Hydrogen Assisted Jet Ignition for the Hydrogen Fuelled SI Engine

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ABSTRACT:
Over a decade of research has gone into the development of combustion initiated with hydrogen assisted jet ignition (HAJI). This paper describes the application of HAJI to an hydrogen fuelled ultra lean burn engine with supercharging. HAJI uses a small pre-chamber built into a standard spark plug body into which hydrogen is injected late in the compression process. On ignition the fuel rich mixture generates OH and H rich jets that traverse the combustion chamber accelerating lean main-chamber flames several times their normal flame speed, allowing repeatable ignition of mixtures as lean as lambda seven for hydrogen main chamber fuel. Thus HAJI has many of the desirable virtues of HCCI engine but with ability to operate without throttling over the entire load-speed range. Application is described to homogeneous charge preparation and results compared with conventional spark ignition and also with gasoline main chamber fuel. A peak thermal efficiency of 40% was achieved at lambda of 3.3 with NOx at less than 0.1 g/kWh. The results represent an improvement in peak thermal efficiency of over 20% and 30% at the 1800 rev/min, 300 kPa IMEP world-wide mapping point speed and load condition whilst achieving the almost zero NOx. Moreover the engine was shown to operate greater than the IMEP of the NA gasoline engine at this NOx condition with the aid of supercharging.

KEYWORDS: Thermal efficiency, nitrogen oxides, lean burn, hydrogen assisted ignition, Australian Research Council.

INTRODUCTION

A long time goal in SI engine combustion development has been to simultaneously reduce the pollutants formed in the combustion chamber and increase thermal efficiency. Otto cycle theory suggests that high compression ratios will give high efficiency accompanied by high peak cycle pressures and temperatures. High temperatures have high NOx forming potential. This can be reduced by dilute (lean or high EGR) mixtures. As will be shown NOx can be almost eliminated (0-2 ppm) if lean homogeneous charge mixtures can be successfully ignited. Two methods of ignition have been studied by the authors, namely homogeneous charge compression ignition (1) and hydrogen assisted jet ignition (HAJI). Problems arise from high compression ratios and low combustion temperatures such as increased surface area to volume ratio, increased wall layer and crevice densities, having the potential to limit the fuel fraction that burns immediately. Further, low combustion temperatures and high expansion ratios give low exhaust temperatures making post engine oxidation of unburnt fuel more difficult.

Hydrogen Assisted Jet Ignition (HAJI)

This paper is a report of a decade’s application of a combustion initiation system which extends the ignition of normally prepared fuel-air mixtures through lean to the ultra lean ($\lambda = 5$ to $7$) region of a wide range of fuels. The combustion enhancement process is hydrogen assisted jet ignition (HAJI). This concept began in our research into prechamber nozzle sizing (2), the study of the effects of hydrogen addition as a flame speed enhancer (3), the development of dedicated hydrogen engines (4), and inspiration from the by the work of Oppenheim (5) and others on jet combustion. The concept of pre-chamber SI combustion initiation is not new, the Honda CVCC(6) and the work of Gusack (7) with the LAG process are two notable examples. A major difference is the size of the HAJI pre-chamber which is much smaller; small enough to fit in a spark plug body, and typically comprises only...
0.7% of the main chamber clearance volume, and is direct injector fuelled with minute quantities of hydrogen (8) and seen in Figure 1.

Figure 1: Schematic of a single orifice HAJI injector

**OBJECTS**

This paper demonstrates how a HAJI equipped SI engine in H₂ main chamber mode can simultaneously reduce emissions and increase thermal efficiency at all loads by utilising ultra lean air-fuel ratios - lean mixture combustion well beyond the stability limit of standard homogeneously charged SI engines. The specific objectives are:

1. To determine the optimum CR, lambda, and boost in a HAJI fitted gasoline and H₂ engine which provides acceptable combustion stability with the lowest NOₓ
2. To demonstrate experimentally the performance, emissions and thermal efficiency benefits of HAJI over its SI counterpart
3. Report on the analysis of the combustion phenomena with the aid of a two zone combustion model.

