

THESIS

IMPACT OF H₂-NG BLENDING ON PERFORMANCE AND EMISSIONS OF STOICHIOMETRIC AND LEAN BURN SPARK IGNITED ENGINES

Submitted by

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ABSTRACT

IMPACT OF H₂-NG BLENDING ON PERFORMANCE AND EMISSIONS OF STOICHIOMETRIC AND LEAN BURN SPARK IGNITED ENGINES

The energy crisis and growing environmental concerns are serious problems faced all over the world today. Renewable sources like solar and wind energy are often perceived to be the solution but high market penetration utilizing these sources directly has limitations. These sources cannot be relied upon for base load and the demand-supply mismatch makes them impractical for peaking applications. To address this, energy storage mechanisms like chemical storage can be employed to smooth the available renewable energy supply over time. More specifically, electrolysis of water can be carried out to create hydrogen, utilizing the electricity produced from solar and wind. This hydrogen may then be blended with natural gas in pipelines to be used in natural gas applications.

Blending hydrogen with natural gas (H₂-NG blend) significantly changes properties of the gas. The goal of this project is to study the impact of H₂-NG blend on spark-ignited internal combustion engines. To evaluate the impact of H₂-NG blend on stoichiometric engine performance, testing was performed on a 7.5 L Cummins Onan Generator Set, model GGHD 60Hz, equipped with an NSCR catalyst. Two different carburetor/lambda sensor combinations were tested with the NSCR catalyst to assess impact of blending different percentages of hydrogen into natural gas on catalyst efficiency as well as engine performance and emissions. Criteria for emissions

considered for this testing was South Coast Air Quality Management District Rule 1110.2 limits of 11 ppmv NO_x, 250 ppmv CO and 30 ppmv VOCs, corrected to 15% oxygen.

Stoichiometric testing was also performed on a Cooperative Fuel Research (CFR) engine to perform combustion analysis. The CFR is an F-2 model manufactured by Waukesha Engine, Dresser Industries. It is a single cylinder, 4-stroke, spark-ignited engine with a constant speed of 940 rpm, which can be operated at various compression ratios from 4:1 to 18:1. An in-cylinder pressure transducer (Kistler model 6061A) was installed for recording detailed in-cylinder pressure data, which was used to analyze engine knock. Base fuel for the engine was a blend of 90% methane (CH₄) and 10% ethane (C₂H₆). The engine was tested at various H₂-NG blends to assess impact of H₂ on engine knock and determine critical compression ratio at each blend, as well as determine impact on ignition delay and combustion rate. Testing was also performed on the CFR engine to evaluate impact of hydrogen on lean burn operation. Increasing percentages of H₂ were added to the base fuel to study the effect on emissions as well as lean burn limit of engine operation.

Results showed that NO_x emissions tend to increase with hydrogen addition, while THC and CO emissions show marked reduction. Up to 10% hydrogen may be added to natural gas; the exact value depends on particular engine configuration and emission norms. Also, adding hydrogen increases engine susceptibility to knock at stoichiometric operation, and improves combustion at lean operation, allowing the engine to operate at leaner equivalence ratios. Operating at lean limit with retarded spark ignition timing to offset faster flame speeds of hydrogen can help reduce NO_x emissions considerably.

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1. INTRODUCTION

1.1 BACKGROUND

Increasing levels of environmental pollution and depleting fossil fuel reserves are indicative of the pressing need for expanding the use of renewable energy. Concerns about climate change, as well as energy security have fueled extensive research in the field of cleaner alternative renewable energy sources. Renewable energy resources are abundant and widespread compared to traditional energy sources, which are concentrated in a limited number of countries. However, in most locations, renewable energy is currently more expensive than traditional energy sources. Recently, renewable energy legislation and government incentives have triggered rapid development in advanced technologies for efficiently harnessing renewable energy.

As per Renewables 2014 Global Status Report, renewable energy provided an estimated 19% of global final energy consumption in 2012 (Figure 1.1), and continued to grow strongly in 2013^[1]. The most significant growth occurred in the power sector, with global capacity exceeding 1,560 gigawatts (GW), up more than 8% over 2012.

Increasingly, renewable energy is considered crucial for meeting current and future energy needs. Modern renewable energy is being used predominantly in four distinct markets: power generation, heating and cooling, transport fuels, and rural/off-grid energy services. United States has some of the best renewable energy resources in the world, which have the potential to meet a rising and significant share of the nation's energy demand. The government has taken many initiatives in a bid to make use of these resources to address the twin challenges of energy security and climate change.

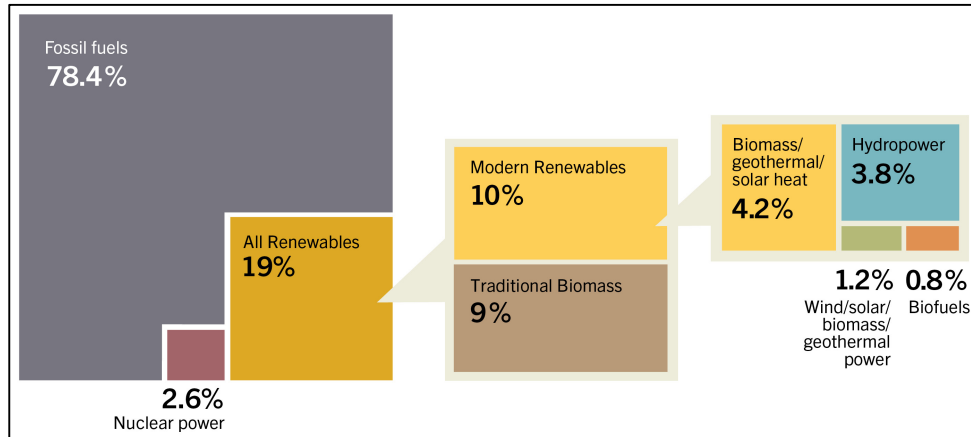


Figure 1.1: Renewable Energy Share of Global Final Energy Consumption, 2012^[1]

