

Effects of Non-Thermal Plasma Reformer Assisted Hydrogen Rich Gas and Hydrogen Enrichment on the Lean-Burn Performance of a GDI Engine

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Abstract: The lean limit of a gasoline-fuelled spark-ignition engine can be increased by adding hydrogen to the engine thus increase the efficiency and also possible reduction of nitrogen oxide emissions. An electrical energy to non-thermal plasma discharge initiates a partial oxidation reaction in turn produces a hydrogen rich gas consisting mainly of hydrogen, carbon monoxide, and nitrogen. Two different gas mixtures were used to simulate the hydrogen rich gas (HRG) and hydrogen enrichment extending lean burn combustion GDI engine impact of various amounts of (HRG) gas were used, ranging from the equivalent of 10% - 30% of the gasoline being reformed in the hydrogen rich gas. Theoretically Hydrogen combustion gas mixture (H_2 , CO, and N_2) and typical non thermal plasma convert to hydrogen rich gas (H_2 , CO, N_2 , and CO_2). However, nitrogen oxides (NO_x) were found to increase hydrogen with hydrogen rich gas addition. Maximum Brake Torque (MBT) Timing verses lambda optimize experiment was conducted when spark timing was observed as a constant parameter. Hydrogen addition and hydrogen rich gas actually increases heat transfer out of the cylinder due to improved quenching distance and higher combustion temperature, thus is a straight improvement of thermal efficiency. If spark timing was retarded to MBT, taking advantage of hydrogen's high burn speed, NO_x emissions exhibited no obvious increase after hydrogen and HRG addition. Engine thermal efficiency increased with the increase of hydrogen and HRG fraction. Unburned HC always decreased with the increase of hydrogen fraction.

Keyword: Non thermal plasma; Hydrogen rich gas; Hydrogen; Gasoline; GDI Engine; Lean burn

1. Introduction

Hydrogen supplementation concept Current dominating engine technologies in the automotive industry include stoichiometric gasoline spark ignition (SI) engines. A gasoline engine is an alternative concept that operates lean and with a homogenous air/fuel combination. Using surplus air in the engine boosts efficiency and lowers pumping losses, resulting in fewer throttles. A homogenous lean charge reduces peak combustion temperatures, resulting in lower engine-out NO_x emissions compared to SI engines. Adding additional air reduces flame speed, leading to longer burn durations and increased combustion unpredictability. Eventually, the mixture becomes too dilute for steady combustion. Gasoline has a low dilution limit and combustion degrades quickly with extra air. Research indicates that adding a modest amount of hydrogen helps.

Fanhua MaYu Wang et al., the fuel supply system for combining hydrogen and natural gas online and its control logic. Micro Motion flow meters of mass flow were used to measure the flow rates of the CNG and H_2 . The flow rate of hydrogen was adjusted using an ALICAT Flow control valve in accordance with the flow rate of CNG and the target hydrogen fraction [1]. Fanhua Ma, Shun Li et al., The power of a hydrogen-enriched compressor natural gas engine was tested to determine the impact of varied compression ratios and modifying the spark ignition time. A stroke might lead to a longer burn time and a greater COV. The heat release for the 3 different CR at 20° CA BTDC [2], Fanhua Ma, Mingyue Wang, et al., examined the impact of hydrogen addition at a high volumetric ratio, 55% greatly extending the lean burn limit, excess air ratio (reciprocal of equivalency ratio) at which COV_{IMEP} at all ignition time by delaying the ignition timings from the MBT spark timings. Particularly at excess air ratios exceeding 1.7, the emission of CO and CH_4 is considerably reduced [3]. DuanHao, Roopesh Kumar Mehra et al examined the compressed natural gas with added hydrogen would

respond to changes in the excess air ratio and ignition angle (HCNG), The ratio of extra air ranged from 1.0 to 1.9. While the prediction ability of NO_x is somewhat subpar, the ideal model for torque or BSFC derived by the SVM approach is quite accurate in terms of the value of the complex correlation. [SOFTWARE] [4]. Studied engine improvement significant option for optimizing combustion and reducing engine emissions is an electronic throttle system. Predictive burning capability was used as a foundation to calibrate the am-phaser actuators (DIVCP) engine's torque and spark sweeps. An SI DIVCP engine must undergo about 100 torque/spark sweeps in order to be calibrated properly, according to an examination of process outputs. [ECU] [5].

G.Schmitz U. Oligschlager, et al., Modern engine ideas require specialized technology for decreasing exhaust pollution and lowering fuel consumption due to the strict emission standards. An autonomous optimization system called VEGA manages the whole calibration procedure, from the first basic mapping through the EUC's final configuration. It is possible to reduce NO_x values by roughly 40%. [EUC] [6] S.R. Munshi, C.Nedelcu and J.Harris et al., A precise blend of hydrogen and NG is delivered on one hose by the FTI (Fueling Innovations Inc) Hydrogen /NG blend dispenser, while pure hydrogen is delivered on a second hose. The post-oxidation PM for HCNG underneath the CSHVR and OCTA cycles, respectively, showed a NO_x reduction of around 56% and 57%. Combining NG and HCNG operations with low emissions [7]. Stuart R. Bell a & Manishi Gupta, et al. conducted research on lean H₂ and natural gas mixes in a spark-ignited engine. Fueling information was collected for MBT Spark timing with a console spark advance of 60 ° (BTDC). When more hydrogen was injected, the lean operating limit based on COV and hydrocarbon (HC) Emissions moved in favor of leaner equivalency ratios. a ratio of equivalents of roughly 0.90. Across a very wide range of equivalency ratio, NO_x Emission fell, reaching a low value of 0.11 g/hp-hr. [9]. These, S. S., Rairikar, et al., examined optimization tactics HCNG Lean burn ignition theory was used in a naturally aspirated gasoline engine with HCNG FIRE thermal simulation. Due to the higher thermal efficiency of the engine, program performance improvements of generally more than 10% are anticipated. The HCNG blend's hydrogen to carbon ratio significantly lowers carbon-based pollutants control in a closed loop, fuel methane management [10] Enrico Conte, Konstantinos Boulouchos, et al., The usage of H₂ in a (GDI) engine has been studied and assessed. A reactive homogenous backdrop is created for cylinder by injecting minute quantities of hydrogen (up to 27% on an energy basis) into the intake port. H₂ addition has incredibly favourable outcomes in terms of NO_x, HC, and efficiency. [11],

Constantin Pana, NiculaeNeguresuc, et al., studied the modelling of the internal functions of the SI Combustor that used gasoline in addition to hydrogen as fuel. Leaner petrol and hydrogen addition ($\lambda = 1.4$) than would be necessary for a gasoline-fueled vehicle to operate steadily. lowering the amounts of CO, HC, and CO₂ emissions that are considerably harmful. When hydrogen injection is utilized, the gas's interior temperature rises under the same working circumstances, increasing the NO_x emission level. The amount of NO_x Emission decreases with leaner combinations [12]. horstenAllgeier, Martin Klenk, et al., possible to calculate flow rates and velocities, heat transfer, temperatures, pressures, effectiveness, power, torque, NO_x, and HC-Emission using the engine software program GT-Power, which is focused on one-dimensional ideal gases. A little rise in CO emissions was noticed, as well as a reduction in NO_x emissions to almost nil. Throughout the FTP testing process, CO₂ emissions from the system decreased by 3.5% [13]

Changwei Ji, Shuofeng Wang, et al. The volume proportion of hydrogen in the inflow rose from 0% to 3% by altering the hydrogen injection pressure in the investigated electric hybrid control module (HECU) that was built to regulate these parameters. According to excess air ratios of 1.2 and 1.4, respectively, for a certain degree of hydrogen addition and duration of gasoline injection. The spark frequency was adjusted from 20 to 50°CA BTDC with intervals of 2 °CA for a certain hydrogen addition amount and surplus air ratio. spark timing being delayed as a result of more post-oxidation. Peak cylinder temperature and NO_x emission both fall as spark advance is reduced. NO_x emissions from the HHGE are less compared to a pure petrol engine at $\lambda = 1.2$, indicating the ideal spark timing. [14]. Hakan Sandquist et al., wall-guided combustion technology used by the DISC engine. the observations made during part-load operation, when burning is stratified. The start of injection (SOI) was changed in relationship to the sequential calibrated to change how long it took to prepare the mixture and how long it took for it to ignite. For each test, the ignition delay was set at the MBT, or maximum braking torque. Volatility has been proven to have a significant impact on HC emission. [15].

