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## THE LEAN LIMIT AND EMISSIONS OF A GASOLINE HAJI SYSTEM THAT EMPLOYS SYNGAS IN PLACE OF HYDROGEN AS THE PRECHAMBER FUEL

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KEYWORDS – Hydrogen Assisted Jet Ignition (HAJI), Lean Burn, Reformed Fuel, Prechamber, Syngas

ABSTRACT - Gas assisted jet ignition is an advanced ignition process that allows ignition of ultra lean mixtures in an otherwise standard gasoline fuelled spark ignition engine. Under typical operating conditions, a small amount of gaseous fuel is injected into a prechamber and then ignited by a spark plug. Upon ignition, the fuel rich prechamber mixture generates a jet of chemically active combustion products that issue through an orifice, which connects to the main chamber, and burns the main charge rapidly and with almost no combustion variability (less than 2%  $COV_{IMEP}$  even at  $\lambda=2.5$ ). Thus gas assisted jet ignition has many of the desirable qualities of HCCI but with the ability to operate without throttling, EGR or thermal intake management over the entire load-speed range. In order to overcome the refuelling and storage problems associated with  $H_2$ , the conventional prechamber fuel used in this process, the viability of other prechamber fuels is assessed based on criteria such as combustion stability, lean limit and emission levels. The prechamber fuels tested consist of syngas or simulated reformed petrol ( $CO$ ,  $H_2$  and  $N_2$ ) and variants of reformed fuel with different component ratios.

### TECHNICAL PAPER – INTRODUCTION AND BACKGROUND TO HAJI

Hydrogen assisted jet ignition (HAJI) is an advanced prechamber (PC) ignition process that involves the use of a chemically active, turbulent jet to initiate combustion of ultra lean mixtures in an otherwise standard gasoline fuelled engine. The HAJI unit installs into the spark plug bore and consists of a small PC, spark plug and PC direct injector (Figure 1). In the HAJI process, a small amount of hydrogen ( $H_2$ ) (about 2% of the main fuel energy or approximately 1 g/km  $H_2$ ) is injected next to the spark plug electrodes inside the PC so that a rich mixture is formed. Once the  $H_2$  mixture in the PC is ignited, the combusting gas travels through one or more orifices into the main chamber (MC) at high speed, where it then entrains and ignites the lean MC charge. The existence of chemically reactive intermediate products (active radicals H and OH) in addition to high levels of turbulence in the jets cause an energy level more than two orders of magnitude higher than that which is found in a spark [1]. Similar ignition benefits of several other prechamber ignition systems, have been previously documented [2-4], with HAJI being unique as its PC volume is less than 1% of the clearance volume. Using HAJI, MC combustion is reliable over a much broader range of air-fuel ratios (AFR)

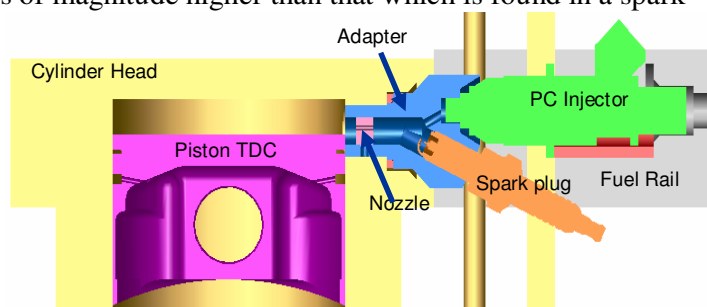


Figure 1 Section view of HAJI installed in the CFR engine

because the jet acts as a distributed ignition source, which can overcome the problems of poorly mixed MC charges and slower burning fuels [5, 6]. The lean limit can be extended to a relative air/fuel ratio ( $\lambda$ ) of 5 at wide open throttle (WOT) conditions with gasoline as the main fuel [7]. Thus, the vigorous jets of chemically active combustion products burn the main charge rapidly and with almost no combustion variability ( $< 2\%$   $COV_{IMEP}$  even at  $\lambda = 2$ ). Due to the leaner operation possible with the HAJI system, combustion occurs at a more moderate temperature, which results in lower oxide of nitrogen ( $NO_x$ ) formation. Lower temperatures also improve efficiency by decreasing dissociation such as carbon dioxide ( $CO_2$ ) to carbon monoxide ( $CO$ ), which normally occurs at high temperatures. Engine efficiency is also increased by operating with excess air, which decreases fuel consumption and allows the engine to run less throttled, greatly reducing the pumping losses [8]. It is even possible to run a HAJI equipped engine in an entirely unthrottled mode in the range of  $\lambda = 2$  to 5. Under these conditions, hydrocarbon ( $HC$ ) emissions become very significant as a result of burning mixtures at low temperatures, particularly increasing the wall quench  $HC$  source as well as reducing the burn up of piston and other crevice sourced  $HC$ s [7]. One of the main obstacles to HAJI is the complexity involved in both producing and storing  $H_2$ . Even though only a small amount of  $H_2$  is required, it is difficult to both refuel and store  $H_2$ . One alternative is to reform part of the fuel on-board to produce a  $H_2$  mixture or syngas. A second alternative to overcome these obstacles, which has been previously explored, is to employ alternative gaseous fuels such as CNG or LPG in place of  $H_2$  in the HAJI PC [9, 10]. In order to determine the viability of the use of reformed fuel in place of  $H_2$  in the HAJI PC, this paper assesses the option of employing  $CO$ , syngas and a 50 %  $H_2$ - $CO$  mixture based on criteria such as lean limit, emission levels and effects on combustion parameters.

## SELECTION CRITERIA AND PROPERTIES OF PC FUELS

The different gaseous PC fuels (for gas assisted jet ignition) were selected for a variety of reasons. Syngas was selected as it has the potential to be generated onboard the vehicle from a  $HC$  based MC fuel, thus eliminating the difficulties of PC refueling. In addition, syngas has been proven to enhance combustion when added to gasoline fueled spark ignition ( $SI$ ) engines [11-14].  $CO$  was chosen as a PC fuel because it is a primary component of syngas (approx. 21 %  $H_2$ , 24 %  $CO$  and 55 %  $N_2$  when reformed from gasoline). The 50 %  $H_2$ - $CO$  mixture was tested to give further understanding of how the different components of syngas affect combustion, while the  $H_2$  was selected as a basis for comparison because it has already been extensively tested with this system [7, 15-17].