California, one of the leading states in utilization of renewable energy resources, has put forth an aggressive goal of increasing energy procured from eligible renewable energy resources to 33% of total procurement by 2020^[2]. In order to meet this ambitious goal, renewable energy alone is not sufficient at the moment. Although the scenario for renewable energy looks very promising, there are still a lot of challenges associated with substantial integration of renewables into large scale power generation. The leading renewable sources of energy at present, namely solar and wind power, are intermittent resources and lack reliability. Their ability to generate power varies by season and even by time of day. Solar energy generates substantial power on a sunny day but no power overnight. Wind energy may be consistent for the most part of the day but it is prone to sudden fluctuations. This unreliability puts limitations on high penetration of these sources as base load and they are impractical for peaking applications, since peak power production periods do not correlate with peak demand.

1.2 NATURAL GAS SCENARIO

Various technologies are being pursued towards the goal of energy storage to help integrate renewables into the power grid. Batteries are excellent for rapid storage and

discharge but have constraints with respect to capacity and long term storage. A viable solution may be 'power to gas' technology to smoothly use the available renewable energy over time^[3]. This technology simply uses excess renewable electricity to produce hydrogen, which acts as an energy storage medium. This hydrogen can then be blended in natural gas pipelines for use in end applications.

United States, with its abundant natural gas resources, already has an extensive and well-developed natural gas pipeline network with good interconnectivity and well-established safety procedures. Figure 1.2 gives a general idea of the extent of the US natural gas pipeline network^[4].

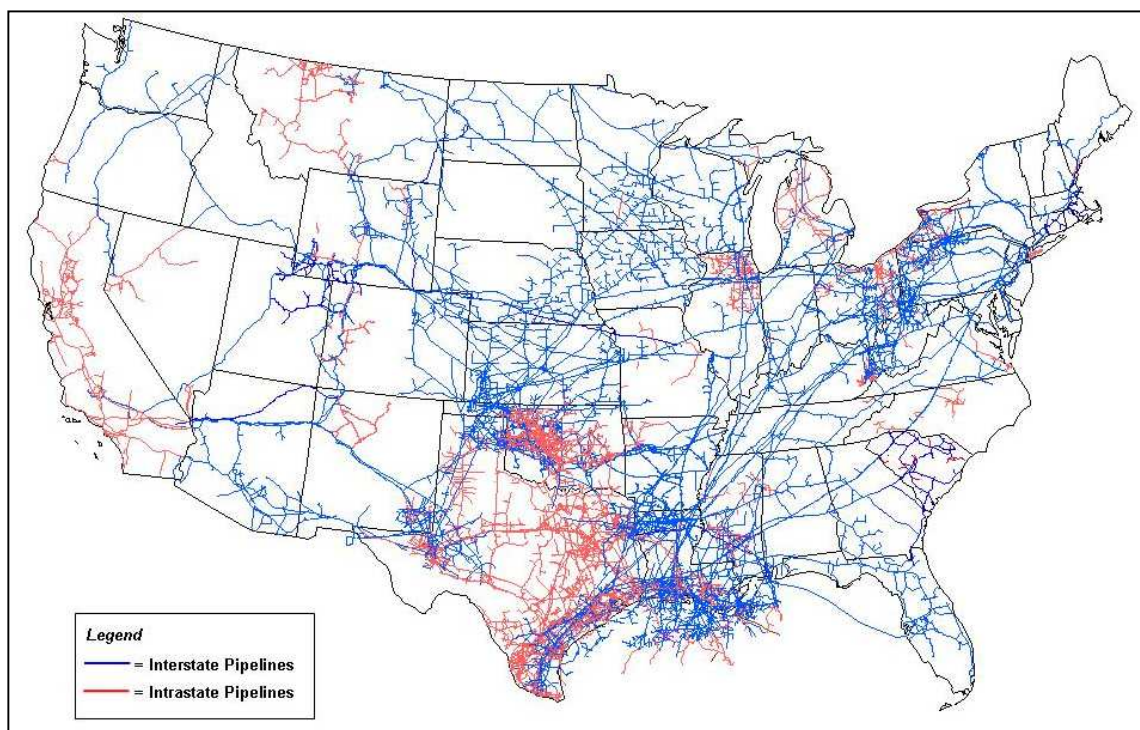


Figure 1.2: US Natural Gas Pipeline Network^[4]

Chemical conversion of electricity to gas allows the existing natural gas pipeline infrastructure to be leveraged for massive-volume, long-term, distributed storage that is cost competitive with other storage technologies^[3]. Basic electrolysis of water, using

electricity produced from renewable sources, produces its components hydrogen and oxygen. The oxygen has commercial value and is sold or utilized and the hydrogen can be deployed in different ways. It can either be used as a fuel by itself or in the process of methanation, along with carbon dioxide (CO_2), to form synthetic methane, or renewable natural gas^[3]. Figure 1.3 presents this concept.

