EXPERIMENTAL AND NUMERICAL STUDY OF A HYDROGEN FUELLED I.C. ENGINE FITTED WITH THE HYDROGEN ASSISTED JET IGNITION SYSTEM

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Abstract
The use of hydrogen as an engine fuel poses several challenges as well as opportunities in engine design and control. These challenges are mainly due to hydrogen’s high flame temperatures at near stoichiometric mixtures, as well as the reactant volume fraction which can reduce the engine power output significantly. However, the wide flammability limits of hydrogen combustion in air mean that engine operation regimes can be achieved without the use of the engine throttle or exhaust after treatment. This paper presents results of experiments and computations for a research single cylinder pressure boosted hydrogen fuelled internal combustion engine (H₂-ICE) fitted with the Hydrogen Assisted Jet Ignition system (HAJI) and running extremely lean mixtures.

Introduction
H₂-ICE is a technology available today and economically viable in the near-term, with a number of test vehicles already presented [1-25]. This technology demonstrated efficiencies in excess of today’s gasoline engines and operate relatively cleanly (NOₓ is the only emission pollutant). There are fewer constraints concerning H₂-ICE compared to fuel cells. A dual-fuel option (H₂/gasoline) is possible and fuel impurities are not an issue. Increased efficiencies, high power density and reduced emissions are possible in the future with multi-mode operating strategies and advancement in ICE design and materials.

Some properties of hydrogen, CNG and gasoline are presented in Table 1. The unique combustion properties of hydrogen can be beneficial at certain engine operating conditions and pose technical challenges at other engine operating conditions. Favorable properties of H₂ are the wide flammability range for ultra lean operation, the high laminar flame speed for good stability and the high octane number for high compression ratios with improved thermal efficiency. Unfavorable properties of H₂ are the high percentage stoichiometric volume fraction with the consequent air displacement effects, the low minimum ignition energy with consequent propensity to pre-ignite, and the small quenching distance for thin thermal boundary layers.

In port fuel injection (PFI) H₂-ICEs, cold-start is not an issue because of the gaseous fuel, and NOₓ is the only non-trivial engine-out emission pollutant (if we ignore the upstream emissions in producing hydrogen). To satisfy SULEV requirements, H₂-ICEs must operate ultra-lean (λ>2.22). However, there are a few fundamental and practical obstacles related to SULEV operating strategies in PFI-H₂-ICEs. One of them is pre-ignition; the ignition of the fuel/air mixture before the spark plug fires. Ignition sources include residual gas causing back firing and engine hot spots, oil contaminants, and others [1]. These produce engine knock-like effects than can lead to engine damage. H₂ is predisposed to pre-ignition, and PFI H₂-ICEs fuelled by compressed hydrogen gas are most susceptible. It is very difficult to operate PFI H₂-ICEs at λ=1 in practice and to avoid pre-ignition the engine is operated lean. Consequently, engine torque (and power) is significantly reduced. With stoichiometric operation and after treatment practically inaccessible, continuous ultra-lean operation with no after treatment leads to low torque (power). Thus advanced H₂-ICEs and SULEV operating strategies are needed.

Advanced H₂-ICEs include pressure boosting (TC), liquid hydrogen fuelling, direct injection (DI), exhaust gas dilution (EGR) and multi-mode strategies. Pressure boosting allows continuous ultra-lean (λ=2.22) operation with improved power densities. Accessible stoichiometric (λ=1) operation with after treatment is obtained by using liquid hydrogen fuelling, exhaust gas dilution and direct injection. In liquid hydrogen fuelling, the cold mixture prevents pre-ignition and allows λ=1 operation. With exhaust gas dilution operation, lean-burn conditions are diluted with EGR such that λ=1 with no excess oxygen (a λ=1.66 operating point with 18% H₂ 44% air, 38% excess air is equivalent to a λ=1 operating point with 18% H₂ 44% air, 38% EGR). With direct injection, the injection timing is optimized (delayed) to prevent pre-ignition and allow for λ=1 operation. Direct injection may be used not only to produce a homogeneous H₂/air mixture, but also to create a stratified H₂/air mixture to reduce emissions and improve efficiency. The challenge is to deliver such a large fuel volume in a few crank angle degrees.

Table 1 - H₂ properties relevant to ICEs [12,13] (* Liquid at 0 °C; " At stoichiometry; " Vapor; “* At 25 °C and 1 atm).