A summary of the properties of the fuels tested, together with gasoline, appears in Table 1. The grey area in the table indicates estimated mixed-fuel properties based on the fuel's components. A comparison of the fuels shows a variation in properties that has significant effect on fuel burning and the possible methods of fuel storage. In the case of HAJI, in order for PC combustion to occur a number of criteria must be met. First, a minimum quantity of fuel must be injected into the PC. This fuel must contain enough energy so that when it is combusted, ignition of the MC fuel occurs. Secondly, the air-fuel mixture from the MC must enter the PC to form a flammable mixture at the time of the spark. The allowable spark timing is therefore affected by the flammability limits of each PC fuel. It is likely that for some fuels, a portion of the fuel that is injected into the PC escapes into the MC while the pressure in the PC is high. Once the MC pressure increases, some of this fuel may be forced back into the PC along with the MC fuel-air mixture. It is also a possibility that some of this escaped PC fuel remains in the MC near the exit of the orifice and actually aids in accelerating combustion of the MC fuel, as it is more easily ignitable than the lean gasoline-air mixture. However, this has the potential to form  $NO_x$  as in lean stratified direct injection ( $DI$ ) engines [18].

Table 1 Comparative properties of the fuels tested [4, 10, 17-19]

	H <sub>2</sub>	CO	50 % H <sub>2</sub> - CO	Syngas	Gasoline
MW	2.02	28.01	15.02	21.50	~110
Energy Density (MJ/kg)	120.0	10.1	17.4	6.1	44.0
Energy Density (kJ/mol)	240	283	261.4	130.7	4840
Stoichiometric AFR (by mass)	34.3	2.5	4.6	1.6	14.6
Stoichiometric AFR (by vol.)	2.4	2.4	2.4	1.2	57.7
Fuel (% by mass) in Stoichiometric Mixture with Air	2.8	28.8	17.9	38.2	6.4
Fuel (% by vol.) in Stoichiometric Mixture with Air	29.5	29.5	29.5	45.7	1.7
Energy in 1 mol Stoichiometric Fuel-Air Mixture	70.8	83.4	77.1	59.7	82.5
Gas Constant – R (kJ/kg K)	4.124	0.297	0.554	0.385	–
Density (kg/m <sup>3</sup> ) 0 °C and 1 atm	0.09	1.25	0.67	0.96	735
laminar flame speed (m/s)	~2.3	~0.4			0.4
LFL (%) (by vol)	4	12	8	16	1.4
UFL (%) (by vol)	75	75	75	37.5	7.6
Lambda at LFL	10.0	3.1	4.8	4.4	1.2
Lambda at UFL	0.14	0.14	0.1	1.4	0.21
Auto Ignition Temperature (°C)	572	609			530
Min Ignition Energy (mJ)	0.02	0.3			0.8

The amount of energy in the HAJI PC is governed by the energy in one mole of a stoichiometric mixture, as the PC size is constant. From Table 1, we can see that a stoichiometric H<sub>2</sub> mixture has about 15 % less energy per mole than CO and about 10 % less than the 50 % H<sub>2</sub>-CO mixture. This would lead one to believe that these fuels may actually provide more thermal energy to the ignition process than H<sub>2</sub>. The low ignition energy, wide rich flammability limit, and increased laminar flame speed of H<sub>2</sub> compared to the other fuels may compensate to some extent for this deficiency. In addition, because the ideal gas constant (R) is notably different with H<sub>2</sub>, its velocity through the HAJI orifice is greater (~ 3 to 5 times faster) in comparison with the other fuels, ultimately affecting the jet penetration into the MC.

## EXPERIMENTAL

A single cylinder, HAJI equipped Waukesha Co-operative Fuel Research (CFR) engine coupled to a dynamometer was used for all experiments. A schematic of the experimental setup and the major engine specifications can be found in the Appendix. A compression ratio of 11 was used as this was experimentally found to maximize thermal efficiency while minimizing COV<sub>IMEP</sub>, in the HAJI equipped CFR engine [15]. A regularly calibrated ADS 9000 exhaust gas analyzer was used to measure NO<sub>x</sub>, O<sub>2</sub>, CO, CO<sub>2</sub> and unburned HC emissions. The engine was instrumented with thermocouples to monitor intake and exhaust temperatures. Pressure data used to calculate the indicated mean effective pressure (IMEP) and the coefficient of variation of the IMEP (COV<sub>IMEP</sub>) was recorded with an air cooled pressure transducer (Kistler Mod. No 601B1) located in a water cooled housing. The COV<sub>IMEP</sub> was calculated over 50 cycles. Airflow was measured using an airflow meter consisting of a calibrated sharp edged orifice plate and differential manometer. Large surge tanks on either side of the orifice plate ensure smooth flow. PC fuel flow was measured using a digital Brooks 5860E gas flow meter calibrated separately for each PC fuel.

### Experimental Test Conditions

All experimental results were obtained at 1200 rev/min and 70 kPa MAP, which represents a just off idle condition for ultra-lean mixtures and thus is a base case for lean limit exploration. Spark advance was adjusted to minimum ignition advance for best torque (MBT) at each test point, with the ignition values used for experiments available in the Appendix. A summary of the test conditions for all experiments can be found in Table 2.