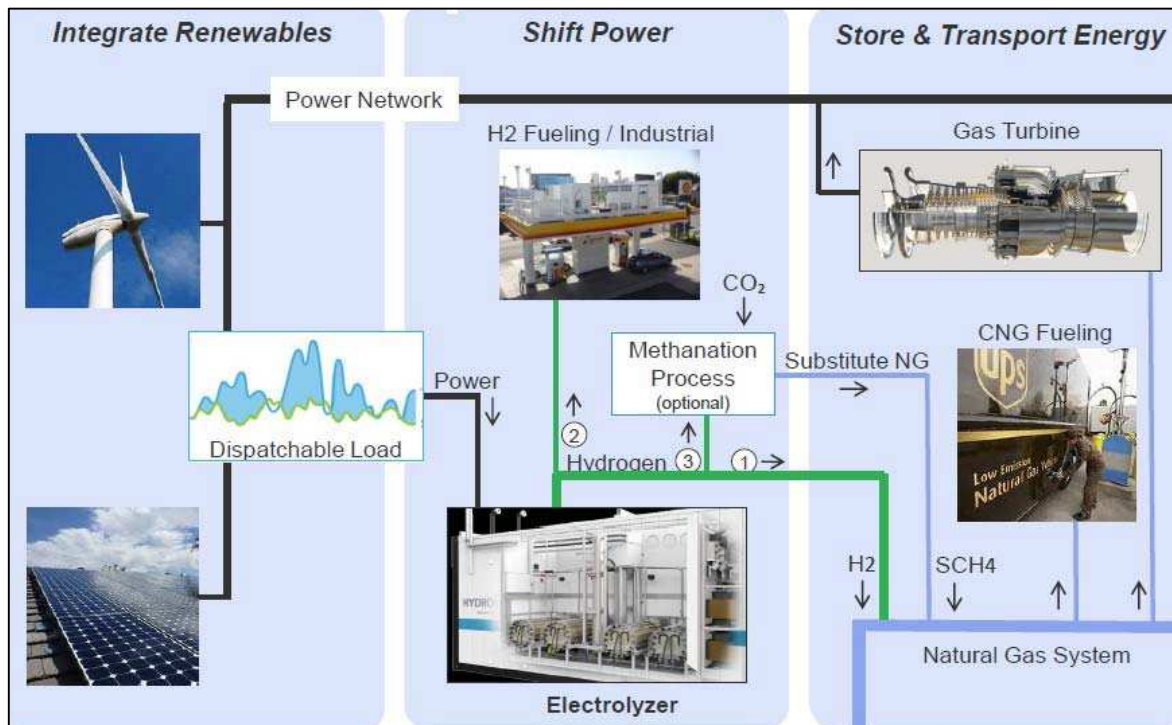


Figure 1.3: Concept of Power to Gas^[3]

Another way of using this hydrogen, which is the focus of this study, is to blend it into the natural gas system to store and transport energy. Natural gas is low cost and cleaner compared to the other fossil fuels, less reactive and easy to store and transport, thus acting as the perfect carrier for hydrogen.

1.3 HYDROGEN-NATURAL GAS (H₂-NG) BLEND

Natural gas, with its excellent properties as a fuel, has become more important in recent years. No energy source supplies a more diverse range of sectors and uses than natural gas namely power generation, industrial sector, space heating and transportation sector. It is composed of a mixture of hydrocarbons with methane as its primary component (85 to 99%), followed by ethane (6 to 10%), propane (3 to 5%), carbon dioxide, water vapor, nitrogen, and other trace gases. Natural gas, although non-renewable, is plentiful, with more and more untapped reserves being discovered all over the world. It has excellent anti-knock properties with a high Octane rating, which enables engines operating on NG to operate at higher compression ratios compared to gasoline^[5] Due to its low carbon to hydrogen (C/H) ratio, use of natural gas results in lower emissions of non-methane HCs, CO and CO₂.

Hydrogen, on the other hand, is known for its excellent combustion characteristics like low ignition energy and high flame speed. It shows considerable reduction in emissions due to its zero C/H ratio. However, currently, it is restricted to being used as an additive only, due to problems with storage and transportation, lack of a developed distribution infrastructure and high costs involved in generation. This problem can be solved with the proposed blending of hydrogen into natural gas pipelines. As a delivery method, this will save substantial infrastructure costs that may be incurred if a separate delivery network needs to be built for hydrogen.

However, several factors need to be taken into consideration associated with this blend. Safety is the most important factor. The potential of increased probability of ignition and subsequent damage poses a risk because of the broader ignition range of hydrogen.

Leakage is another concern. Permeation rates for hydrogen are about 4 to 5 times faster than for methane in typical polymer pipes used in the US natural gas distribution network. Leakage in steel and ductile iron systems mainly occurs through threads or mechanical joints. Leakage measurements for steel and ductile iron gas distribution systems (including seals and joints) suggest that the volume leakage rate for hydrogen is about a factor of 3 higher than that for natural gas. Though gas loss from service lines is economically negligible, leakage into confined spaces may pose a safety risk. High-pressure gaseous hydrogen is a potential safety hazard due to problems of material resistance. However, given the pressures and stress levels occurring in the natural gas distribution system, this is not a major concern^[4].

If the above concerns are addressed, adding hydrogen to natural gas can significantly reduce greenhouse gas emissions in end applications like engines. Table 1.1^[6] gives a comparison of some of the properties of hydrogen and natural gas.