<table>
<thead>
<tr>
<th>Property</th>
<th>Hydrogen</th>
<th>CNG</th>
<th>Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>0.0824</td>
<td>0.72</td>
<td>730°</td>
</tr>
<tr>
<td>Flammability limits (volume % in air)</td>
<td>4–75</td>
<td>4.3–15</td>
<td>1.4–7.6</td>
</tr>
<tr>
<td>Flammability limits (λ)</td>
<td>10-0.14</td>
<td>2.5-0.62</td>
<td>= 1.43-0.25</td>
</tr>
<tr>
<td>Auto ignition T in air (K)</td>
<td>858</td>
<td>723</td>
<td>550</td>
</tr>
<tr>
<td>Min. ignition energy (mJ)</td>
<td>0.02</td>
<td>0.28</td>
<td>0.24</td>
</tr>
<tr>
<td>Flame velocity (m/s)</td>
<td>1.85</td>
<td>0.38</td>
<td>0.37-0.43</td>
</tr>
<tr>
<td>Adiabatic flame T (K)</td>
<td>2480</td>
<td>2214</td>
<td>2580</td>
</tr>
<tr>
<td>Quenching distance (mm)</td>
<td>0.64</td>
<td>2.1</td>
<td>2</td>
</tr>
<tr>
<td>Stoichiometric fuel/air ratio</td>
<td>0.029</td>
<td>0.069</td>
<td>0.068</td>
</tr>
<tr>
<td>Stoichiometric vol. fraction</td>
<td>29.53</td>
<td>9.48</td>
<td>= 2°</td>
</tr>
<tr>
<td>Lower heating value (MJ/kg)</td>
<td>119.7</td>
<td>45.8</td>
<td>44.79</td>
</tr>
<tr>
<td>Heat of combustion (MJ/kg air)</td>
<td>3.37</td>
<td>2.9</td>
<td>2.83</td>
</tr>
<tr>
<td>Research octane number</td>
<td>&gt; 120</td>
<td>140</td>
<td>91-99</td>
</tr>
</tbody>
</table>

A few multi-mode strategies are available. Operation may be ultra-lean (λ=2.22) at low engine load, with exhaust gas dilution...
(EGR) stoichiometric ($\lambda = 1$) with after treatment at medium engine load and finally stoichiometric ($\lambda = 1$) with after treatment at high engine load. Alternatively, it may be ultra-lean ($\lambda > 2.22$) at low engine load and ultra-lean ($\lambda > 2.22$) or lean ($\lambda = 1.43$) with lean NOx trap (LNT) with pressure boosting supercharger at medium or high engine load. In case of direct injection hydrogen fuelling, it may also be stratified ultra-lean ($\lambda = 5$) at idle, ultra-lean ($\lambda > 2.22$) at low engine load, stratified lean ($1 < \lambda < 2.22$) with LNT after treatment at medium engine load, stratified stoichiometric ($\lambda = 1$) with after treatment at high engine load.

This paper focuses on the development of a pressure boosted, throttle-less PFI-H2ICE. Combustion in the main chamber of a pressure boosted ASTM-CFR single cylinder research engine of homogeneous H2-air mixtures from stoichiometric to extremely lean is analysed experimentally and numerically. This engine is equipped with the Hydrogen Assisted Jet Ignition (HAJI) system.

The HAJI technology was developed and patented by the third author in 1992 to improve ignition of premixed mixtures of air and different fuels. High thermal efficiency may be achieved through reduced pumping, heat, and chemical dissociation losses and increased ratio of specific heats. In addition, the higher turbulent flame speed caused by the jets and chemically controlled active species produced by HAJI results in shorter burn duration of premixed mixtures of air and different fuels [2,3].

### Single cylinder research engine

The test engine is an ASTM-CFR engine manufacturer by Waukesha Motor Co., Waukesha, Wisconsin, US. This is a single-cylinder engine having capacity 611.7 cm³, bore 82.5 mm, stroke 114.3 mm, valve seat insert inside diameter 30.1 mm, connecting rod length 254.0 mm, ports minimum diameters 31.7 mm, compression ratio infinitely variable, combustion chamber plane and cylinder diameter 82.5 mm, stroke 1143 mm, bore 82.5 mm, stroke 114.3 mm, valve seat insert inside diameter 30.1 mm, connecting rod length 254.0 mm, ports minimum diameters 31.7 mm, compression ratio infinitely variable, combustion chamber plane and cylinder diameter 82.5 mm, stroke 1143 mm. EVO=50° BBDC, EVC=15° ATDC. The standard engine is regulated to a steady value of 100°C. This also allowed the oil to circulate through the engine was consistently monitored and regulated to a steady value of 100°C. H2 is measured by a digital Brooks 5860E gas flow meter. The air flow through the engine is measured with a calibrated orifice meter and the corresponding calibration constants were developed based on the British Standard BS1042.