Stuart R. Bell & Manishi Gupta et al., a traditional spark-ignited engine that uses a lean combination of H₂ and natural gas. Spark advanced for natural gas fueling at $\phi = 0.84$ was 39 degrees before TDC compared to 30 degrees before TDC for combinations of natural gas mixed with 5, 10, and 15 percent hydrogen by volume. Lean limit extension and the addition of H₂ to natural gas resulted in a drop in NO_x emissions that reached a lower limit of 0.11 g/hp-hr. throughout a very wide range of equivalency ratio. [16]. M. Salah Boulahlib, Florence Medaerts, et al. Studied three different fuel types: pure CH₄, natural gas, and an 85% CH₄/15% H₂ combination of CH₄ and hydrogen. While it decreased CO₂ (by about 11%), NO_x (by about 32%), exhaust gas temperature (by about 5%), and CO (by about 6%). Methane must not have been able to burn properly due to hydrogen. Only methane has a superior combustion, and adding hydrogen to a lean operation only marginally accelerates auto-ignition while changing the reactivity speed time of auto-ignition. [17]. Hao Duan, Yue Huang, et al., The steady-state calibrating obtained measurements of an HCNG engine are analysed using the SVM technique based on the precision of NO_x emission predicting. With a training random sample of 270, combining MAP and gasoline equivalency ratio split sample yields the best SVM regression model. [18] J.B. Green, Jr., N. Domingo, et al., The examined plasma-boosted spore reformers are small, robust, and offer quick reaction. SI engines may run extremely lean compared to stoichiometric burning without a particulate filter hydrogen is added to the primary fuel. This leads to a substantial decrease in nitrous oxides (NO_x) output. [19]

Fushui Liu, M. Zuhaib Akram, et al., With an ignition energy of 37 MJ, an isooctane-air-H₂ combination was ignited from 0.8 to 1.2. Under a 500- μ s injector opening, the injector delivers a single blast with such a volume of 1.466x10⁻³ ML. For all hydrogen concentrations, the lean flammability limits of isooctane-air combinations were raised to an excess air coefficient of 0.2. the molar concentration of a short-lived reactive H, OH, and O rose, enhancing the lean combustion products and burning velocity. [20]. Fanhua Ma, Yu Wang, et al., Studied the effect of H₂ addition on cycle-by-cycle variation (CCV) in an SI Engine Two types of fuels, CNG and 80/20 (in volume) CNG/hydrogen mixtures, COV_{IMEP} not exceeding 10% for acceptable vehicle drivability. NO_x emission would get increased by hydrogen addition at a given lambda and ignition timing, but since MBT ignition timing [21]. Edward J. Tully, et al., studied hydrogen is introduced to an internal combustion lean limit can be raised. This approach reduces engine NO_x emissions by up to 99 percentage points at the top concentration limit by diverting a small portion of the fuel (10%–30%) to the reformer, where it becomes combined therewith air and partially oxidized to plasma gas.

[22]. Bansal, B.B and Mathur, H.B., et al., gasoline fuel alone is not easily reacted and releases little enthalpy it during ignites and first stage of combustion, hydrogen acts as an active species of equivalency ratio. Due to these factors, hydrogen is the best material to augment gasoline with in order to achieve ultra-lean burning. [23]. Miqdam T. Chaichan., et al., the impact of additional H₂ on OST (optimal spark time) as a function of engine speed The addition of H₂ delayed OST by roughly 20 degrees BTDC, resulting in the best spark timing and maximum break power within equivalency ratios of $\phi = 1.0$ and 1.15. Ignition running was not possible for H₂ = 80, at this percentage, as well as for this ignition timing. Break power dropped with H₂ addition by volumetric for variety of ($\phi = 0.85 - 1.35$), and yet this combination also caused engine shutdown. [24]. Nicolae Apostolescu, et al., To assess the laminar combustion speed and the change of the lean combustibility limit, it was examined how adding hydrogen to addition rose, the ratio across gH₂=1.5% and gH₂=3% decreased more rapidly. While running with more air, the emission of incomplete combustion hydrogen decreased; nevertheless, NO_x [25].

T.D Andreea, P.F. Henshaw, et al., The COV_{IMEP} began to rise over 10% in blends thinner than $\phi = 0.65$. The cyclic variability seemed to decrease with increasing hydrogen addition. Absent hydrogen, it COV_{IMEP} starts to climb by over 10% for variations less than $\phi = 0.85$. The COV_{IMEP} in some cases decreased by 30% with the hydrogen supplementation while operating without any additive chemicals. The increasing peak in - cylinder temps and faster combustion caused an increase in NO_x emission. [26]. R.F. Stebar and F. B. Parks et al., H1New PC Chand Smutzer, et al., HALO Utilizing spark efficiency improvement during testing J-gap plugs were employed in order to keep up with the field applications, and the coils were equipped with 151 MJ of benchmark spark energy. The engine's output was set at around 7 bar IMEP, with a proportional AFR of 2, which corresponds to 100% surplus combustion air or 9% m Molecular oxygen in the emissions (selected to reduce NO_x). [Technical/Scientific Report] [27] Alan N. Drew, David J. Timoney, et al., the throttle position transportation of hydrogen mixes in an unstable condition in one dimension was studied using

computer software. The program ignition of SPARKSIM -H₂. Early cycles following the beginning of hydrogen injection upstream of the throttle body showed satisfactory concordance with measurable and expected in cylinder IMEP values. [28]. Scog –Jae Lee, Kum-Jung Yoon, et al., In HMC, Fundamental studies on hydrogen-fueled engines and vehicles control ECU drives the injection exclusively, and peak-and-hold type current is employed to reduce injector motion delay. There are plans to raise the present 1.3 Mpa hydrogen gas supply. If the fuel-to-air equivalency ratio is at or near 0.7, the highest value over 25%. As a result, the fuel-air equivalency ratio that is around 0.6 and 0.9, which is fairly low, is the most effective. The main contaminant in emissions from hydrogen engines is NO_x. [Vehicle Powered by Hydrogen from Hyundai Motor Company] [29]. FarhadSalimi, Amir H. Shamakhi, et al., The thermodynamics of a SI engine running on hydrogen are simulated quasi-dimensional fashion. In this study, data collected are used to evaluate MATLAB software Th relevance spark advance, A/F Ratio, and variable cam on the hydrogen engine caused the NO_x Concentration to be closest to $\phi = 0.8$. in SA This parameter's primary impacts are those of the VVT Mechanism's application of valve lift variation, releasing time and length variability, and throttle position variation. [30]. G.W. Koroll, R.K. Kumar, et al., The maximum amount of hydrogen that may be present in a combination without exceeding its flammability limit is mixtures possessing a hydrogen content of 9% to 70%. The double-kernel methodologies used to determine the turbulent and laminar burning velocities of hydrogen-air mixes in a 17-L vessel. Burning speeds for hydrogen-air mixtures [31]

2. Concept of Hydrogen Rich Gas Enrichment GDI Engine

Developing hydrogen on-board utilizing a non-thermal plasma partial oxidation fuel reformer process is an option to storing hydrogen on the vehicle. An on-board fuel reformer has the ability to boost efficiency and drastically decrease emissions, according to multiple studies [32]. A portion of the fuel, typically 10% to 30% by volume, is redirected to the reformer in this concept. There, it is combined with air and partially oxidized, producing mostly nitrogen, carbon monoxide, and hydrogen. Figure 1 shows the GDI engine intake manifold mixing the primary air/fuel charge with this hydrogen-rich gas.