Table 2 Test Conditions

Speed	1200 rev/min
MC Fuel	95 RON Gasoline
PC Fuels	H <sub>2</sub> , CO, Syngas, 50 % H <sub>2</sub> -CO mixture
MAP	70 kPa
$\lambda$	~1.5 $\rightarrow$ Lean Limit ( $COV_{IMEP} > 10\%$ )
IMEP	600 kPa at $\lambda=1.2$ to 180 kPa at $\lambda=2.5$
Compression Ratio	11
Spark Timing	MBT
End of PC Injection	80-90° BTDC

The MC fuel used for the experiments was 95 RON commercial grade gasoline. The PC fuels were injected into the PC with a direct injector and were always rich of stoichiometric. The PC fuel flow rate was varied to achieve good combustion stability, with higher quantities needed for leaner mixtures of the main charge. Injection duration varied from 20-50° CA depending on the quantity of PC fuel required. The injection pressure was set to 550 kPa for CO and syngas and 400 kPa for H<sub>2</sub> and the 50 % H<sub>2</sub>-CO mixture. Although the PC injector is normally operated at 400 kPa with H<sub>2</sub>, the pressure variation between fuels is due to the fuel compensation required as the same DI injector was used for all fuels. Since the fuels have different energy densities, different quantities are required to achieve the rich PC mixtures that facilitate active radical formation and thus MC combustion.

Before data was acquired, the engine was warmed up to operating conditions (~80°C) with H<sub>2</sub> as the PC fuel. Following warm up,  $\lambda$  was adjusted to 1.2 (where the engine can operate with no PC fuel) and the PC fuel was changed. Next,  $\lambda$  was gradually increased until the lean limit was reached. For the purpose of this paper the lean limit is defined to be 10 %  $COV_{IMEP}$ , although this is a low value for close to idle operation. At idle with spark ignition, a  $COV_{IMEP}$  of more than 20 % is often found [19]. The variation in IMEP with  $\lambda$  at 70 kPa MAP is shown in Figure 2 (upper). Prior to the lean limit of each fuel, which is indicated on graphs with the vertical lines, there is almost no difference in IMEP with the different PC fuels as most of the energy originates from the gasoline MC fuel. The fuel flow rate on a mass basis used at each test point for both the gasoline and each of the PC fuels is shown in Figure 2 (middle). From this figure, it is apparent that much more syngas is required than the other fuels, which is due to the fact that it is comprised of approximately 50 % inert N<sub>2</sub>. From Figure 2 (lower), which shows the PC fuel energy as a percentage of the gasoline energy, it can be seen that on an energy basis approximately the same amount of each fuel was required to ignite the MC fuel. All  $\lambda$  values presented in this paper are inclusive of both the main and PC fuels as shown in Equation 1. The stoichiometric AFR is calculated for the PC-MC fuel combination in each case.

$$\lambda = \frac{Airflow / (PCfuelflow + MCfuelflow)}{AFR_{stoichiometric_{MC+PC\_combination}}} \quad (1)$$

## RESULTS AND INTERPRETATION

The effect of each of the PC fuel on combustion stability in lean mixtures is shown Figure 3. From the figure it can be seen that H<sub>2</sub> extends the lean limit of the gasoline MC fuel furthest to  $\lambda = 2.5$ , followed by the 50 % H<sub>2</sub>-CO mixture, which extends the lean limit to  $\lambda = 2.3$ . Syngas, which has been shown to enhance combustion in lean mixtures [11-14], extends the lean limit to  $\lambda = 2.2$ , while CO extends the lean limit to  $\lambda = 2.15$ .