In order to operate the CFR engine in boosted mode, a 200 litre tank pressurized to 8 bars is connected to the engine. Exhaust gas emissions are measured using an ADS 9000 Super Five Gas Analysit. It measures the concentrations of CO2(%), COV(%), O2(%), HC(ppm), and NOx(ppm). These exhaust products are used to calculate the AFR by performing a chemical balance of the reactants and products. A Kistler 601B1 piezoelectric pressure transducer mounted in the cylinder head is connected to a 462-A-05 PFC charge amplifier and used for in-cylinder pressure measurement.

The main chamber H2 flow is measured with a series of sonic nozzles calibrated for H2. The pre-chamber H2 is measured by a digital Brooks 5860E gas flow meter. The air flow through the engine is measured with a calibrated orifice meter and the corresponding calibration constants were developed based on the British Standard BS1042.

Before any data is collected, the water jacket temperature circulating through the engine was consistently monitored and regulated to a steady value of 100°C. This also allowed the oil to warm up as the engine was run for approximately 15 minutes at $\lambda = 1.6$ and 1800 rpm. This warm up period allowed the IMEP and...
BMEP outputs to stabilize and the ADS9000 exhaust gas analyser to be warmed.

**Figure 2** - Schematic layout of the engine including controllers, sensors and data acquisition systems.

**CAE model**

The operation of the ASTM–CFR single cylinder research engine with HAJI is also modelled by using the GT-POWER [26] CAE software. GT-POWER is an industry-standard engine simulation tool, specifically designed for both steady state and transient performance simulations, used by engine and vehicle makers and suppliers.

GT-POWER’s ‘predictive’ SI turbulent flame combustion model is used in this paper. This model includes effects of the cylinder’s geometry, spark-timing, charge motion and mixture properties. It is assumed that the combustion is flow driven once flame kernel becomes larger than the turbulent length scale. The initial growth of the flame depends on the laminar flame speed. This speed is a function of fuel, dilution, temperature and pressure. Once the flame entrains unburned mixture, the mixture is assumed to burn after a slight delay (based on flame thickness). The laminar flame speed is calculated by the following equation:

\[
S_L = \left( B_m + B_a \cdot (\Phi - \Phi_m)^\gamma \right) \cdot \left( \frac{T_u}{T_{ref}} \right)^\alpha \cdot \left( \frac{p}{p_{ref}} \right)^\beta \cdot (1 - 2.06 \cdot RMF^{0.77})
\]

where \( S_L \) is the laminar flame speed, \( B_m \) the maximum laminar speed, \( B_a \) the laminar speed roll-off value, \( \Phi \) the in-cylinder equivalence ratio, \( \Phi_m \) the equivalence ratio at maximum speed, \( T_u \) the temperature of the unburned gas, \( RMF \) the mass fraction of the residuals in the unburned zone, \( \alpha \) a temperature ratio exponent function of \( \Phi \) [29], \( \beta \) a pressure ratio exponent function of \( \Phi \) [29], \( \gamma \) a dilution exponent multiplier, \( T \) the temperature and \( p \) the pressure. The default constant laminar speed roll-off value \( B_a \) is modified as a function of the intake flow equivalence ratio \( \Phi_i \) to properly simulate combustion in extremely lean conditions with HAJI.

**Results and discussion**

In conventional spark plugs, the spark timing is the time of spark and the initial spark size is the same as the gap between the sparkplug electrodes. With HAJI, the spark plug ignites the richer pre-chamber mixture, and the jet then ignites the leaner main chamber. The geometry of the head and piston and the location of the equivalent spark plug define the geometry of the flame. Equivalent spark timing and initial spark size must be prescribed.

A laminar flame speed correlation is provided in [26] for \( H_2 \) down to an equivalence ratio of 0.1 below which flame quenches. This correlation is based on [27]. A correction is applied to the base flame speed to account for the effect of temperature, pressure and dilution. Once the flame entrains unburned mixture, the mixture is assumed to burn after a slight delay (based on flame thickness).

Experiments and computations have been performed for the engine operating points (manifold air pressure \( MAP \), equivalence ratio \( \Phi \), ratio of HAJI to total hydrogen, spark advance \( SA \)) presented in Table 2. Other engine operating conditions are engine speed 1800 rpm, compression ratio 11, HAJI injection timing 90° BTDC, water temperature 100° C and air pressure (dry) 99.5 kPa. Spark advances are not maximum brake torque (MBT) values. Experimental data was collected by Hamori in 2002 [3].
Results of experiments and computations are presented in Figure 3-6. Decreasing $\Phi$ has obvious effects: the air flow increases because the hydrogen flow reduces, the energy available for combustion reduces, the laminar flame speed reduces, the combustion rate deteriorates, the spark timing is advanced to compensate the reduced rate of combustion, the peak pressure reduces, IMEP reduces. As MAP increases, the air flow rate increases. However, IMEP does not increase proportionally to the air flow rate because of the different combustion rate and spark advance.