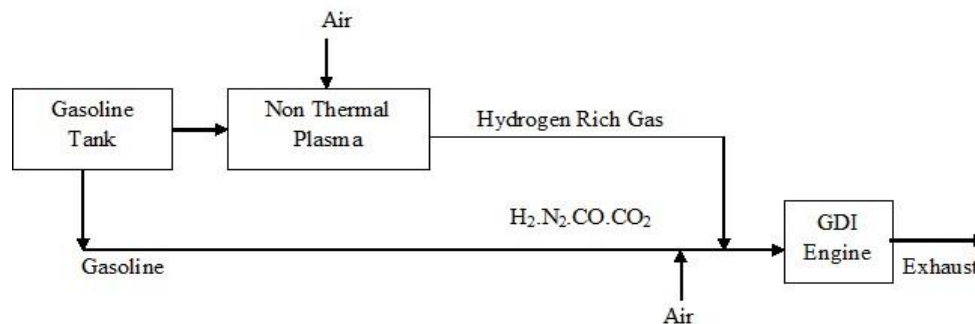
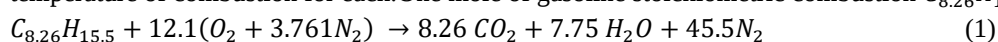
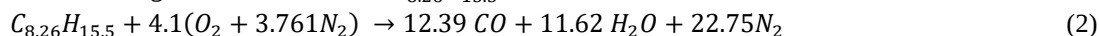


Figure 1. NonThermal plasma Hydrogen Rich Gas Engine Concept

The plasma fuel reformer (PFR) generated hydrogen moles, carbon monoxide moles, plasma discharge's electric power added to the gas, the hydrogen input flux, the petrol input flux, and the reduced temperature of combustion for each. One mole of gasoline stoichiometric combustion $C_{8.26}H_{15.5}$



One mole of gasoline half oxidized $C_{8.26}H_{15.5}$



In actuality, there are extra chemical energy losses due to the over oxidation of some CO and H₂ molecules to CO₂ and water. Due of the ongoing development of non-thermal plasma, our tests utilized bottled gas that included a representative output of this technology. Based on the chemistry described above, there is one gas known as the hydrogen rich gas. The usual hydrogen rich gas is an additional gas that contains CO₂ to indicate over oxidation. This typical hydrogen-rich gas exemplifies the current state of the art in terms of output. The chemical energy of the hydrogen-rich gas will be lower than the heating value per unit volume of the

air/fuel mixture since the reaction involving this gas is exothermic. There is a correlation between lean limit operation and combustion and emissions measurements.

The exothermic nature of the non thermal plasma reaction implies that the gas produced by the reaction has less chemical energy than the gasoline that was utilized to lean burn GDI Engine. A measure of these losses is the non thermal plasma efficiency, which is the hydrogen rich gas Lower Heating Value (LHV) divided by the gasoline plasma torched to produce the gas.

3. Design of Non-Thermal Plasma Fuel Reformer

In one aspect, the design of Non thermal plasma fuel converter comprising first electrode and second electrode separated from the first electrode by an electrical insulator and disposed to create a gap with respect to the first electrode so as to form a discharge volume adapted to receive a fuel/air mixture. A power supply is connected to the first and second electrode and adapted to provide voltage and current sufficient to generate a plasma discharge within the discharge volume. Fluid flow is established in the discharge volume so as to stretch and deform the plasma discharge. Schematic view Figure 2.

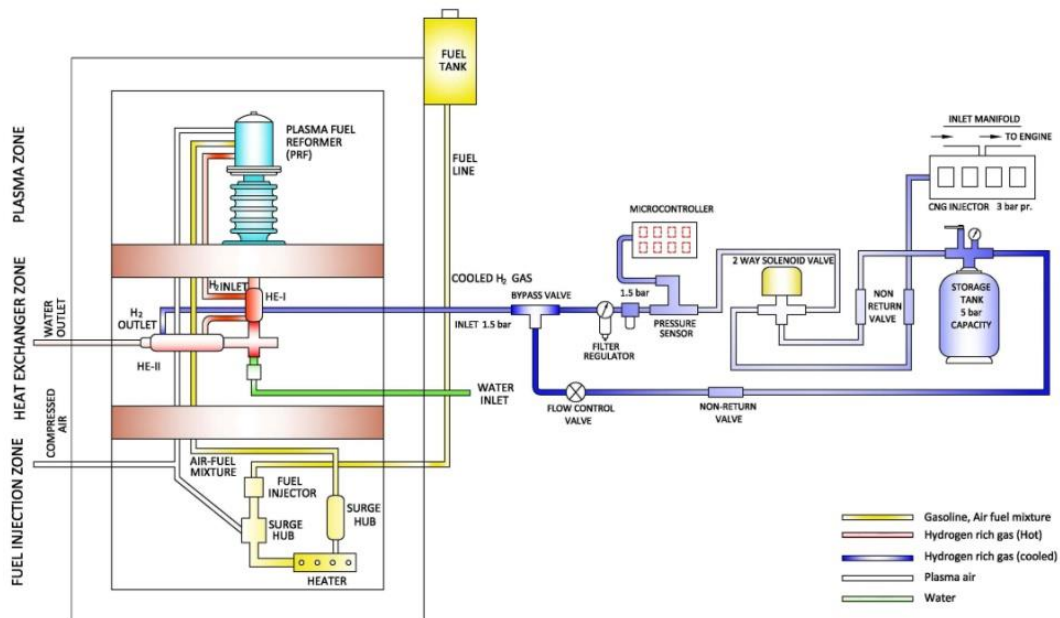


Figure 2. Schematic view of Non-Thermal Plasma Fuel Reformer hydrogen rich gas produce reaction zone

A plasma discharge's "cycle frequency" describes how often its discharges repeat itself. The chemical reaction initiated by each discharge will persist and propagate in the region of the rich fuel/air mixture local to the quasi-uniform volumetric plasma discharge, so the natural cycle frequency for the non thermal fuel converter in the illustrative preferred embodiment will typically be on the order of numerous (1-20 kv).

Table 1. Specification details of Non-Thermal Plasma Fuel Reformer

Non-Thermal Plasma Fuel Reformer	Parameters
Diameter of anode	1.8 mm
Volume – fuel	0.4 – 0.6 kg/h
Arc Length	25 -35 mm
Arc – Input	12 V
Arc - Output	15,000 V
Arc – Frequency	50 Hz
O ₂ /C ratio (A)	0.6 to 0.85

The PFR utilizes the benefits of a half oxidation process in order to function. Fig.2 Air is used as the plasma-forming gas in the PFR device, and it functions at pressures higher than the air around it. An ongoing discharge across an electrode gap generates a plasma area into which air and fuel are delivered constantly. The half oxidation process provides most heat due to its exothermicity. The half oxidation reaction releases around 15 percent of the fuel's heat energy in the circumstances of liquid fuels. The Plasma Fuel Reformer (PFR) is a focused portion of equipment with three distinct but interconnected sections: the fuel injection zone, the plasma generating-fuel reaction zone, and the hotness exchanger zone.

The AFR rangerich mixtures $\lambda < 1.0$ for the non-thermal plasma fuel reformer, therefore it requires a minimum air pressure of 1.5 bar and a fuel flow rate of 0.4-0.6 kg/h. the nonthermal plasma reaction produced hydrogen-rich gas A quasi-uniform volumetric plasma release causes "volumetric ignition" of chemical reaction in the bulk fuel/air mixture. Plasma and expanded volumetric discharge maximise plasma-fuel/air mixture interaction and reactivity. Select a plasma and liquid turbulence rich air-fuel mixture for the most efficient chemical reaction. Based on the air-fuel ratio, the oxygen-carbon (O/C) ratio can be anywhere from 1 for stoichiometric half oxidation to 2 for $(CH_2)_n$ liquid hydrocarbon fuels. The optimal O/C ratio for stacking is 1.2, however 1 is acceptable. Reformer efficiency and gas composition as a function of operating factors (pressure, temperature, air-to-ratio, input flow rates) are of primary interest at present.

4. Equivalent Percent Hydrogen and Hydrogen Rich Gas Definition

In order to conduct hydrogen addition experiments in a way that is directly comparable to hydrogen rich gas addition experiments, it was necessary to establish an acceptable definition of the corresponding percent hydrogen. Figure 3 shows a schematic of the air and fuel flows into the engine. Although the H_2 , CO, N_2 , and CO_2 enter the engine as a single stream in the lean burn GDI engine, Figure 3 is equally valid since all of the HRG mix prior to combustion.

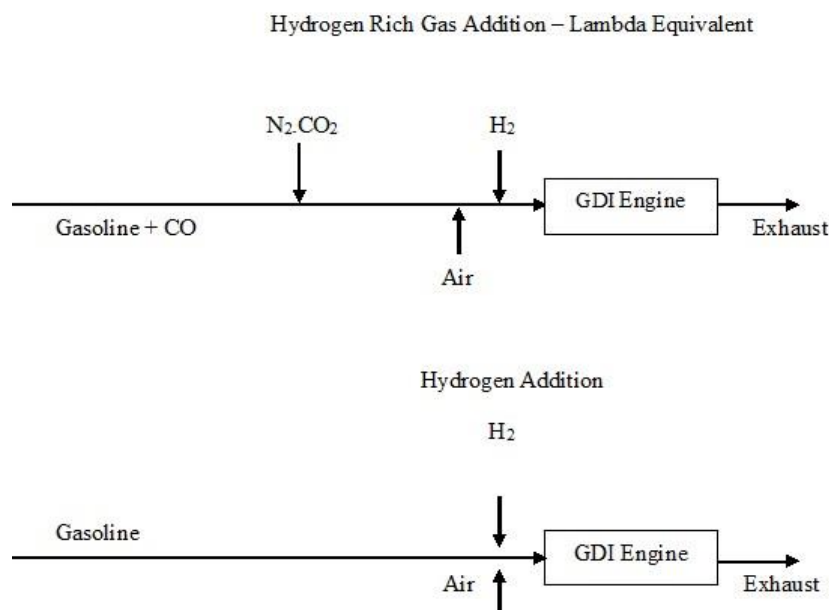


Figure 3 Experimental Setup for Hydrogen Rich Gas and Hydrogen Addition

This schematic highlights the resemblances between the hydrogen rich gas and hydrogen addition experiments. The equivalent percent hydrogen should be defined in such a way that a direct comparison between the HRG addition and hydrogen addition experiments quantifies the effect of the HRG components other than the hydrogen.