**APPARATUS AND PROCEDURE**

Previous HAJI work in the CFR engine by Lumsden (9) established that speed has less effect on emissions than AFR. A mid-speed of 1800 r/min, corresponding to a typical engine r/min frequently used in the European emission test cycle, was therefore chosen for most of this study (tests were also performed at 1200 r/min). Inlet temperature, port-induced cylinder motion, cam timing, and combustion chamber shape were held constant throughout the experiments and EGR (exhaust gas recirculation) was not explored. Eliminating these variables enabled the target parameters such as compression ratio CR, air/fuel ratio or Lambda (the relative air/fuel ratio) and manifold absolute pressure MAP to be more thoroughly examined.

The specification of the CFR engine normally used for aviation fuel octane rating is given in Table 1 and shown schematically in Figure 2.

A Motec M4 engine control unit (ECU) was used to control spark timing and H₂ injector duration and timing in both SI and HAJI modes. The ECU also allowed for outputs to be logged in real-time via a computer interface.

The use of a reference wheel and a GT101 hall effect sensor fitted to the camshaft allowed the detection of both engine crank angle and cycle position. A Bosch ignition module (0227 100 124) was
connected to a Bosch MEC 718 coil supplying energy to the spark plug with a transistorised coil ignition system.

### Table 1 Specification of the test engine

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASTM – CFR Single Cylinder Research Engine</strong></td>
<td></td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Waukesha Engine Co.</td>
</tr>
<tr>
<td>Capacity</td>
<td>611.7 cm³</td>
</tr>
<tr>
<td>Bore x Stroke</td>
<td>82.6 x 114.3</td>
</tr>
<tr>
<td>Engine Control Unit</td>
<td>MOTEC M4</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>5 to 20 infinitely variable</td>
</tr>
<tr>
<td>Combustion Chamber</td>
<td>Plane Cylindrical</td>
</tr>
<tr>
<td>Inlet valve Opening</td>
<td>10° ATDC</td>
</tr>
<tr>
<td>Inlet valve Closing</td>
<td>34° ABDC</td>
</tr>
<tr>
<td>Exhaust Valve Opening</td>
<td>40° BBDC</td>
</tr>
<tr>
<td>Exhaust Valve Closing</td>
<td>15° ATDC</td>
</tr>
<tr>
<td>Dynamometer Type</td>
<td>AC, constant speed, belt driven to engine, variable pulley sizes for speed selection.</td>
</tr>
<tr>
<td>Fuel</td>
<td>Commercial Grade H2 (99% purity)</td>
</tr>
</tbody>
</table>

**Figure 2**  
Schematic layout of the test engine and ancillaries

A Delco 3 bar MAP sensor allowed the manifold air pressure to be monitored. In order to dampen fluctuations caused by pressure pulsations in the plenum, a small diameter copper tube restrictor was placed between the intake plenum and the MAP sensor. Emissions were measured using an
ADS9000 multi-gas analyser. Cylinder pressure was measured using a Kistler 603B1 piezo-electric pressure transducer which together with crank position indicator allowed the real-time calculation of IMEP (indicated mean effective pressure) and its coefficient of variation COV of IMEP.

In an SI engine, the role of the spark plug is vital for optimum engine operation. In contrast, the operation of the HAJI unit is not sensitive to the type of spark plug and is more dependent on the design of the prechamber volume, the number of orifices, and their diameters, length and orientation of these orifices.

The HAJI nozzle used in this research was designed to have the following characteristics:

- Single orifice with a 2mm diameter to allow moderately jet penetration, maximise jet temperature, and allow the use of spherical flame modeling;
- 0.9cc pre-chamber as the international patent application by Watson (12) states that the prechamber must be sized between 0.5-2% of the clearance volume, which falls into the range of CR=4.4 to CR=15 respectively;
- 3mm orifice length which was determined via a parametric study.

RESULTS OF MEASURED PERFORMANCE

The cylinder pressure results obtained are illustrated in Figure 3 which shows example cylinder pressure, rate of pressure rise and mass burn fraction with crank rotation. The latter is obtained by the E-Cobra code written by one of the authors (10).