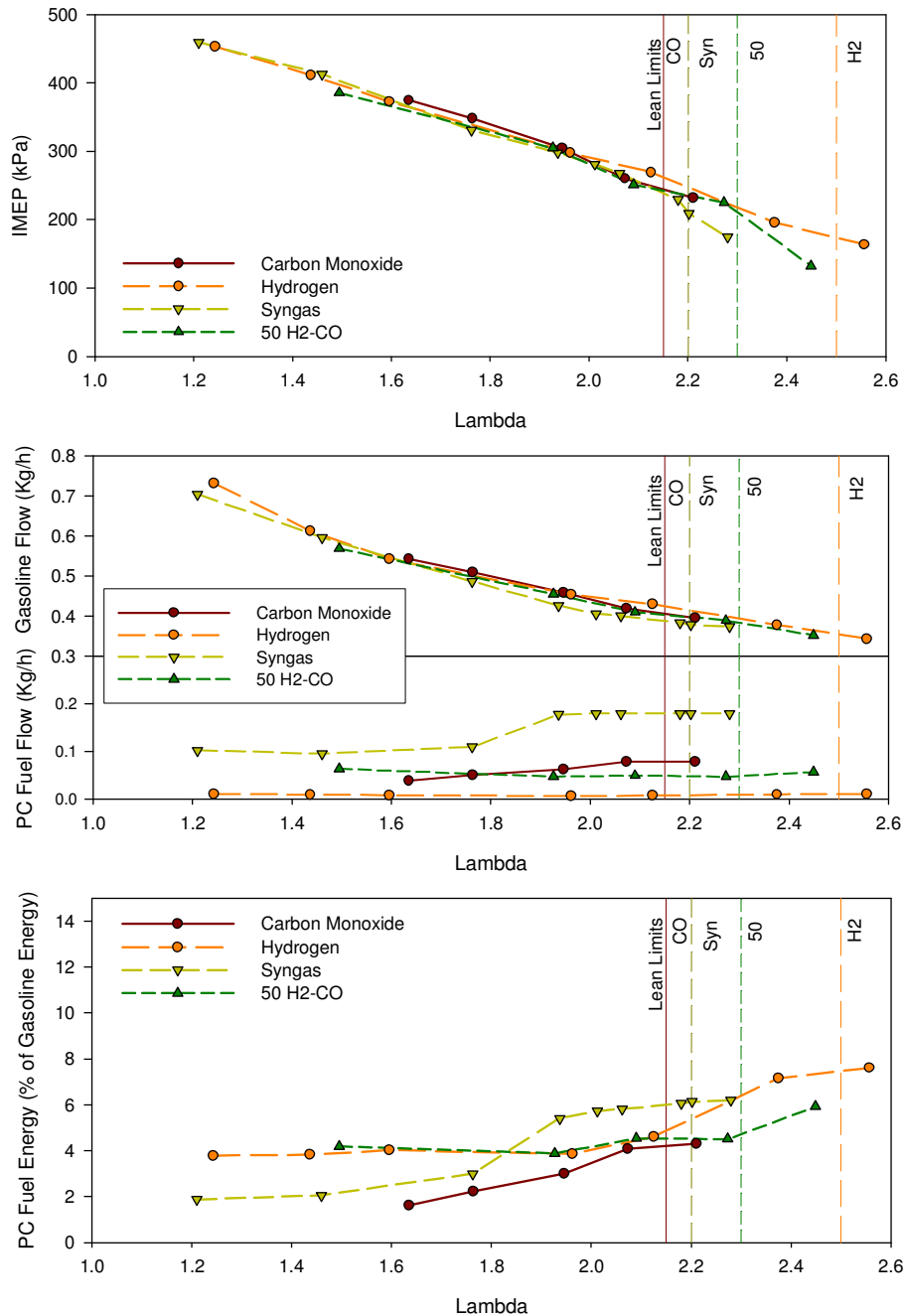


Figure 2 Upper- IMEP variation with  $\lambda$ . Middle- PC fuel and gasoline fuel flow (kg/h) with varying  $\lambda$ . Lower- PC fuel energy as a % of the gasoline energy with varying  $\lambda$  (70 kPa MAP, 1200 rev/min, CR = 11, MBT ST)

The extension of the gasoline lean limit by the mixed PC fuels follows the trends that one might expect based on the H<sub>2</sub> and CO PC fuel results. The 50 % H<sub>2</sub>-CO mixture, which has characteristics of both H<sub>2</sub> and CO, results in an extension of the lean limit that is approximately half way between that achieved with each individual fuel. The syngas mixture, comprised of approximately 50 % N<sub>2</sub> and 25 % of both H<sub>2</sub> and CO, extends the lean limit only slightly further than the CO. This was expected as there is only limited volume in the PC and therefore because the N<sub>2</sub> in the PC fuel displaces some of the MC fuel-air mixture, poorer PC combustion results. All of the PC fuels, however, extended the lean limit much further than  $\lambda=1.25$ , which is the leanest possible in gasoline SI mode with the CFR engine at this MAP.

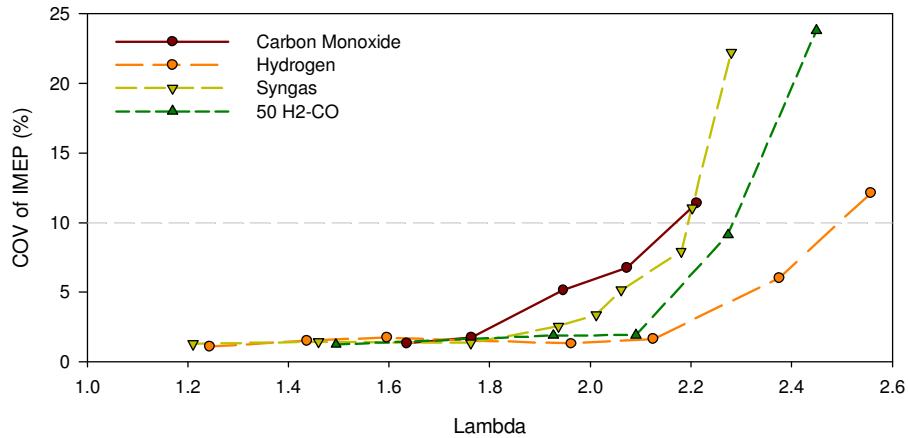


Figure 3 Effect of PC fuel on lean limit (10 %  $COV_{IMEP}$ ) (70 kPa MAP, 1200 rev/min, CR = 11 and MBT ST)

### Effect of PC Fuel on Emissions

The effects of each PC fuel on indicated specific (IS)  $NO_x$ , HC and CO emissions are shown in Figure 4. When  $\lambda$  is less than 1.9, IS $NO_x$  emissions become very low for all of the PC fuels. The IS $NO_x$  emissions resulting from all three  $H_2$  containing PC fuels are similar for all  $\lambda$  values, reflecting similar peak combustion temperatures. When  $H_2$  is used, local hot spots originating from the PC fuel combustion may contribute to the higher  $NO_x$  levels. It has been shown that both HC and CO emissions generally follow the same trends as  $COV_{IMEP}$  [20], which is the case here. The HC emissions first increase as the mixture becomes leaner due to a decrease in combustion temperature and associated increase in quench gap. Further increases in HC emissions as  $\lambda$  approaches and then surpasses the lean limit are initially due to slow and partial burning cycles and eventually misfiring cycles. The ISCO emissions are strongly influenced by  $\lambda$ , as can be seen in Figure 4. Initially the CO emissions are low for all fuels, since in lean conditions the excess  $O_2$  oxidizes the majority of CO to  $CO_2$ . As combustion becomes unstable with each of the PC fuels, CO emissions rapidly increase due to the partial oxidation of the increasing quench, crevice and oil layer HCs that emerge during the expansion and exhaust strokes and partially burn [4]. It is important to note that the level of ISCO emissions for the CO containing PC fuels is not elevated prior to the lean limit of each PC fuel, indicating that the CO emissions are not PC sourced and that the PC fuel is completely combusted as it propagates out of the PC and ignites the MC gasoline. Thus, the PC fuel does not heavily influence the ISCO emissions prior to each PC fuel's lean limit.

### Effect of PC Fuel on Combustion Parameters

The 0-2.5 % and 2.5-90 % mass fraction burn (MFB) durations are shown in Figure 5. Because this experiment focused on the PC fuel's ability to initiate MC fuel combustion, it was important to examine the first segment of the burn, thus the 0-2.5 % MFB data is shown. From Figure 5 (upper) it is evident that the flame initiation period does not increase substantially with increasing  $\lambda$ , a phenomena most likely due to the fact that the PC  $\lambda$  remains lower due to increasing amounts of PC fuel with increasing overall  $\lambda$ . Both the  $H_2$  and the 50 %  $H_2$ -CO mixture have approximately the same 0-2.5 % MFB durations for all  $\lambda$  values, indicating that the high laminar flame speed and high production of active radical species of the combusting  $H_2$  is also a characteristic of the 50 %  $H_2$ -CO mixture. The lower levels of  $H_2$  present in the syngas do contribute to a partial flame enhancing effect, however not to the same extent as with the 50 %  $H_2$ -CO mixture.