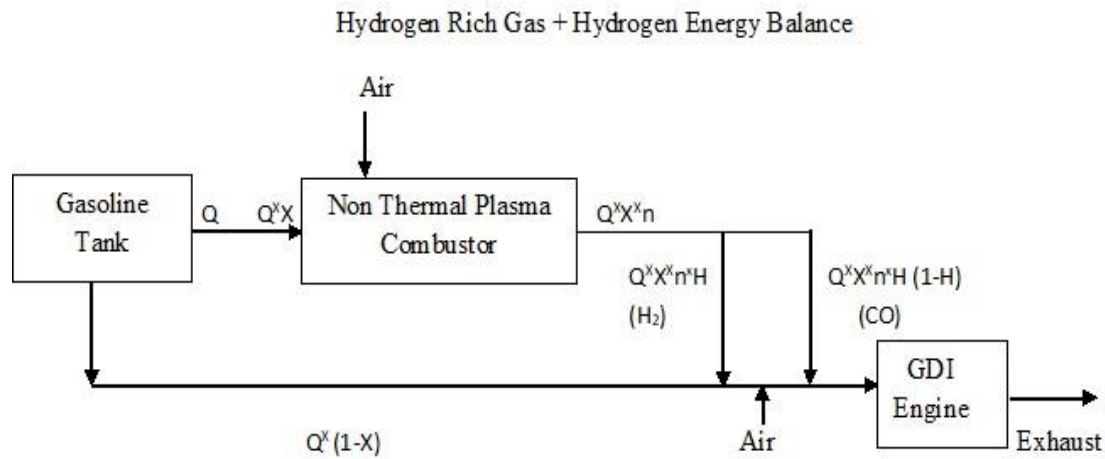


Figure 4: Energy Balance With Hydrogen Rich Gas

Evidently, a legitimate comparison can be made by equating the percentage of total energy delivered by the hydrogen.

Figure 4 illustrates an energy balance on the system. From Figure 4 we can form a ratio of the energy provided by hydrogen to the total energy entering the engine:

$$\frac{Q_{H_2}}{Q_{GDI\ Engine}} = \frac{Q_{ind} \cdot X \cdot \eta_{Plasma} \cdot H}{Q_{ind} \cdot X \cdot \eta_{Plasma} + Q_{ind} \cdot (1-X)} = \frac{X \cdot \eta_{Plasma} \cdot H}{1 + X(\eta_{Plasma} - 1)} \quad (3)$$

Where,

Q = Chemical Energy

η_{Plasma} = Non Thermal Plasma Efficiency

H = Fraction of the hydrogen rich gas energy that is supplied hydrogen

X = Plasma Reformed Fraction (Equivalent Percentage Hydrogen Rich Gas)

$$H = \frac{n_{H_2} \cdot MW_{H_2} \cdot LHV_{H_2}}{n_{CO} \cdot MW_{CO} \cdot LHV_{CO} + n_{H_2} \cdot MW_{H_2} \cdot LHV_{H_2}} \quad (4)$$

Where:

LHV = Lower Heating Value

n_c = Moles of Component X

All of the variables on the right hand side of equation (4) are known for the hydrogen rich gas case. Inserting these values into (4) gives $H=0.4521$. Finally, inserting numerical values for H and the hydrogen rich gas efficiency into equation (2) gives:

$$\frac{Q_{H_2}}{Q_{GDI\ Engine}} = \frac{0.3876 \cdot X}{1 - 0.1426 \cdot X} \quad (5)$$

Equation (5) can be used to calculate the fraction of the total energy entering the engine that should be provided by hydrogen to match a certain hydrogen rich gas experiment. For example, $X=10\%$ gives 3.97% as the fraction of the total energy provided by hydrogen. In other words, setting the hydrogen energy fraction equal to 3.97% in a hydrogen addition experiments will provide an equivalent percent hydrogen rich gas of 10%.

5. Engine Modification

The extending lean burn combustion for GDI engine for the specified engine design optimization work. A modified mono-cylinder 4 stroke, 5 Horsepower Diesel engine. Extend the clearance volume in-cylinder bTDC to set compression ratio (CR) 11:7 gasoline direct injection (GDI) system) addition of hydrogen and hydrogen rich gas enhance the combustion and in-cylinder pressure with reduce the engine knocking, the diesel injector system removed from the engine and a fake flange installed in the place of the gasoline pump. The

engine head space is constrained by the design of the GDI injector to cylinder thus the engine head drilled M10 and M14 size hole sectioned and studied to determine the place for installing the combustion pressure sensor and fuel injector, spark plug. Table 1: gasoline direct injection (GDI) Engine Parameters

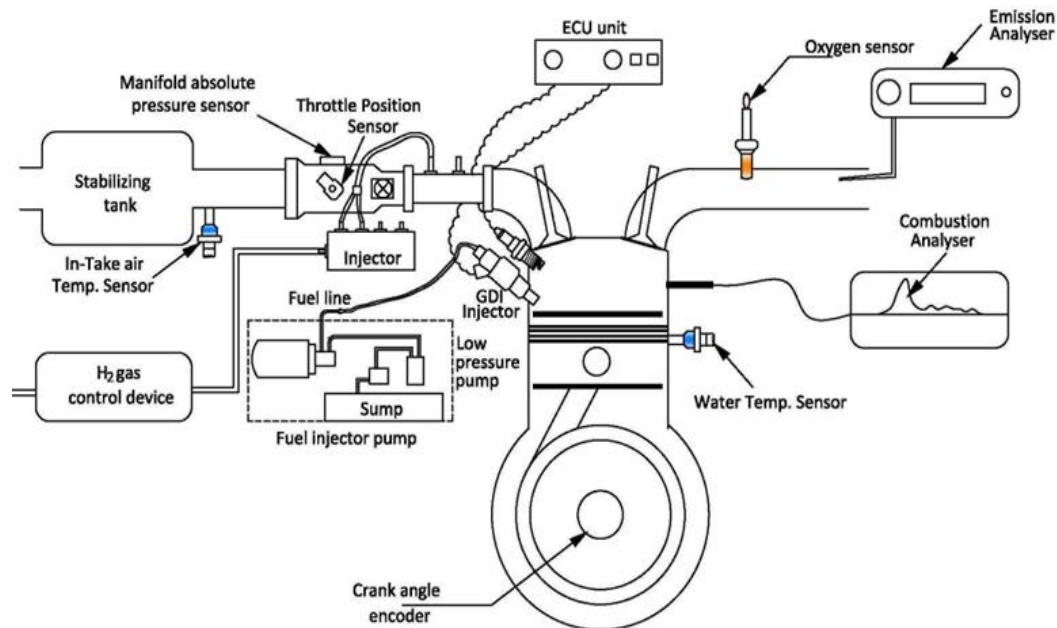


Figure 5.Experimental Conformation of Lean Burn gasoline direct injection (GDI) Engine

Table 2: Gasoline Direct Injection (GDI) Engine Parameters

Engine Design	Hybrid gasoline direct injection (HGDI) Engine, Mono cylinder, water cool
Gasoline fuel	Extending lean limit
Hydrogen	Enhancement with weight proportion (p)
D×L	80mm× 110mm
Extend the clearance volume	484 Clearance Volume
CR	11:7
Injection angle	145°.2' bTDC
chamber for combustion	Open circumpolar type
Piston	Piston, flat-bowl
IgnitionDischarge type	Plug with a coil
Injector	Internal whirl
Max Speed/Power	1400 revolutions per minute /3.7 Kw
Peak torque	23.55 Newton meter

6. Experimental Teston Enrichmentof Hydrogen and Hydrogen rich gas (HRG) – Gasoline Mixture Lean Limit Condition

The core components of the experimental setup are the gasoline direct injection (GDI) system) gasoline injection operating extending the lean limit synchronously on board for hydrogen and hydrogen rich gas enrichment maximum brake torque, the eddy current dynamometer for power measurement depicted.1 in order to improve engine performance, the hydrogen processes are associated as an auxiliary device. Figure 6The engine calibration using WinOLS software, VCDS and MAG Pro 2×17 (DECU) the injector assembly, and the onboard hydrogen Hybrid gasoline direct injection (HGDI) are the three central constituents of the testing engine.