Figure 3 Typical pressure diagrams, their derivatives and mass burned fraction (MBF) for SI and HAJI.
For the results at $\lambda=1$ and $\lambda=1.85$ are presented in Figures 3, analysis was carried out by analysing consecutive individual cycles, which were used to develop ensemble average diagrams. As an example Figure 3 (top) shows the 40 individual cycles for pressure vs. CA for $\lambda=1$, $\lambda=1.85$ and motoring condition. The thick lines represent the ensemble average of all three conditions. Therefore each data point for peak pressure, location of 50% MFB, peak temperature etc were derived from the ensemble average of 40 consecutive cycles. This technique was used to ensure with 99.9% confidence that the population mean differed from the sample mean by no more than +/- 3% (11). Analysis of sets of ten 40 cycle sequences at low $\lambda$ values showed that the IMEP varied less than +/- 1% and at high $\lambda$ values less than 2%.

Figure 4: HAJI-H₂ - IMEP (top), CoV of IMEP (middle), MBT (bottom).@ 1800r/min. Varying Lambda @CR=11 (left), MAP=90kPa CR varying, (right), dark shaded area indicates backfire limited conditions.
The results have been summarised as contour plots according to the constraints of Table 2

**Table 2** Summary of results presentation

<table>
<thead>
<tr>
<th>Ignition Mode: HAJI-Hydrogen (HAJI-H₂)</th>
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<tbody>
<tr>
<td>Speed</td>
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<tr>
<td>Spark Timing</td>
</tr>
<tr>
<td>CR vs. Lambda (λ) contour plots at MAP = 90 kPa</td>
</tr>
<tr>
<td>Lambda (λ) vs. MAP contour plots at CR = 11 (HUCR)</td>
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</tbody>
</table>

IMEP is influenced by λ and MAP Figure 4 (top) consequently an increase in one or the other or both will increase the magnitude of IMEP. It is worth noting that in naturally aspirated mode at MAP=90kPa (WOT) the engine was backfire limited at λ=1.79, where IMEP=460kPa. The results were extrapolated out to λ=1 where IMEP=600kPa could be achieved in the absence of backfire. However at MAP=190 at λ=2.1 an IMEP of 1044kPa was recorded with the total elimination of backfire. This was concluded to be the results of additional cooling of the combustion surfaces and reduction in the backflow of hot residual gases. Furthermore along the Optimum Performance Line, OPL, a maximum of 850kPa IMEP can be produced. This is a substantial increase in IMEP when considering that at best (backfire free) at λ=1 in naturally aspirated mode only 600kPa IMEP can be achieved and is about 30 kPa above the gasoline normally aspirated operation.

**Figure 5**: HAJI-H₂ – Indicated thermal efficiency (top), indicated specific NOx (bottom).@ 1800r/min. Varying Lambda @CR=11 (left), MAP=90kPa CR varying, (right), dark shaded area indicates backfire limited conditions.
Figure 5 shows that for any given $\lambda$, the maximum thermal efficiency occurs at around CR=11. Peak thermal efficiency on the CR vs. $\lambda$ plot occurs at $\lambda=2.5$ and at CR=11. When observing the MAP vs. $\lambda$ plot, it is clear that thermal efficiency can be further increased to 39% by boosting the MAP to 160kPa at $\lambda=3$. This means the thermal efficiency can be increase by ~30% going from a $\lambda=1$ engine operating at a MAP=90, to a $\lambda=3$ engine operating at a MAP=160kPa. Following the OPL in Figure 5 (bottom), the engine out NO$_x$ in HAJI-H$_2$ mode is ~0.1g/kWh. This low NO$_x$ capability is maintained at all load points while achieving exceptional combustion stabilities. The operation of a H$_2$ engine at near $\lambda=1.79$ should be avoided as it produces up to 18g/kWh of NO$_x$, which is due to the high flame temperatures of H$_2$ seen later. Overall, the insensitivity of NO$_x$ to MAP means that inlet boost can be increased beyond 200kPa if higher power output is required while maintaining 0.1g/kWh NO$_x$ capability.

Figure 6: HAJI-H$_2$ – peak cylinder pressure (top), peak pressure rise rate (bottom), @ 1800r/min. Varying Lambda @CR=11 (left), MAP=90kPa CR varying, (right), dark shaded area indicates backfire limited conditions.