Table 1.1: Properties of Hydrogen and Natural Gas (Reprinted^[6])

Fuel Characteristics	Hydrogen	Methane
Equivalence ratio ignition lower limit in NTP air	0.1	0.53
Mass lower heating value (kJ/kg)	119,930	50,000
Density of gas NTP (kg/m ³)	0.083764	0.65119
Volumetric lower heating value at NTP (kJ/m ³)	10,046	32,573
Stoichiometric air-to-fuel ratio	34.20	17.19
Volumetric fraction of fuel in air, $\lambda=1$	0.29	0.095
Burning speed in NTP air (cm/s)	265-325	37-45
Flame temperature in air (K)	2318	2148
NTP denotes normal temperature (293.15 K) and pressure (1 atm)		

Hydrogen and natural gas have complementing properties. Hydrogen has a wider flammable mixture range, lower ignition energy and a burning speed approximately 7

times that of methane, all of which are helpful to improve engine's lean burn capability. Hydrogen has a higher mass-specific LHV, almost three times that of methane. However, due to its low density, it suffers from a markedly low volumetric heating value compared to methane. Also due to its high burning rates, a hydrogen fueled engine is prone to knocking, which is offset in the H₂-NG blend by the lower flame speed of natural gas. Thus H₂-NG blend can have favorable properties of both its components.

Blending hydrogen with natural gas, however, changes the properties of the gas. 10% hydrogen with natural gas reduces the Wobbe index by 3% and the heating value by 7%. The Wobbe index is an indicator of the interchangeability of fuel gases, defined in the specifications of gas supply and transport utilities. It is a ratio of high heating value of a gas and square root of its specific gravity with respect to air. The higher the Wobbe number, the greater the heating value of the quantity of gas that will flow through a hole of a given size in a given amount of time^[7]. Most end applications are designed for a specific Wobbe band so a significant change in Wobbe index can have an impact on the end applications. Hence, natural gas applications downstream of the hydrogen injection point must be compatible with the amount of hydrogen blended.

Running higher percentage of hydrogen in an engine designed only for natural gas can cause engine damage due to knocking. Electronic Control Unit (ECU) calibration maps are usually developed for a particular fuel composition, which may be ineffective for H₂-NG blends resulting in high emissions. An assessment of the percentage of hydrogen that may safely be blended in without adversely affecting engine performance or running out of emissions compliance needs to be made. This is one of the primary objectives of this study.

1.4 EXHAUST EMISSIONS FROM SPARK IGNITED ENGINES WITH H₂-NG BLEND

The main criteria pollutants that need to be considered, when running spark ignited engines with hydrogen-natural gas (H₂-NG) blends, are oxides of nitrogen (NO_x), total hydrocarbons (THC) and carbon monoxide (CO). These emissions are typically reported in parts per million dry (ppmd). The emission norms considered for this study are specified by South Coast Air Quality Management District (AQMD) Rule 1110.2^[8] - Emissions from Gaseous and Liquid-Fueled Engines: NO_x 11 ppm @15%, CO 250 ppm @15%O₂ and volatile organic compounds (VOCs) 30 ppm @ 15% O₂. Non-criteria pollutants like carbon dioxide (CO₂), ammonia (NH₃) and formaldehyde (CH₂O) are also considered.

Natural gas has methane as its primary component, with small amounts of ethane, propane and other gases. It is considered a 'cleaner' fuel when compared to the traditional fossil fuels, since particulate matter emissions are negligible and most of the THC emissions are methane, which is chemically inert and does not contribute to ozone formation like higher HCs. CO emissions are considerably less, and CO₂ emissions are also lower than gasoline/diesel due to higher H/C ratio of natural gas. Natural gas does not contain aromatic compounds such as benzene and contains less dissolved impurities like sulfur compounds. Low flame speed and relatively low combustion temperatures reduce NO_x emissions, even at higher compression ratios. THC emissions can be lower compared to gasoline engines, since gaseous state of natural gas avoids wall wetting effects on intake manifold and cylinder liner at cold start conditions. However lower combustion temperatures can result in increased THC for stoichiometric mixtures, due to higher light-off temperatures required by the catalyst for oxidation of CH₄, which is the dominant component in THC for natural gas. Also, slow flame propagation velocity for

lean mixtures can result in misfire and incomplete combustion. This is offset with introducing hydrogen into the natural gas as fuel. Hydrogen, with its zero carbon content, further increases the H/C ratio of the fuel, reducing THC emissions. Also, its higher flame speed increases combustion efficiency and widens lean limit, effecting further reduction in THC and CO. On the other hand, NO_x emission becomes a problem with H₂-NG blend because of higher combustion temperatures. NO_x emissions can be reduced by operating at lean mixtures or employing NSCR catalyst at stoichiometric mixtures. NO_x emissions are primarily composed of nitric oxide (NO) and nitrogen dioxide (NO₂). NO_x levels are strongly dependent on combustion temperatures and increase exponentially with temperature. Hence, high engine out NO_x emissions are seen near stoichiometric equivalence ratio while the least at lean flammability limit due to reduced temperatures. In contrast, high THC and CO emissions occur at the lean limit, and decrease as equivalence ratio approaches stoichiometric. THC and CO emissions are also high in rich mixtures ($\phi > 1$), due to insufficient oxygen available for complete combustion. Figure-1.4^[9] depicts typical trends of these emissions with respect to equivalence ratio.