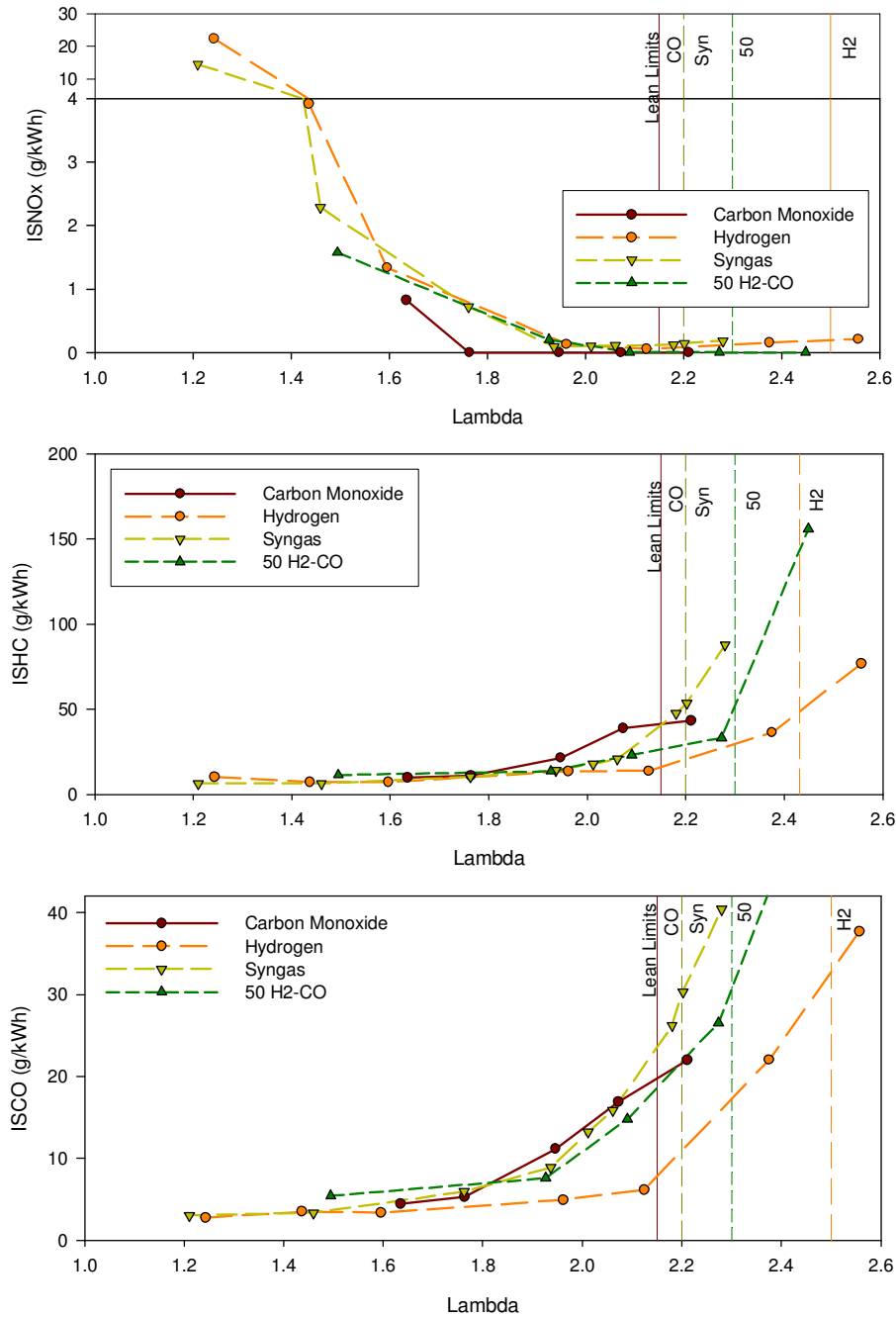


Figure 4 Effect of PC fuel on ISNOx (upper), ISHC (middle) and ISCO emissions (lower). (70 kPa MAP, 1200 rev/min, CR = 11 and MBT ST)

Figure 5 (middle) shows that the 2.5-90 % MFB duration increases with  $\lambda$  for all of the PC fuels due to lower combustion temperatures, which decrease the rate of flame propagation. It should be noted here that data points leaner than the lean limit should be examined with caution, as large errors may occur in the MFB calculations due to the presence of incomplete burning or even misfiring cycles. When CO is employed as the PC fuel the 2.5-90 % MFB duration is noticeably longer than that of the H<sub>2</sub> containing PC fuels and may be attributable to the CO jet's lack of H and OH radicals, which enhance combustion in the propagating flames of the other PC fuels.

The effect of each of the PC fuels on the peak mass burn rate (MBR) is shown in Figure 5 (lower). In all cases the peak mass burn rate decreases in leaner mixtures and at the lean limit with each fuel the peak MBR is approximately 0.03 / deg, suggesting that combustion becomes very unstable when the peak MBR is below this as was also found in experiments completed using alternative fuels [9, 10]. Further MFB and MBR data for each of the PC fuels at both  $\lambda = 2$  and the lean limit can be found in the Appendix.