The magnitude of peak pressure (Figure 6 top) increases with increasing CR and MAP. At any given MAP the peak pressure increases up to around $\lambda=3$ and then decreases as the mixture is leaned out further. The peak pressures at $\lambda=1$, MAP=90 and at $\lambda=3$, MAP=170 are of similar order (5Mpa), however, the IMEP is about 100kPa higher and the NO$_x$ is reduced from 30g/kWh to 0.1g/kWh at $\lambda=3$. The rate of pressure rise ($dp/d\theta$) is an indicator of how fast combustion occurs. In HAJI-H$_2$ mode it is up to 200kPa/deg (Figure 6 bottom). This is expected as HAJI-H$_2$ mode shows high MBR and short burn duration. $dp/d\theta$ at low $\lambda$ conditions is dominated by combustion energy release as close to TDC the contributions from the piston motion is minimal. At high $\lambda$, MBR decreases and consequently MBT becomes advanced. In these cases, $dp/d\theta$ is affected both by compression and combustion. Despite the additional effect of decreasing volume, the rate of pressure rise is still lower than at low $\lambda$. 

Figure 6 : HAJI-H$_2$ – peak cylinder pressure (top), peak pressure rise rate (bottom), @ 1800r/min. Varying Lambda @CR=11 (left), MAP=90kPa CR varying, (right), dark shaded area indicates backfire limited conditions.
RESULTS FROM DATA ANALYSIS

Figure 7: HAJI-H₂ – peak cylinder temperature (top), peak pressure rise rate (bottom). @ 1800r/min. Varying Lambda @CR=11 (left), MAP=90kPa CR varying, (right), dark shaded area indicates backfire limited conditions.

As shown in Figure 7 (top), the peak cycle temperature is mainly a function of $\lambda$, and it is unaffected by CR or MAP. The peak combustion temperature varies from 1400K to 2700K. Along the OPL, the temperature is about 1800K, which is primarily responsible for the reduction of NOx from 30g/kWh (at $\lambda$=1) to 0.1g/kWh (at $\lambda$=3) (Figure 6.3). The insensitivity of combustion temperature to MAP is the mechanism which allows the engine to be boosted while maintaining almost zero NOx.

Figure 7 (bottom) shows that the total burn duration is strongly dependent on $\lambda$ and varies little with CR and MAP. Near $\lambda$=1, the flame propagates through the entire combustion chamber in less than 20 CAD and at around $\lambda$=6 it takes approximately 60 CAD. Along the OPL the total burn duration varies from 40 to 53 CAD, this is approximately 20 CAD less than what is observed in HAJI-G (gasoline) mode (10). This is interesting because in HAJI-H₂ mode this OPL is around $\lambda$=3, as opposed to $\lambda$=1.9 for HAJI-G. This indicates that for an equivalent MAP and CR at a given $\lambda$, the reaction rate-limited combustion is higher for HAJI-H₂ than for HAJI-G.

The location of peak flame speed in Figure 8 (top) is dependent on CR, MAP and $\lambda$. High flame speeds occur in both $\lambda$=1 and $\lambda$=6 mixtures. Flame speed is influenced by density, the relative amount of energy in the prechamber jets as they influence the MBR and flame surface area, hence, for a given $\lambda$, peak flame speed increases as the CR increases. However, flame speed drops as MAP is increased. This is because high pressures actually have the tendency to lower flame speeds. High flame speeds are also observed at high $\lambda$ values early in the compression stroke near MBT. Here, the
flame’s surface is small and cylinder pressures are low, both of which have the tendency to increase flame speed.

![Figure 8](image)

**Figure 8**: HAJI-H<sub>2</sub> – peak flame speed (top), turbulent/laminar flame speed ratio (FSR<sub>a</sub>) at 50% MBF (bottom).@ 1800r/min. Varying Lambda @CR=11 (left), MAP=90kPa CR varying, (right), dark shaded area indicates backfire limited conditions.