Advancements in combustion process and exhaust after-treatment systems has improved exhaust emissions significantly since the 1970s. Precise control of air/fuel ratio (AFR) and effective after-treatment for a given equivalence ratio (ϕ) reduce emissions without sacrificing engine performance. Lean burn engine operation may require Selective Catalytic Reduction (SCR) technology or a lean NO_x trap for controlling NO_x emissions and an oxidation catalyst for CO and THC. A three way catalyst/Non-selective Catalytic Reduction (NSCR) is considered to be the most effective for stoichiometric operation. NSCR operation is studied as part of this project.

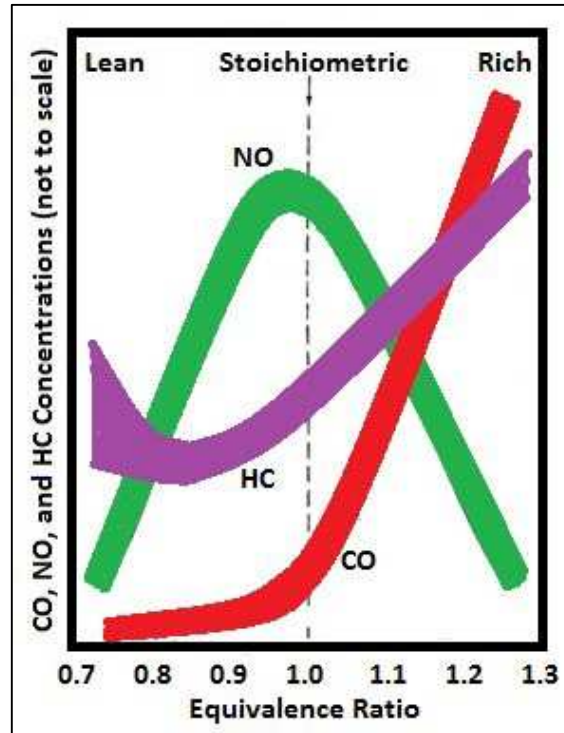


Figure 1.4: Typical Emissions Trends in a SI Engine^[9]

1.5 OUTLINE

This study focuses on stationary spark ignited natural gas engines as end application subjected to a blend of hydrogen and natural gas in varying percentages. The study attempts to answer following research questions:

- What is the amount of hydrogen that can be blended in with natural gas, while complying with emissions limits as per South Coast AQMD rule 1110.2?
- What is the impact of blending hydrogen with natural gas on the critical compression ratio?
- What is the impact on lean burn limit when adding hydrogen to natural gas as fuel?
- Is there an improvement in emissions for lean burn operation?

In order to answer these research questions, following objectives were outlined for this study:

- i) Evaluate impact of H₂-NG blend on performance and emissions of stoichiometric engine operation using NSCR catalyst with λ sensor and carburetor control.
- ii) Analyze engine combustion, with increasing H₂ percentage blends, to assess impact on engine knock, critical compression ratio and optimum ignition timing.
- iii) Evaluate impact of H₂-NG blend on lean burn engine performance and emissions.

Chapter 2 presents a literature review aimed at understanding previous work done in assessing this impact of blending hydrogen in natural gas on the performance and emissions of spark ignited natural gas engines. Chapter 3 discusses the experimental setup and procedure for this study. Thereafter, Chapter 4 presents experimental results for impact on stoichiometric engine operation, addressing objectives (i) and (ii). Chapter 5 presents results obtained for impact on lean burn engine operation, fulfilling the third objective.

2. LITERATURE REVIEW

2.1 LEAN BURN ENGINES

This literature review studies the effect of blending hydrogen with natural gas as a fuel to spark-ignited engines. The study, specifically, attempts to answer two principal questions: (a) What is the impact of adding hydrogen to natural gas on lean burn engines?, and (b) What is the impact of adding hydrogen to natural gas on 3-way catalyst operation in a stoichiometric engine?

2.1.1 Impact on Pollutants

Impact on NO_x emissions:

Antonio et al, in their review of H₂-NG blends^[10], point out the impact of adding hydrogen to natural gas (NG) fuel on NO_x emissions (Figure 2.1). NO_x emissions are the lowest for NG fuel, and increase with increase in hydrogen percentage in the blend, with highest NO_x emissions for pure hydrogen. This is thought to be caused by hydrogen's faster burn rate which leads to shorter ignition lag, earlier peak pressure and thus higher combustion temperature. For higher λ values, reduction in heat of combustion reduces NO_x due to decrease in temperature.

Similar results are presented by Xu^[11], for engine operation without optimizing spark ignition timing (Figure 2.2). They suggested that when adding more than 20% hydrogen by volume into CNG, lean mixture combustion and ignition timing optimization could significantly decrease NO_x emission and maintain a relatively higher thermal efficiency under certain fixed engine conditions.