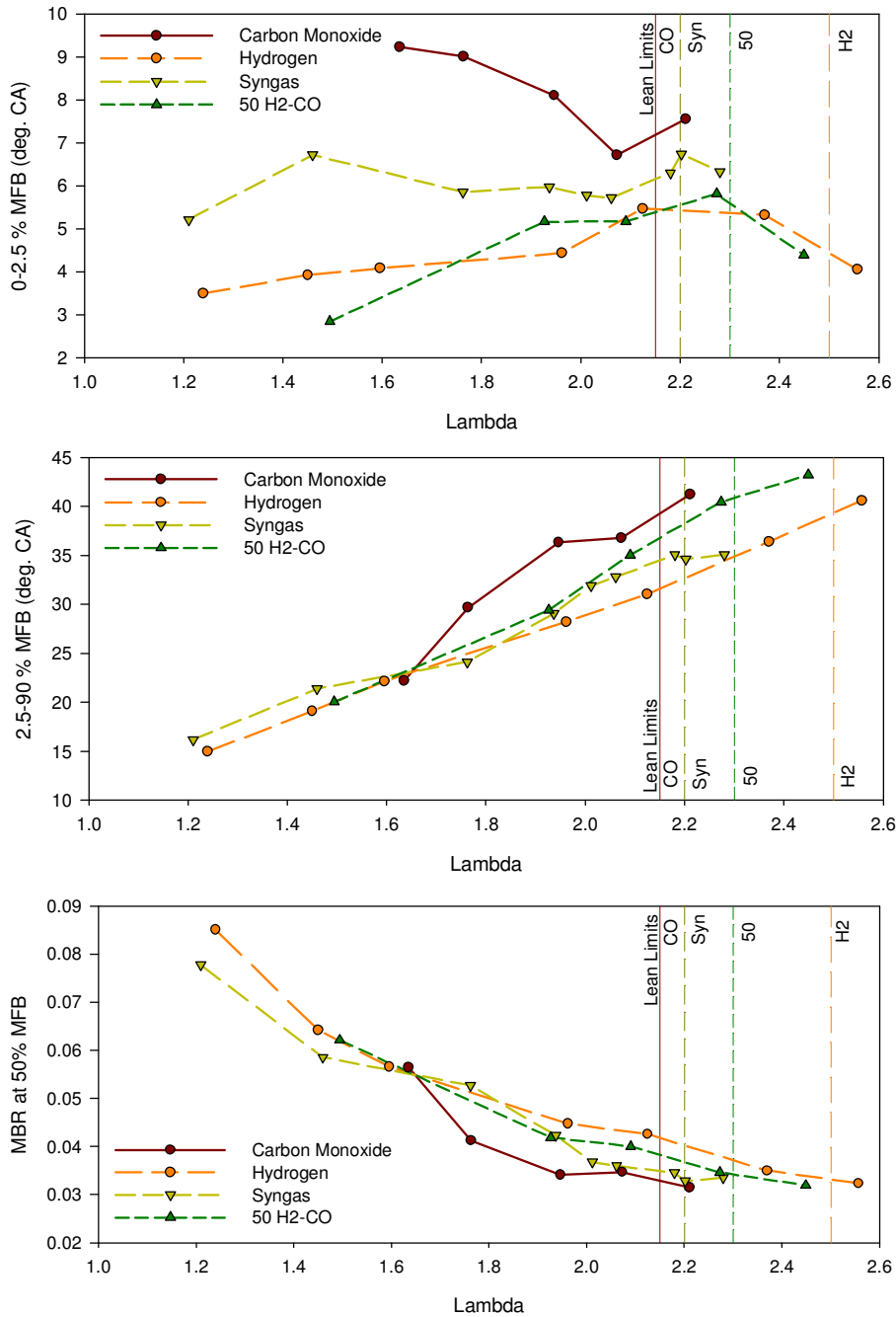


Figure 5 Upper- Effect of PC fuel on 0-2.5 % MFB duration. Lower- Effect of PC fuel on 2.5-90 % MFB duration (70 kPa MAP, 1200 rev/min, CR = 11 and MBT ST)

## CONCLUSIONS

Syngas has been shown to extend the lean limit of a gasoline fuelled MC engine when used in place of H<sub>2</sub> in the HAJI system. Syngas, which can be reformed from the main fuel onboard the vehicle, offers a more practical solution to applying HAJI to a gasoline or other liquid fuel engine, with no supplementary fuel storage or refuelling of H<sub>2</sub> required.

The results show that H<sub>2</sub> extends the MC lean limit furthest to  $\lambda = 2.5$  while syngas extends the lean limit to  $\lambda = 2.2$ . The other two fuels tested, CO and the 50 % H<sub>2</sub>-CO mixture extend the lean limit to  $\lambda = 2.15$  and  $\lambda = 2.3$ . This range in the extension of the engine's lean stable operating limit, indicates that the level of ignition enhancement of the PC fuel is dependent on a variety of factors including flame speed and the generation of chemically active combustion products and not solely on the energy contained in the PC fuel.

The HC, CO and NO<sub>x</sub> emissions are affected to varying extent by the PC fuel at certain values of  $\lambda$ . NO<sub>x</sub> emissions are higher with H<sub>2</sub> containing PC fuels until  $\lambda$  exceeds 1.9. The cause of the increase appears to be due to the higher peak temperatures produced by the H<sub>2</sub> in the PC fuel, especially for only slightly lean MC mixtures. Otherwise, the NO<sub>x</sub> emissions do not appear to be strongly affected by the PC fuel. As the lean limit is approached with any of the PC fuels, both the HC and CO emissions rise rapidly due to the rise in cyclic variability and the deterioration of combustion stability. The slightly lower HC emissions that occur with H<sub>2</sub> when  $\lambda < 2.1$  may be due to H<sub>2</sub>'s larger production of active radicals, which have been shown to help decrease the level of quench and piston crevice sourced HCs [5]. Nevertheless, prior to the lean limit, HC and CO emissions do not vary greatly between PC fuels.

The combustion parameters indicate that the faster a PC fuel can ignite the MC gasoline, the further it is able to extend the MC lean limit. Therefore, those PC fuels with shorter MFB durations were shown to extend the MC lean limit further. It was also found that fuels with higher MBRs (at an equivalent  $\lambda$ ) could extend the MC lean limit more than fuels with lower values. Furthermore, it is suggested that combustion becomes unstable when the peak MBR is less than 0.03 /deg as the lean limit occurs at this point with all of the PC fuels.