The presented experimental and computational results agree surprisingly well, and within the estimated accuracy of the numerical techniques and in spite of the unorthodox ignition system. When reference is made to standard spark plug ignition, these results show that HAJI can be modelled to an acceptable degree for design purposes at least in a reasonably orthodox manner. Of course, HAJI increases the flame speed, and produces a faster growth rate of the flame kernel, for an advanced transition from laminar combustion to turbulent combustion, and a faster main turbulent combustion.

![Figure 3 – Experimental and computational air flow rate vs. equivalence ratio.](image1)

![Figure 4 – Experimental and computational IMEP vs. equivalence ratio.](image2)

![Figure 5 – Experimental and computational peak pressure vs. equivalence ratio.](image3)

![Figure 6 – Experimental and computational location of peak pressure vs. equivalence ratio.](image4)
### Table 2 – Engine operating points.

<table>
<thead>
<tr>
<th>MAP [kPa]</th>
<th>Φ Tot.</th>
<th>HAJI/Tot.H2</th>
<th>SA [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>0.564</td>
<td>0.024</td>
<td>20</td>
</tr>
<tr>
<td>90</td>
<td>0.413</td>
<td>0.031</td>
<td>22</td>
</tr>
<tr>
<td>90</td>
<td>0.370</td>
<td>0.034</td>
<td>28</td>
</tr>
<tr>
<td>90</td>
<td>0.295</td>
<td>0.041</td>
<td>32</td>
</tr>
<tr>
<td>90</td>
<td>0.226</td>
<td>0.053</td>
<td>36</td>
</tr>
<tr>
<td>90</td>
<td>0.180</td>
<td>0.065</td>
<td>40</td>
</tr>
<tr>
<td>120</td>
<td>0.734</td>
<td>0.146</td>
<td>-1</td>
</tr>
<tr>
<td>120</td>
<td>0.581</td>
<td>0.169</td>
<td>2</td>
</tr>
<tr>
<td>120</td>
<td>0.446</td>
<td>0.200</td>
<td>5</td>
</tr>
<tr>
<td>120</td>
<td>0.378</td>
<td>0.255</td>
<td>7</td>
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<tr>
<td>120</td>
<td>0.277</td>
<td>0.342</td>
<td>14</td>
</tr>
<tr>
<td>120</td>
<td>0.221</td>
<td>0.414</td>
<td>26</td>
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<tr>
<td>120</td>
<td>0.170</td>
<td>0.519</td>
<td>48</td>
</tr>
<tr>
<td>150</td>
<td>0.666</td>
<td>0.121</td>
<td>3</td>
</tr>
<tr>
<td>150</td>
<td>0.442</td>
<td>0.169</td>
<td>5</td>
</tr>
<tr>
<td>150</td>
<td>0.280</td>
<td>0.247</td>
<td>9</td>
</tr>
<tr>
<td>150</td>
<td>0.240</td>
<td>0.296</td>
<td>15</td>
</tr>
<tr>
<td>150</td>
<td>0.190</td>
<td>0.375</td>
<td>36</td>
</tr>
<tr>
<td>190</td>
<td>0.486</td>
<td>0.122</td>
<td>-1</td>
</tr>
<tr>
<td>190</td>
<td>0.323</td>
<td>0.169</td>
<td>5</td>
</tr>
<tr>
<td>190</td>
<td>0.279</td>
<td>0.200</td>
<td>15</td>
</tr>
<tr>
<td>190</td>
<td>0.214</td>
<td>0.258</td>
<td>27</td>
</tr>
<tr>
<td>190</td>
<td>0.179</td>
<td>0.292</td>
<td>45</td>
</tr>
</tbody>
</table>

The spark ignition turbulent combustion model parameters have to be recalibrated with experiments for different engine configurations to adjust the effects of turbulence intensity and length scale.

### Conclusions

This paper has presented results of experiments and computations for a hydrogen fuelled internal combustion engine (HICE) fitted with the Hydrogen Assisted Jet Ignition (HAJI) system. The engine used pressure boosting and continuous operation to ultra-lean over a range of equivalence ratios and manifold air pressures. The measured influence of equivalence ratio, manifold air pressure and spark advance is captured surprisingly well by the simulations. Of course, experiments and computations then also agree very well for air flow and IMEP values.

This study shows that simple and computationally inexpensive SI turbulent flame combustion models may be used for engine design if experimental data for the particular application are collected first. Validation of the model is an essential element of its application. When reference is made to standard spark plug ignition, these results show that HAJI can be modelled in a reasonably orthodox manner. HAJI is observed to increase the flame speed and produces a faster growth rate of the flame kernel, for an earlier transition from laminar combustion to turbulent combustion, and a faster main turbulent combustion.

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