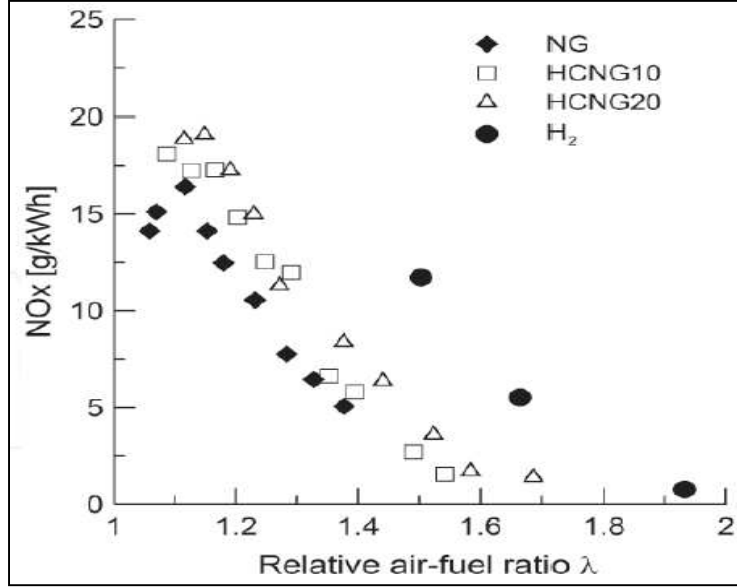


Figure 2.1: NOx vs Relative AFR^[10]

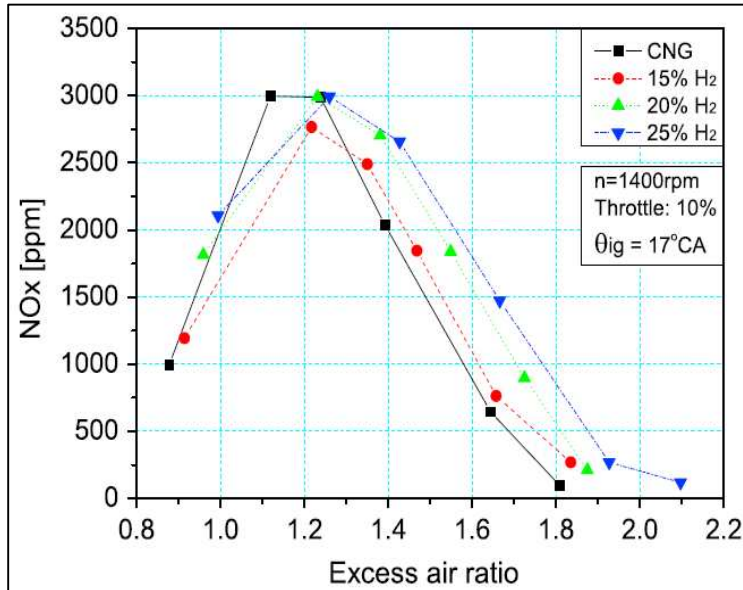


Figure 2.2: NOx vs Excess Air Ratio^[11]

This is because addition of hydrogen significantly extends the lean burn limit. While methane (principal constituent of natural gas) can be ignited for $0.6 \leq \phi \leq 1.3$, the addition of H₂ extends the ignition limits to the range $0.5 \leq \phi \leq 1.4$.

Fanhua et al^[12] examined effects of 20% hydrogen addition on emissions control and cycle-to-cycle variation on a 6 cylinder spark ignited (SI) NG engine. It was found that NOx emissions increased with hydrogen addition (Figure 2.3) at a given λ and ignition timing. However, due to this faster burn rate, maximum brake torque (MBT) ignition timing is retarded with hydrogen addition, resulting in no obvious rise in NOx emissions at MBT after hydrogen addition (Figure 2.4).

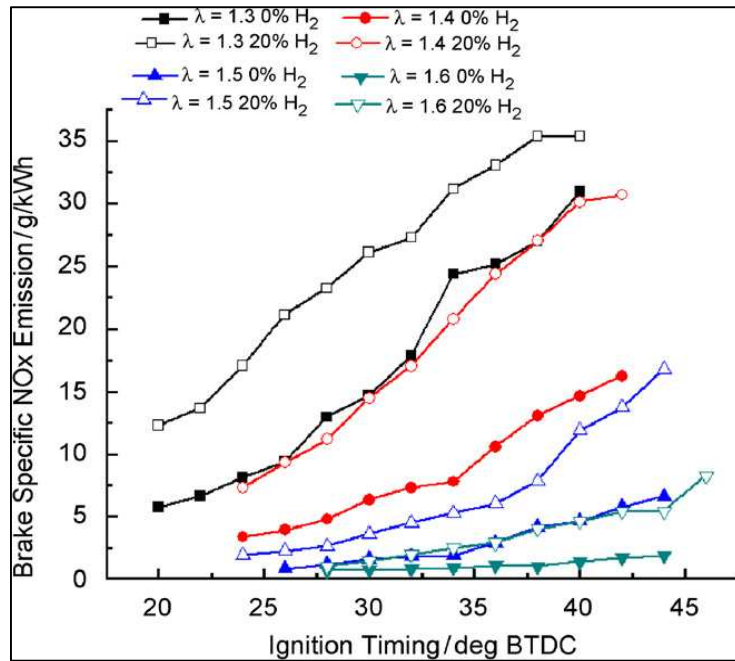


Figure 2.3: BSNOx vs Ignition Timing^[12]

Similarly, Genovese et al^[13] tested two buses for urban transit service, fueled with H₂-NG blends with different percentage of hydrogen (5%, 10%, 15%, 20% and 25% of hydrogen by volume). Road tests showed a reduction of 40% in NOx emission for 5%, 10% and 15% of H₂ when the ignition advance timing was reduced by 1 to 3 deg. For higher percentages of H₂ such as >20%, it has been evidenced that only tuning of the ignition advance is not sufficient to recover the increased NOx emissions caused by the

higher temperatures in combustion chamber. In order to improve the NO_x emissions, a leaner AFR is feasible with H₂-NG fuel at higher H₂ percentages.