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## APPENDIX

### Experimental Setup and Engine Specifications

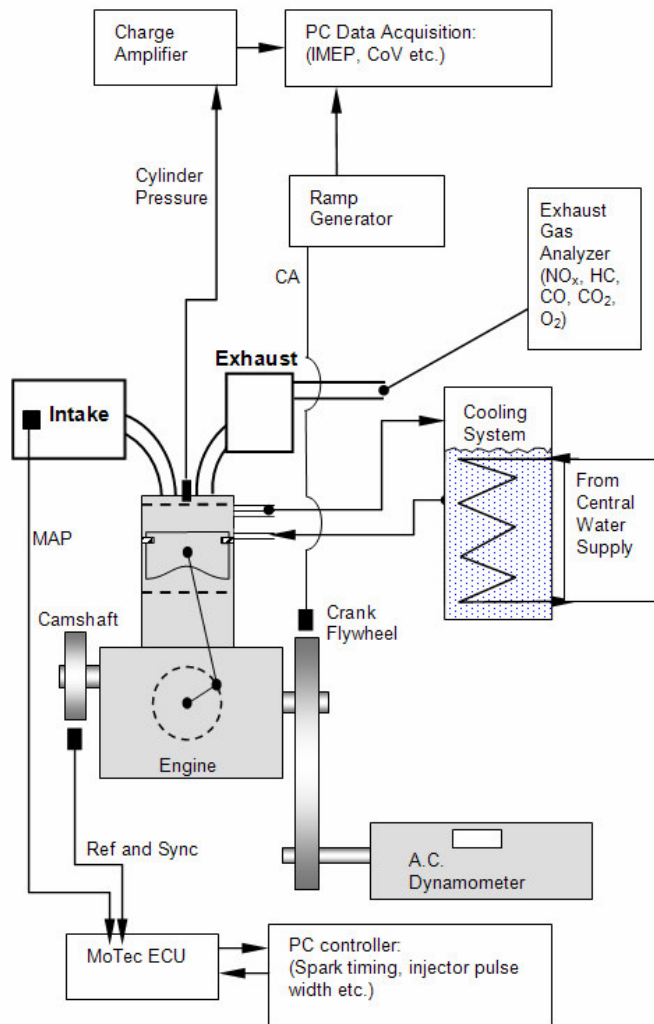


Figure 6- Experimental setup including controllers, sensors and data acquisition systems

Table 3 Research engine Specifications

Make	Waukesha ASTM
Version	High Speed
Swept Volume	612 cm <sup>3</sup>
Bore	82.6 mm
Stroke	114.3 mm
Compression Ratio	11:1

## MBT Spark Timing and Thermal Efficiency

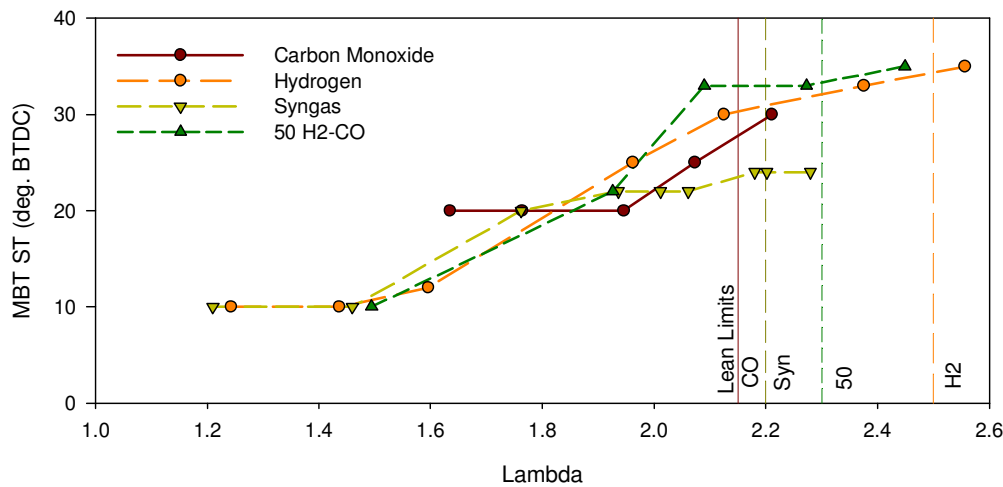


Figure 7 Variation in MBT spark timing with  $\lambda$  when H<sub>2</sub>, CO, syngas and 50 H<sub>2</sub>-CO are used as the PC fuel (70 kPa MAP, 1200 rev/min, CR=11)

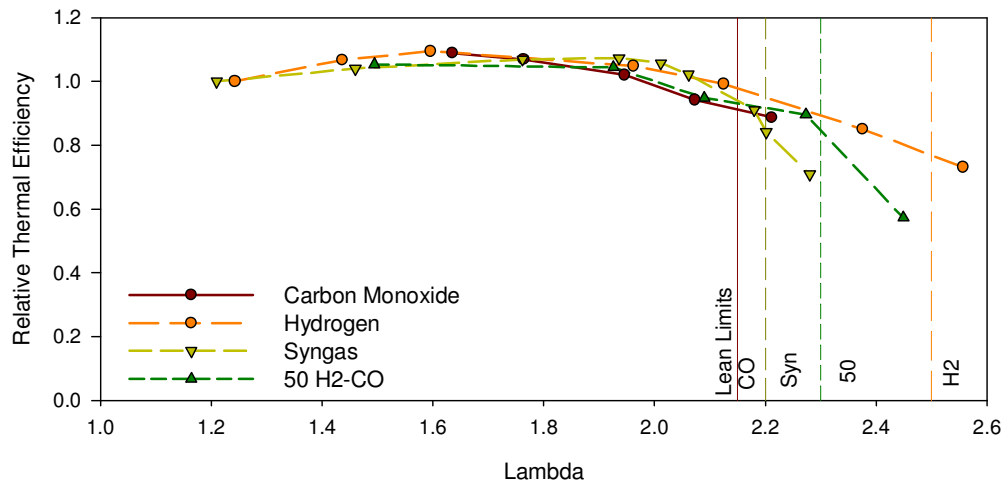


Figure 8 Variation in relative thermal efficiency with  $\lambda$  when H<sub>2</sub>, CO, syngas and 50 H<sub>2</sub>-CO are used as the PC fuel (relative to H<sub>2</sub> at  $\lambda=2$ ) (70 kPa MAP, 1200 rev/min, CR=11)

## Further Combustion Analysis Results

The MFB vs. MBR data for each of the PC fuels at  $\lambda = 2$  and at the lean limit are shown in Figure 9 upper and middle respectively. The numbers in parentheses in each graph's legend indicate the energy content of the PC fuel as a percentage of the gasoline energy content. Both of these figures show the speed of combustion relative to the amount of fuel burned and are independent of the actual fuel mass burned. In addition, the diagrams show the short ignition delay and high initial burn rates present with the gas assisted jet ignition process. The first hump present in the figure is indicative of the PC fuel burning and penetrating into combustion chamber. Following this, there is a momentary deceleration in combustion where the jet energy is dissipated and the MC fuel begins to burn.