The GDI engine extending lean limit operation with Hydrogen and hydrogen rich gas supplementation continuously spark advance and maximum brake torque timing for the constant port fuel injection pressure hydrogen and HRG Enhancement with weight proportion (p) to wide-ranging equivalence ratio $\lambda < 1.66$ at with a hydrogen with HRG weight proportion (p) fraction of $\lambda = 1.96$. gasoline direct injection (GDI) engine with hydrogen fraction in weight proportion (p) of substantial leeway of the engine's lean operation limit. was maintained at 0.04 lb/min (18 g/Cycle equivalence ratio was $\lambda = 1.72$ and the hydrogen weight proportion (p) = 0.0571 with isooctane and operation at a lean limit equivalence Ratio

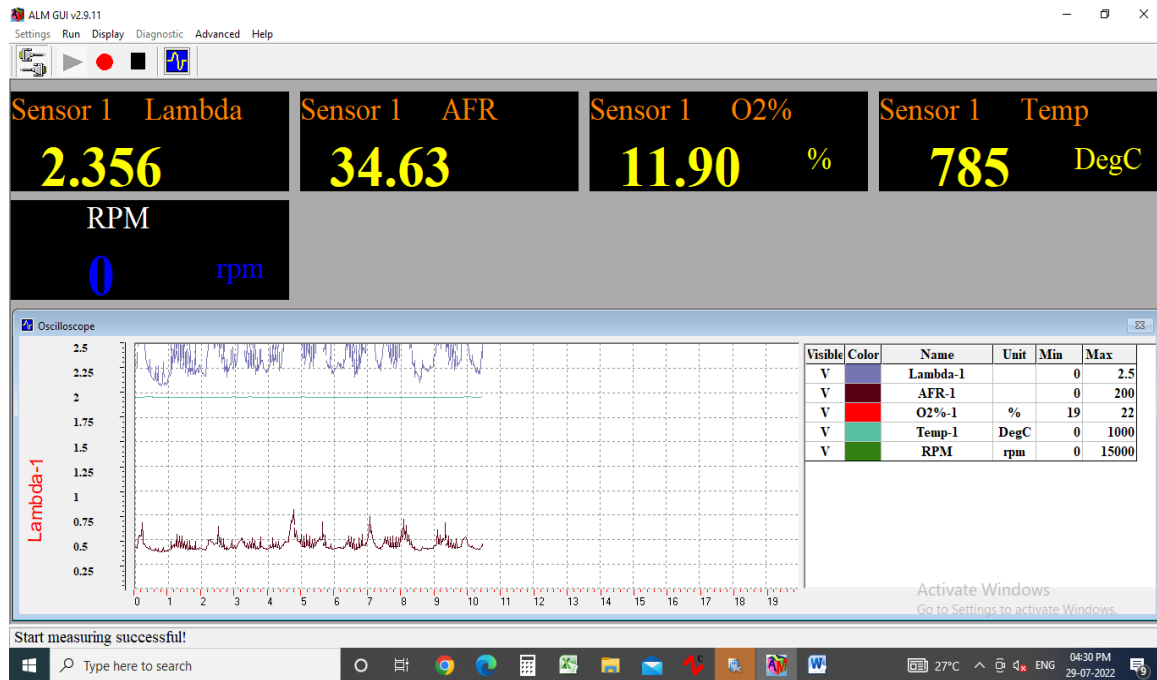


Figure 6: GDI Engine control Software

The initial lambda sweep was conducted with gasoline as the single component to establish a reference point. Three different Hydrogen and reformed fractions of fuel (10%, 20%, and 30%) were examined for the HRG addition conditions. The HRG was reproduction using bottled gas, therefore the reformed percentage will also be referred to as the HRG equivalent percent. The use of a HRG to reform 10% of the gasoline meant, for instance, that the flows into the engine were matched to what could have been achieved with a real HRG. The tests made use of both the ideal HRG gas and the more commonplace HRG gas. A consistent pressure source for the injector is provided by the fuel delivery system. The digital electronic control system used specific programmed to calculate and analogue and digital input form cam sensor, crank sensor, crank angle encoder, to manage the injectors injection quantity timing correlate with hydrogen port fuel injection timing °CA bTDC. In addition, it was unknown how the N₂ and CO in the HRG gas would affect the engine's lean combustion limitations

7. Result and Discussion

7.1 Evaluation of the non thermal plasma reformer efficiency

The non thermal plasma reformer efficiency is the ratio of the energy in hydrogen at reactor output to the energy input from gasoline fuel. we anticipate the conversion of carbon monoxide to hydrogen.

The following equation is then used to determine the non thermal plasma reformer's efficiency:

$$\eta_{ref} = \frac{(n_{CO} + n_{H_2}) \Delta H_{H_2}}{n_{fuel} \Delta H_{fuel} + NP_{ele}} \quad (6)$$

With n_{H_2} the hydrogen molar flux emitted by the non thermal plasma reactor, n_{CO} the carbon monoxide molar flux emitted by the non thermal plasma reactor, n_{fuel} the input gasoline flux, ΔH_{H_2} the lower heat of combustion for hydrogen, ΔH_{fuel} the lower heat of combustion for gasoline, and NP_{ele} the electrical power provided to the gas by the non thermal plasma discharge.

The conversion rate of non thermal plasma reforming input gasoline with various equivalence ratios which has been converted into H_2 , CO , and CO_2 or light hydrocarbon in the plasma reactor are presented. It is evaluated using the following equation.

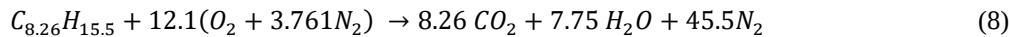
$$U_{Gasoline} = \frac{n_{CO,dry}}{n_{C,in}} = \frac{n_{CO,dry} + n_{CO_2,dry} + n_{CH_4,dry}}{7n_{C_{8.26}H_{15.5}}} \quad (7)$$

The plasma fuel reforming hydrogen rich gas measure by Nexis GC -2030 analyzer output of the hydrogen rich gas ratio of the different elements (H_2 CO N_2 CO_2 H_2O)

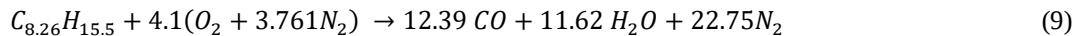
Table 3. Combustion stoichiometric for hydrogen rich gas

Equivalence ratio λ	H_2	CO	N_2	CO_2	H_2O
0.25	16.85	15.72	71.05	0.80	2.83
0.2	18.71	16.10	71.05	1.20	4.70
0.16	19.98	16.30	71.05	1.44	6.00

The plasma fuel reformer (PFR) generated hydrogen moles, carbon monoxide moles, plasma discharge's electric power added to the gas, the hydrogen input flux, the petrol input flux, and the reduced temperature of combustion for each. One mole of gasoline stoichiometric combustion $C_{8.26}H_{15.5}$



One mole of gasoline Partial oxidized $C_{8.26}H_{15.5}$



Data from electrical characterizations have been stored on a personal computer with the help of a numerical oscilloscope and an oscilloscope, The high voltage across the electrodes was successfully measured. A 20 KV @ 10 ohm resistance was attached connecting the electrode in question while the secondary electric circuit and the voltage were measured with a high voltage probe to determine the spark plug excessive voltage electric current. To calculate how much gasoline was transformed into hydrogen, carbon monoxide, and light hydrocarbons by the plasma reactor, we need to know the conversion rate.

Nearly 15% of fuel heating system value is released during Partial oxidation. The equilibrium gas species from the POX reaction (Eq. 9) is illustrated in Table 3.

Reformer efficiency and conversion rate improve with increasing temperatures and high air ratios, with a maximum efficiency at non plasma operating temperature 1110 K .

An ideal hydrogen rich gas (HRG), a typical HRG with 10%, 20%, and 30% hydrogen addition and a hydrogen rich gas using purely gasoline as fuel were considered for the test. MBT spark timing, burn duration data, combustion variability, hydrocarbon emissions, nitrogen oxide emissions, engine-only efficiency, and overall fuel system efficiency, accounting for HRG losses, the data will be shown on both the standard lambda scale and a fraction scale.