Fanhua^[12] analyzes the effects on performance and emissions based on testing carried out on a six-cylinder, single point injection, SI NG engine at hydrogen fractions of 0%, 30% and 55% by volume, under different excess air ratio (λ) values at MBT operating conditions. They found that in the range of excess air ratios above 1.8, NO_x can be reduced to very low levels and high hydrogen addition does not visibly increase NO_x emission higher than that of pure natural gas operation. NO_x emission can be kept an acceptable level at lean burn conditions and with high hydrogen addition.

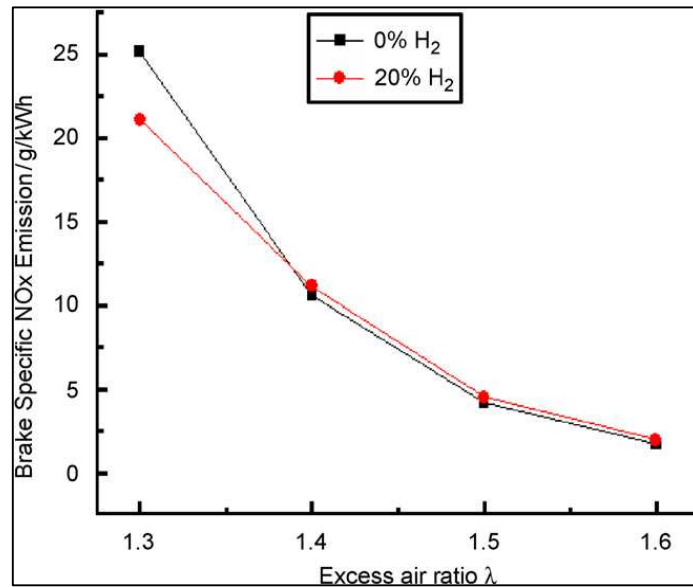


Figure 2.4: BSNO_x vs Excess Air Ratio^[12]

Ortenzi et al^[14] attempted to test two different blends, characterized by hydrogen percentages of 10% and 15%, on a 2.8 CNG Euro III (with three-way catalytic converter). Mainly, modifications were made to the control system (ECU) to test the two blends at both stoichiometric/rich and lean mixtures. Their results for stoichiometric tests are discussed later (in section 2.2). For the lean burn testing, the maximum λ was limited to

1.45 due to significant power losses observed with increase in λ . Even so, NO_x values were found to be lower than the tests using pure CNG at the λ values tested.

Bauer and Forest^[15] tested a one cylinder CFR engine with mixtures of hydrogen in methane of 0, 20, 40 and 60% by volume, which resulted in an increase in NO_x. The authors found that the addition of hydrogen increased BSNO due to its higher flame temperatures (Figure 2.5).

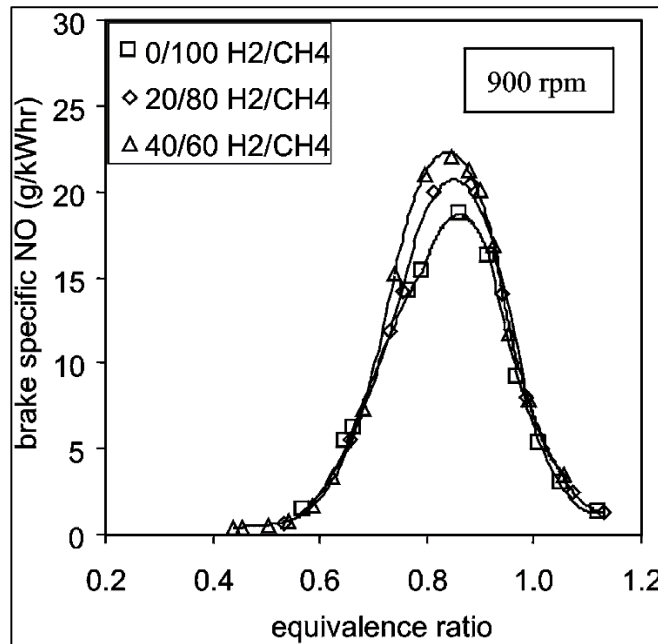


Figure 2.5: BSNO vs Equivalence Ratio^[15]

Hydrogen addition up to 40% increased peak BSNO approximately 5g/kWh (30%). However, they also observed that the addition of hydrogen allows the engine to run ultra-lean while producing very low amounts of NO_x.

Impact on HC, CO, CH₄ emissions:

Xu et al^[11] showed that HC emissions tend to decrease (Figure 2.6) with increase in hydrogen percentage in the H₂-NG mixture, owing to reduced C/H ratio, faster flame propagation as well as improved combustion efficiency. Another important reason for

reduced HC emissions is the lower quenching distance of hydrogen which improves combustion completeness.

Fanhua et al^[16] observed a similar impact on CO emissions (Figure 2.7), where CO emissions at a particular λ decreased with increase in hydrogen percentage.