The FSR<sub>a</sub> shown in **Figure 8** (bottom) is the ratio of the turbulent to laminar flame (S<sub>t</sub>) speeds. FSR<sub>a</sub> varies relatively little with CR and MAP and is primarily a function of λ. This is due to the dramatic decrease in S<sub>t</sub> at high λ conditions. Values of FSR<sub>a</sub> > 100 should treated cautiously as S<sub>t</sub> calculations are unreliable in that range. At low MAP along the OPL line, the FSR<sub>a</sub> is initially around 6 but when MAP exceeds 90kPa, the magnitude of the FSR<sub>a</sub> exceeds 100. It is worth noting that according to the Damkohler relationship, when FSR=100 the turbulent flame surface area is 100 times larger than the smooth laminar flame area. This would indicate an extraordinarily wrinkled turbulent flame in the combustion chamber, which is very unlikely in the presence of low turbulence intensity. Hence, this indicates that the chemical effects of HAJI previously reported (8,9) are playing a dominant role.

**COMPARISON WITH SPARK IGNITION AND GASOLINE**

The most influential variable affecting the combustion stability enumerated as CoV of IMEP for SI and HAJI is λ, as seen in **Figure 9** (top). SI-G performs well around stoichiometric, however it fails to operate acceptably beyond λ=1.35. SI-H<sub>2</sub> is backfire limited below λ=1.48 and unable to operate satisfactorily above λ=2.5. In gasoline mode at λ=1, when the SI engine was fitted with HAJI, the CoV of IMEP dropped from 1.8% to <0.9%. HAJI also extended the acceptable lean limit (<5% of CoV of IMEP) for gasoline to λ=2.1 and for H<sub>2</sub> to λ=5.
In the SI-H₂ mode the engine became backfire limited at $\lambda = 1.48$ and in HAJI-H₂ mode at $\lambda = 1.7$, corresponding to 580kPa and 520kPa IMEP respectively. It is worth noting that backfire is a power limiting factor only at this operating point (WOT), and that in lean supercharged HAJI-H₂ mode >1000kPa IMEP was developed as already discussed above.

In Figure 9 (middle) all modes around $\lambda = 1$, NOₓ emissions climb above 15g/kWh. As $\lambda$ increases combustion temperatures drop and the rate of NOₓ formation decreases dramatically. In a gasoline fueled SI engine, NOₓ reduce to 5g/kWh and fueled with H₂, NOₓ can be reduced to 0.54g/kWh. In contrast, HAJI in both gasoline and H₂ mode can reduce the NOₓ to 0.1g/kWh. In gasoline mode, this translates to a reduction of >99% in NOₓ emissions over its SI counterpart and in H₂ mode to a reduction of >90%. It is worth noting that as $\lambda$ increases in HAJI mode, NOₓ emissions start to climb up again. This is due to the reduction in thermal efficiency and an increase in combustion temperature and residence time due to more advanced spark timing at high $\lambda$ values.

Finally in examining calculated burn times it has been found as expected that HAJI not only decreases the initial burn duration, but also decreases the total burn duration as is shown in Figure 9 (bottom). This allows the spark timing to be retarded, which results in an increase in thermal efficiency and reduced residence time at high temperatures for less NOₓ production. The greatest
reduction in total burn duration is achieved in HAJI-H2 mode at any given $\lambda$. HAJI-G reduces the total burn duration over SI-G by up to 50% at any given $\lambda$ and HAJI-H2 reduces the total burn duration over SI-H2 by up to 36%. In summary, the remarkable burning ability of $H_2$ is demonstrated in HAJI-H2 mode at $\lambda=6$, where the total burn duration is equal to the $\lambda=1$ SI-G engine.

CONCLUSIONS

HAJI has many of the desirable virtues of HCCI engine but with ability to operate without throttling, EGR or thermal intake management over the entire load-speed range. The applications have been described in this paper using: the high speed CFR engine with variable compression ratio, and supercharging to study supercharge pressure-compression ratio interactions have been studied for liquid and gaseous fuels and particularly hydrogen. It has been shown that with HAJI, the hydrogen engine can operate with no NOx emission (< 5 ppm) and with a two fold improvement in thermal efficiency at 300 kPa IMEP load and 1800 or 1200 r/min speed operating conditions. With the aid of supercharging the engine can exceed its normally aspirated gasoline MEP and still produce no NOx. Evidence not reported in this paper indicates that, with a four-valve per cylinder arrangement and central HAJI, a production engine with this technology should be competitive on efficiency with a fuel cell power unit and highly competitive on performance and cost.

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REFERENCES