MBT Ignition Delay verses relative burn durations can be estimated using MBT time. Figure 7 displays MBT spark timing for both ideal and typical HRG tests. More HRG gas leads to a closer MBT timing to top dead center at a fixed lambda. Ideal and typical HRG data match well at all HRG levels' equivalent percent.

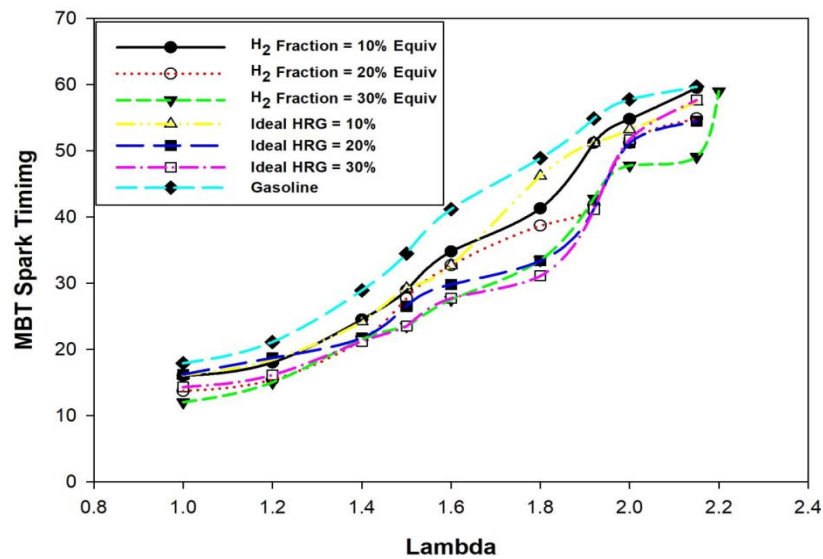


Figure 7: MBT Spark Timing versus. Lambda

This is because the ideal HRG gas contains nitrogen, which dilutes the results of the hydrogen addition studies even further. Illustrates the effects of diluting something, the 10% and 20% curves are virtually perfectly aligned. And at the 30% HRG comparable level, the optimal HRG burns slightly faster than the direct H₂ addition. This demonstrates that producing H₂ with an on-board HRG has no negative impact on combustion and actually results in combustion that is at least as rapid as, and sometimes quicker than, using direct hydrogen addition.

7.2 Burn Duration

In the development of ECU, it was demonstrated that the burning duration is highly sensitive to thermal dilution. Data from the experiment's electronic control unit between 10% and 90% burn angle at a constant lambda are displayed in Figures 8. It has been found that the optimal HRG experiments have shorter burn times than the average HRG trials. The burn times, however, look very different when plotted against lambda. However, when the burn times are plotted versus lambda, the perfect HRG tests have noticeably shorter burn times for the same dilution.

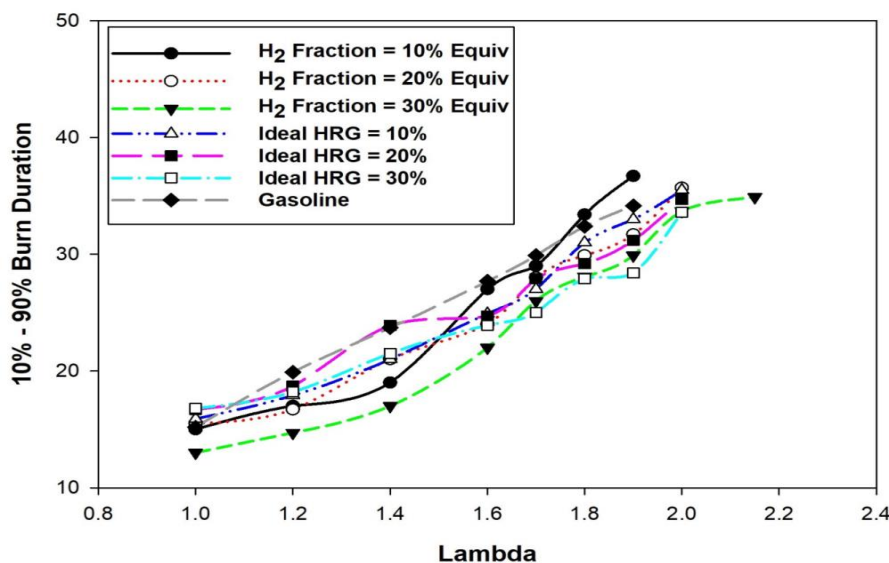


Figure 8: 10%-90% Burn Duration versus. Lambda

7.3 Combustion Stability

The second parameter that has a direct impact on engine efficiency is the stability of the combustion process. If all cycles burned at the same rate, then all NIMEPs would be equal. In actuality, combustion fluctuates between cycles, and as a result, burn times also vary. At a given operating condition, the spark timing is always the same, irrespective of how long the burn lasts. When there is combustion variability, the optimal spark timing is the MBT. This is because the average NIMEP is maximum at this instant. This does not yield the highest possible NIMEP in every cycle. The effect on the mean NIMEP is minimal when the variation between cycles is minor.

The in-cylinder pressure was recorded for 400 cycles at each operating condition. Each crank-angle resulted in one pressure reading, for a total of 720 readings each cycle. The effort per cycle was determined using a engine calibration using WinOLS software, VCDS and MAG Pro 2×17 (DECU)[5]. The NIMEP was computed using this information, and it is simply the work per cycle divided by the volume that was moved.

For the ideal hydrogen rich gas (HRG) and the hydrogen addition tests, the COV of NIMEP vs lambda is plotted in Figure 9. The lean combustion limit is increased in a predictable manner by the addition of hydrogen.

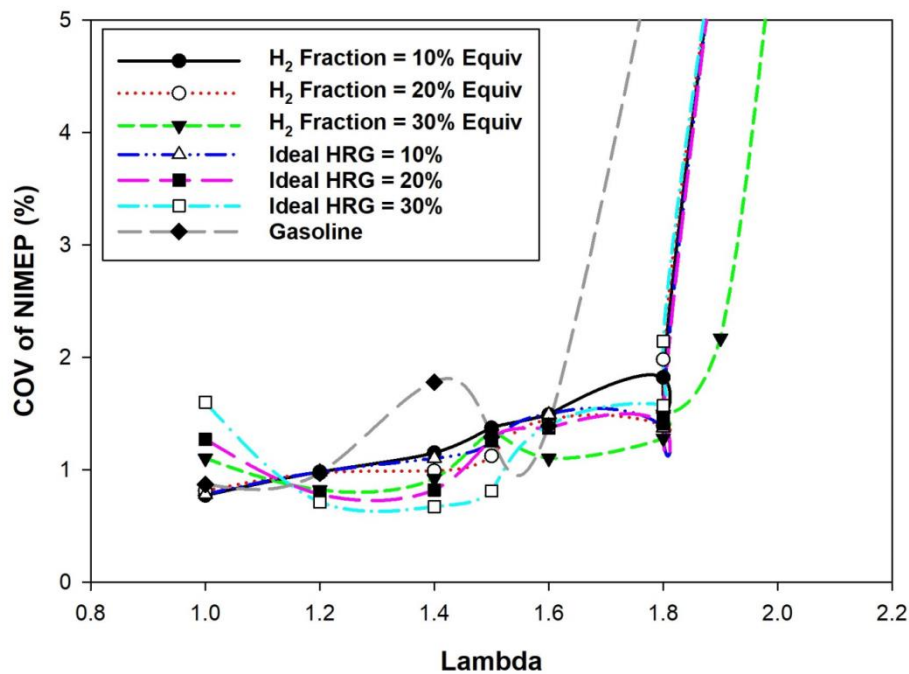


Figure 9: COV of NIMEP versus. Lambda

Experiments with hydrogen show that the lean limit rises by 0.1 lambda for every 10% increase in the percentage of HRG from gasoline-only to 30% HRG. Comparing the hydrogen addition example to the ideal HRG, the lambda at which the combustion quality starts to decline is much higher in the latter. While the increments in lambda at which combustion deteriorates are smaller for the HRG addition cases compared to the hydrogen addition cases, increasing the amount of HRG gas has the same effect.

