained to be the unstable supply of hydrogen from the local supply grid fed by a tube trailer and the flashback events occurring at large negative load-steps.

The engine efficiency in hydrogen mode proved to be much higher than the gasoline's which could be further improved by optimizing engine parameters such as valve or spark timing to the newly introduced hydrogen fuel.

Most of the observed phenomena of interest, e.g. flashback and NO_x emissions, were found to be strongly connected to the prevalent load and lambda. To minimize the risk of rising NO_x concentrations, but in general also the occurrence of flashbacks, a lambda of 1.8 to 2 is optimal for this engine without lowering the nominal power to an unnecessary extent.

For the intended use as a generator for mobile lighting solutions, the CO_2 reduction over its lifetime can be more than 5 tonnes, presuming renewable sourcing of hydrogen.

Ongoing Work

After completing a full project cycle, starting with a broad literature review, all the way through mathematical analysis of fluid dynamic and chemical nature, ending with a detailed assessment of the recorded data, a lot of potential for future research was identified:

- **Sensor and engine setup:** A constant and simultaneous monitoring of pressures along the fuel and intake system, together with a temperature and pressure sensor reaching into the combustion chamber, would allow deeper understanding of the observed phenomena. Furthermore, altered valve and spark timing could possibly lead significant improvements regarding flash-backs.
- **Fuel Delivery System and Emissions:** New hydrogen storage technologies could lead to improved stability in hydrogen supply pressure as well as a reduced number of pressure regulators. Further, such a setup would allow the validation of the concept of a portable hydrogen genset.