Figure 9 upper shows the effect of each of the PC fuels on the MBR at approximately  $\lambda = 2$ . There is some variation in the MBR between the fuels, most notably with the CO, which has a lower peak burn rate than the other fuels indicating that it is closer to its lean limit. The 50 % H<sub>2</sub>-CO mixture has the next lowest MBR, which is unexpected as it extends the lean limit of

the gasoline further than the syngas. However, the data presented in the diagram for the H<sub>2</sub>-CO mixture is at  $\lambda = 2.09$  compared with  $\lambda = 2.00$  for the syngas, which is most likely the cause of the lower peak MBR. Figure 9 middle and lower shows the MBR data at the lean limit for each PC fuel and here it can be seen that in all cases the peak MBR and the overall burn profiles are similar for all of the fuels although  $\lambda$  varies at the lean limit. The greater difficulty in igniting the leaner MC charge can be seen when both H<sub>2</sub> and the 50 % H<sub>2</sub>-CO mixture are used in the PC, with larger decelerations in the burn rate following the initial hump present in these cases.

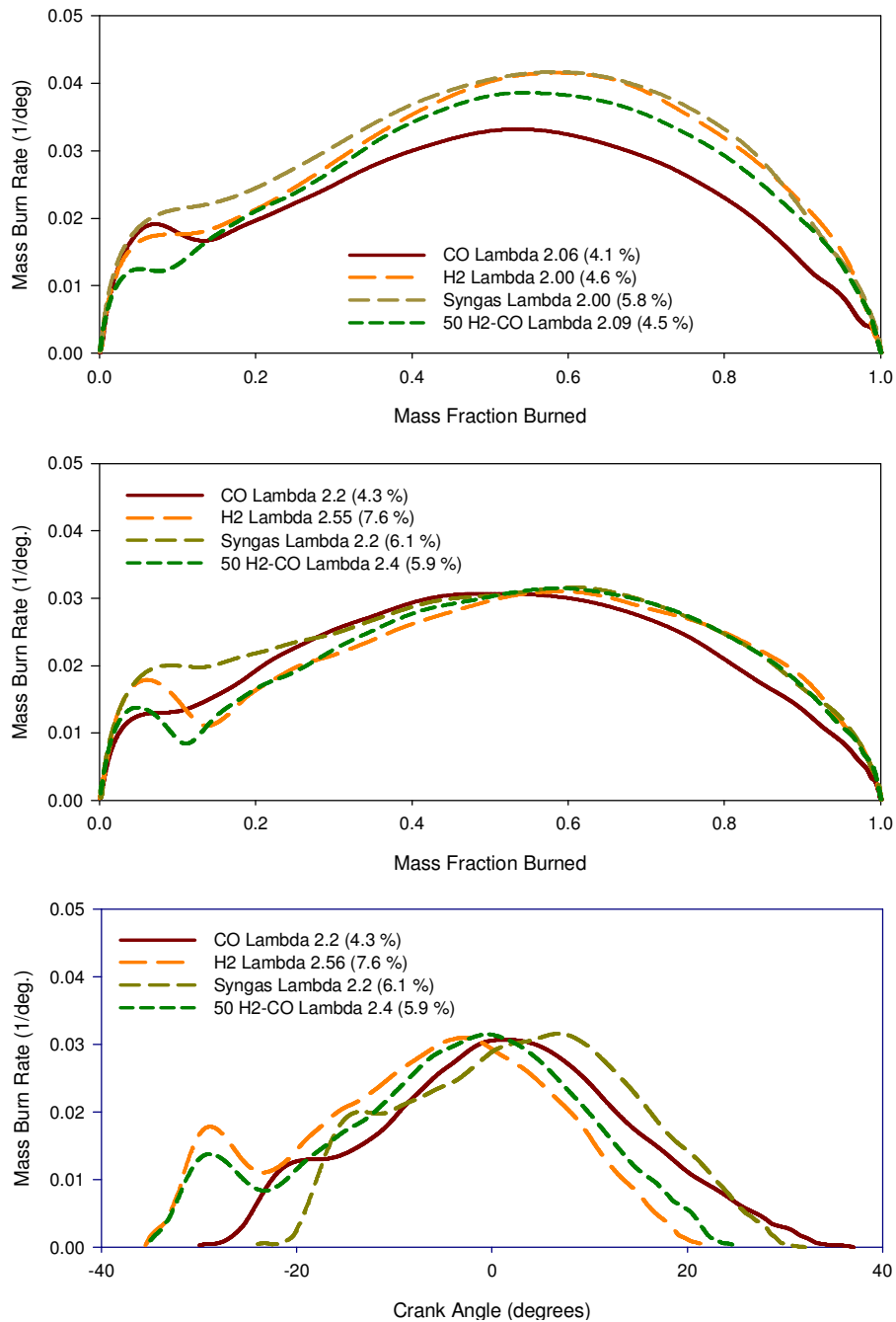


Figure 9 Upper- MFB vs. MBR for PC fuels at  $\lambda = 2$ . Middle- MFB vs. MBR for PC fuels at 10 % COV<sub>IMEP</sub>. Lower- CA vs. MBR for PC fuels at 10 % COV<sub>IMEP</sub>. (parenthesis indicate PC fuel energy as a percentage of the gasoline energy. 70 kPa MAP, 1200 rev/min, CR = 11 and MBT ST)