7.4 Hydrocarbon Combustion Efficiency

Incomplete combustion has a direct influence on the efficiency of the engine. For the intent of calculating the hydrocarbon combustion efficiency of the engine, the mass flow rate of air and fuel into the engine can be utilized in tandem with the data on hydrocarbon emissions: The composition of the exhaust can be used to make a calculation about the molecular weight distribution of the exhaust. The AVL DIGAS 444N Gas Analyzer hydrocarbon analyzer has provided information regarding the hydrocarbon concentration, which is denoted by CH_c . Given that the HC analyzer outputs the HC concentration in PPM, the chemical formula that

should be utilized to determine the average molecular weight of the hydrocarbon in the exhaust. Figure 10 shows hydrocarbon combustion efficiency depends on burnt gas temperatures and combustion stability.

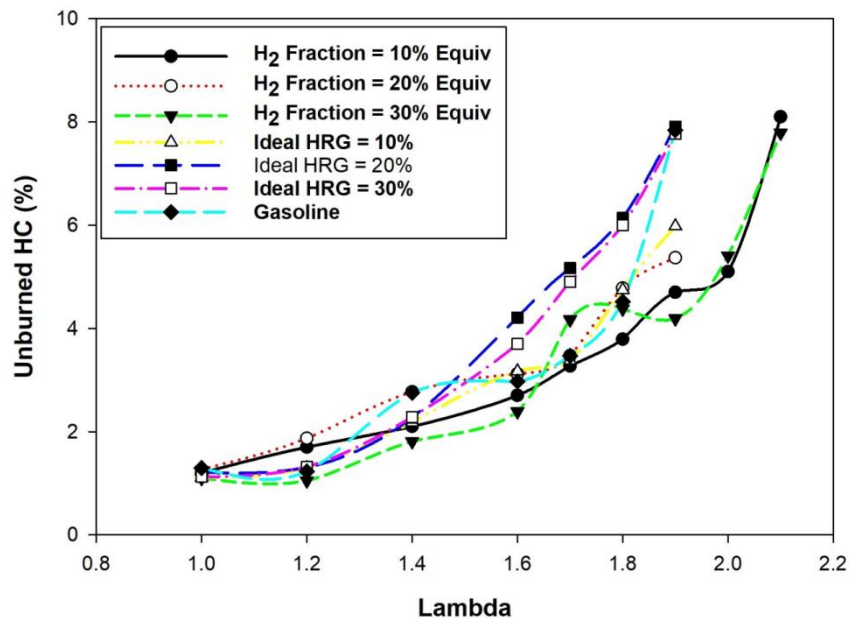


Figure 10: Percent Unburned Hydrocarbons versus. Lambda

The ideal HRG burnt gas temperature is higher than the typical HRG gas temperature at a fixed lambda due to its higher heating value. Additionally, the ideal HRG has a reduced COV compared to the typical when plotted against lambda. When plotted versus lambda, the ideal HRG gas ought to emit fewer hydrocarbon emissions compared to the typical gas due to increased combustion efficiency and burnt gas temperatures. Approximately 1.5% of the hydrocarbon fraction remains unburned at stoichiometric conditions.

7.5 Emissions of NO_x

The peak temperatures at which the combustion occurs and the oxygen content play a pivotal role in NO_x generation [6]. The generation of NO_x close to stoichiometric circumstances is intricate. The NO_x equilibrium can be driven by even a tiny increase in surplus air, leading to higher NO_x emissions. influence the NO_x equilibrium in ambiguous ways that are hard to narrow down. At higher dilution levels oxygen is abundant and the addition of excess air will only impact NO_x generation through the diluent effect by reducing burnt gas temperatures. Thus, the influence of oxygen content and peak temperatures varies from stoichiometric to partially lean conditions.

Experimentation with perfect HRG and addition of hydrogen considered for graphing NO_x emissions versus lambda on a logarithmic scale. Shows the Figure 11percentage of HRG gas is raised the impact on NO_x emissions is significant. At a lambda of 1.0, for instance, reducing the percentage of ideal HRG gas used from 10% to 30% reduces NO_x emissions by around 40%. In addition, the typical experiments exhibit lower emissions compared the ideal HRG studies. These two findings are typically attributed to diluted effects.

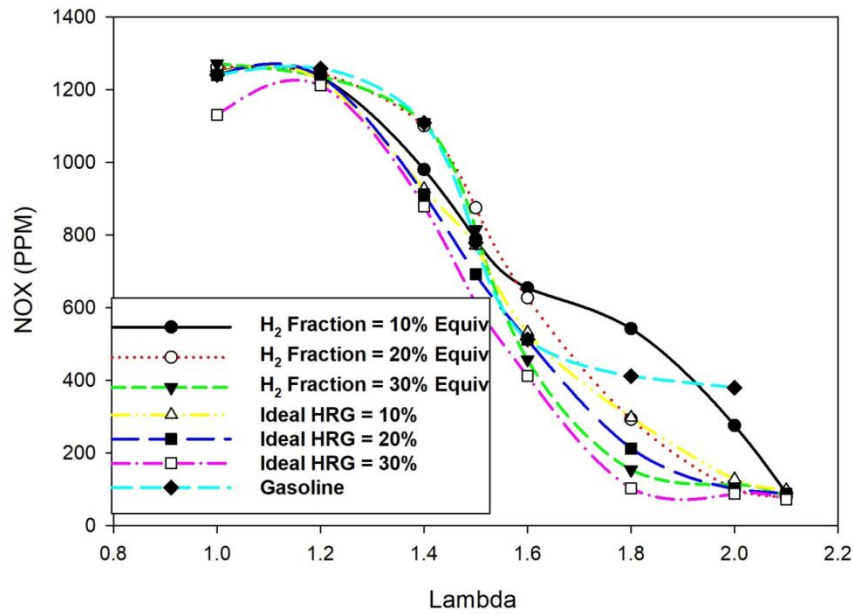


Figure 11: NO_x emissions versus. Lambda

7.6 Cylinder pressure

Figure 11 shows the cylinder pressure efficiency compares to the advance MBT timing of the ideal hydrogen rich gas (HRG) and hydrogen (10 - 30 %) enhancement. Generally, the GDI engine can reach its highest efficiency maximum pressure occurs at start of injection 100°bTDC and maximum brake torque timing 25 ° bTDC. In enhancement at the 30 % of equivalent hydrogen rich gas level of ideal HRG is slightly faster burning a than the direct H₂ addition and spark timing engine work in compression stroke but also decrease combustion temperature which is respectable for reducing NO_x emission.

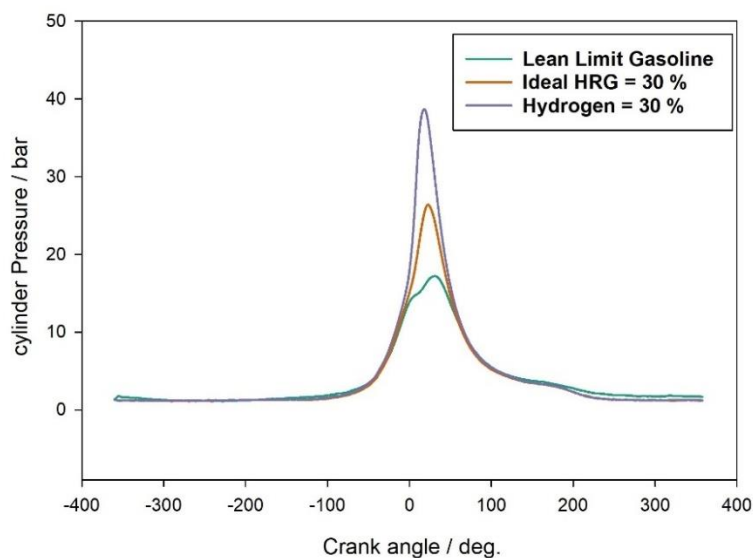


Figure 12: Crank angle verses pressure for fuel blend of (10 - 30 %) hydrogen rich gas and hydrogen fraction GDI engine speed 1400 rpm, $\lambda = 1.72$

7.7 Net Heat Release Rate

Figure 12 shows the net heat release rate of ideal hydrogen rich gas and hydrogen 0%-30% plotted verses crank angle. extending lean limit at low values of lambda the combustion process is both fast and stable and the

addition of hydrogen rich gas has only a small impact on burn duration. Comparing the gasoline only case and the 30% ideal HRG case shows that at a lambda of 1.72 the spread the dilution level increases the curves begin to separate as the hydrogen in the ideal HRG has an increasingly positive effect on the combustion process. The impact of ideal HRG gas on burn duration is expected to grow as lambda is increased. Looking at the typical and ideal HRG trials the match in burn duration is good although as lambda is increased the ideal HRG gas burns faster than the typical ideal HRG gas.

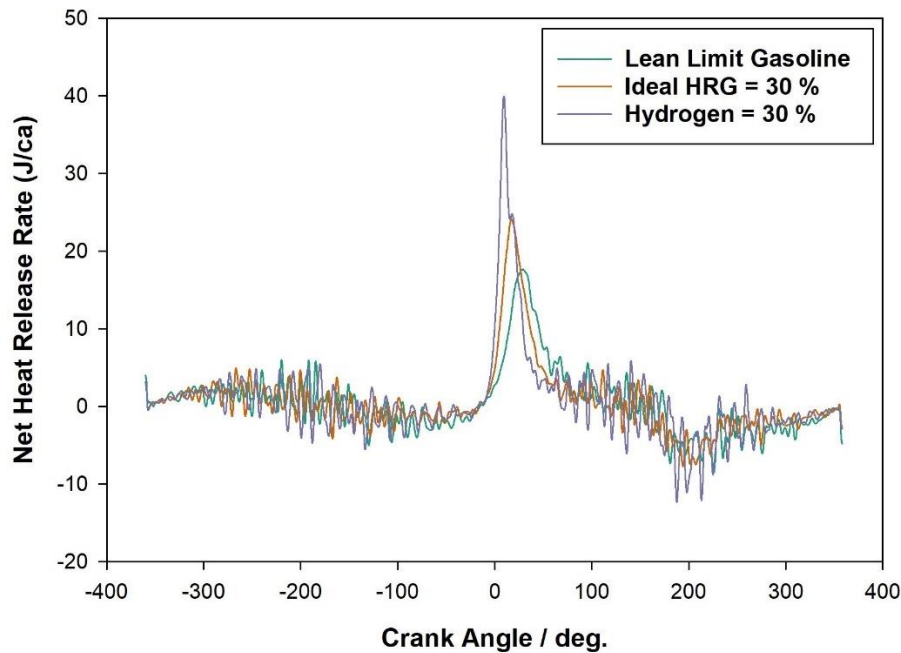


Figure 12: Crank angle versus Net heat release rate for fuel blend of (10 - 30 %) hydrogen rich gas and hydrogen fraction GDI engine speed 1400 rpm, $\lambda = 1.72$

Comparing the gasoline only case and the 30% ideal HRG case shows that at a lambda of 1.72 the spread the dilution level increases the curves begin to separate as the hydrogen in the ideal HRG has an increasingly positive effect on the combustion process. The impact of ideal HRG gas on burn duration is expected to grow as lambda is increased. Looking at the typical and ideal HRG trials the match in burn duration is good although as lambda is increased the ideal HRG gas burns faster than the typical ideal HRG gas.

7.8 Flexibility in Engine Fuel Conversion Efficiency

The efficiency of the engine alone plotted versus lambda for both the typical and ideal HRG instances. As the engine is run lean, the efficiency will suffer due to changes in three factors: burn time, combustion inefficiency, and combustion variance. Offsetting these negative effects on efficiency is the elimination of pumping inefficiencies beneath lean conditions, improved cycle efficiency owing to the reduced specific energy of lean burned gases, and reduced heat dissipation due to the decreased burnt gas temperatures. This is consistent with the prior results showing that the detrimental effects of burn duration, combustion ineffectiveness, and combustion unpredictability are minor at the outset and are not significantly affected by the comparable percentage of HRG and hydrogen. All three, however, grow significantly closer to the lean limit, Efficiency is predicted to improve nearly linearly in the outset due to the dominance of efficiency-boosting factors, before the detrimental effects of a longer burn time, less efficient combustion, and deteriorating combustion stability become significant. Efficiency will peak and fall at this point. At a fixed lambda the infusion of HRG gas culminates in greater engine efficiency. This is primarily due to the fact that as additional HRG gas is injected the total molar flow rate into the engine is raised and therefore the pumping inefficiencies are reduced. In addition the peak efficiency occurs at a greater lambda due to using extension of the lean limit

from the HRG gas. Reduced pumping inefficiencies and an increased lean limit cause the inclusion of HRG gas to cause a change in the curve upward and to the right.

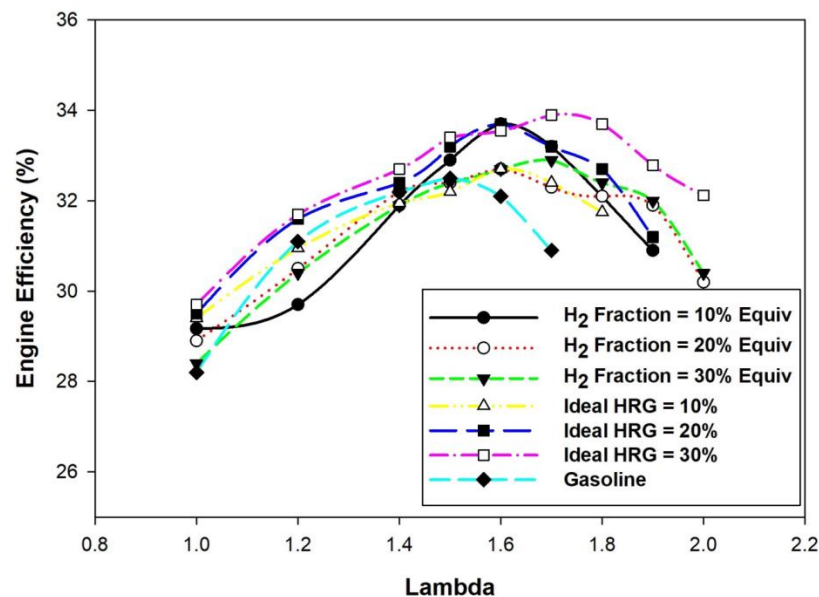


Figure 12: Engine Only Efficiency vs. Lambda

The overall system efficiency of the ideal HRG is higher than that of a normal HRG. In addition, all of the ideal HRG data sets the exterior out at about the same efficiency of 32%. What this means is that the efficiency advantages from operating at higher reformed fractions in the engine alone were roughly cancelled out by increased losses in the HRG. Shows Figure 12 maximum efficiency for the ideal HRG studies is roughly 12.3% higher than the stoichiometric case with simply gasoline.

The usual HRG experiments have a reduced efficiency than the ideal HRG experiments due to the reduced HRG efficiency. As the reformed portion enhances the optimum efficiency of the typical HRG studies diminishes. An obvious way to increase efficiency is to either increase HRG efficiency or build the engine so that it can function on lower HRG fractions. It's worth noting that the peak efficiency occurs in the gasoline only trial. That is to say, the HRG losses more than cancel out the engine's efficiency benefits from using a HRG. However, due to combustion variability difficulties and pollution regulations, gasoline-only engines are often unable to operate at this peak efficiency point and are instead limited to the stoichiometric operating point.

8. Conclusions

The net indicated fuel conversion efficiency of a Hydrogen and HRG fuelled engine has the potential to increase significantly. For the tested engine and operating conditions, the maximum net indicated fuel conversion efficiency was achieved at 20% ideal HRG peak efficiency point, a 12.7% improvement over the baseline case of the engine operating stoichiometrically on gasoline only.

The term substantial reductions in NOx emissions were noticed when operating at high dilution levels. Near the upper dilution limit, NOx emissions from the engine exhaust were reduced by as much as 99% when high concentrations of hydrogen rich gas (HRG) were employed. The NOx reduction reached over 92.7% at maximum efficiency.

Increasing the dilution raised the percentage of unburned hydrocarbons. At low levels of dilution, this value was not affected by the fuel mixture that was being used, nor was it affected by the comparable percent of hydrogen addition. HRG decreased the proportion of unburned hydrocarbons in the more concentrated mixtures.

The CO in the HRG gas had a marginally better influence on combustion, as shown by a comparison of studies using hydrogen addition to those using HRG addition. This replicated in the efficiency, emissions, and

combustion stability data. The fact that CO has a larger dilution limit than gasoline is suggested to account for this observation.

Engine lean burn limit could be extended by hydrogen rich gas and hydrogen addition mainly due to hydrogen's broader burn limit and fast burn speed. 10%, 20%, and 30% hydrogen extended lean limit to Equivalence ratio $\lambda = 1.82$, $\lambda = 2.09$, and $\lambda = 2.4$, respectively, compared to Equivalence ratio $\lambda = 1.72$ for gasoline.

The hydrogen rich gas reformer experiences severe losses, which have a direct bearing on the overall efficiency of the system. Hydrogen rich gas and Hydrogen addition was beneficial to the assuagement of the trade-off relation between HC and NO_x emission.

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