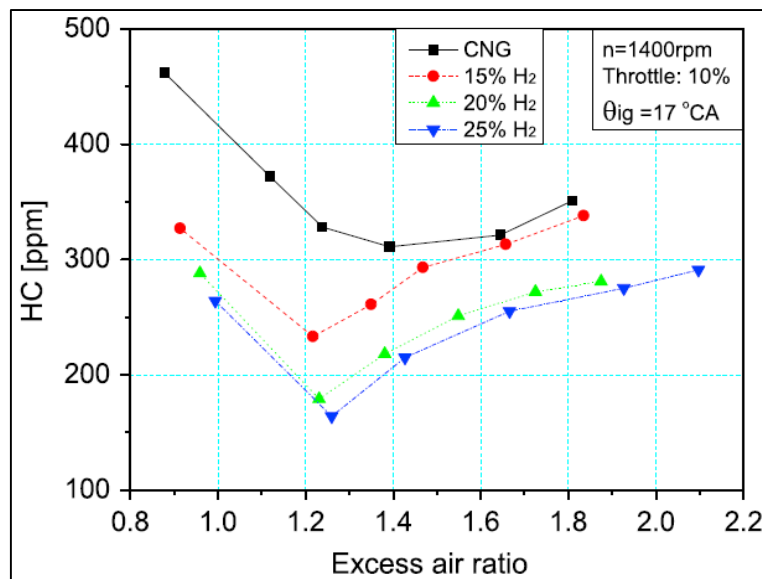


Figure 2.6: HC vs Excess Air Ratio^[11]

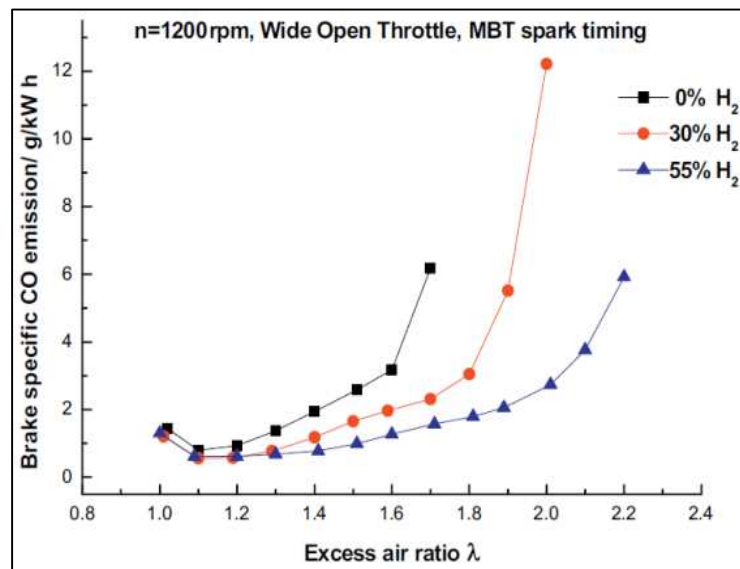


Figure 2.7: BSCO vs Excess Air Ratio^[16]

It was observed that the minimum value of CO emission occurs at a larger λ as more hydrogen is enriched. This is because hydrogen enrichment expands the lean burn limit.

A similar trend was observed for CH₄ emissions[16]. The little drop in low λ area was thought to be due to the increase of oxygen content while the steep rise was because of the unstable combustion after lean burn limit. It was found that under a certain λ , the more hydrogen is enriched, the less unburned CH₄ is emitted (Figure 2.8).

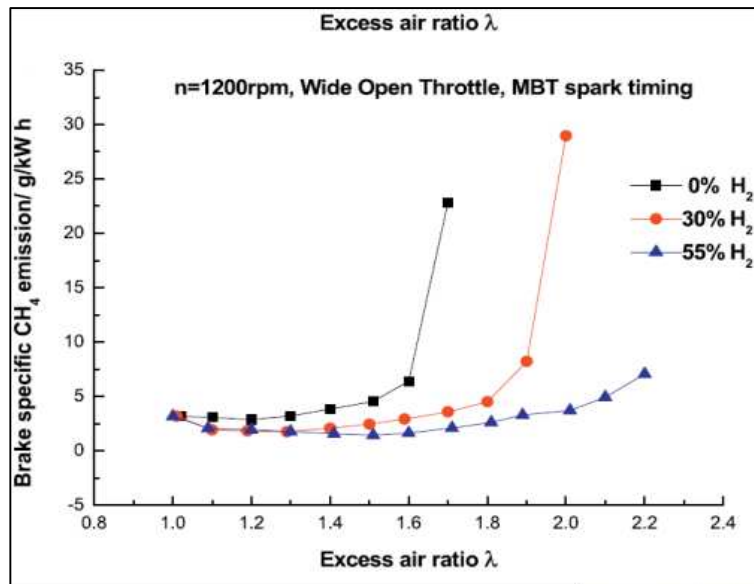


Figure 2.8: BSCH₄ vs Excess Air Ratio^[16]

Impact on CO₂ emissions:

CO₂ emissions are generally known to decrease with increase in H₂ fraction, owing to reduced C/H ratio. Genovese et al^[13] made an interesting observation that 2.71 kg CO₂ emissions per 1 kg of CH₄ were observed, instead of the theoretical 2.75 kg expected. The emissions of CO₂ in g/km, decreased by 23% with higher percentages of H₂ and by 6% with lower contents of H₂ (Figure 2.9), almost 3-5 times emissions predicted with Carbon atom substitution alone. This improvement in CO₂ emissions was

thought to be due to increased engine efficiency, in addition to the reduced carbon content in fuel. The left bars in Figure 2.9 denote the actual percentage reduction in CO₂ emissions as calculated from these measured values, while the right bars denote the theoretical reduction.

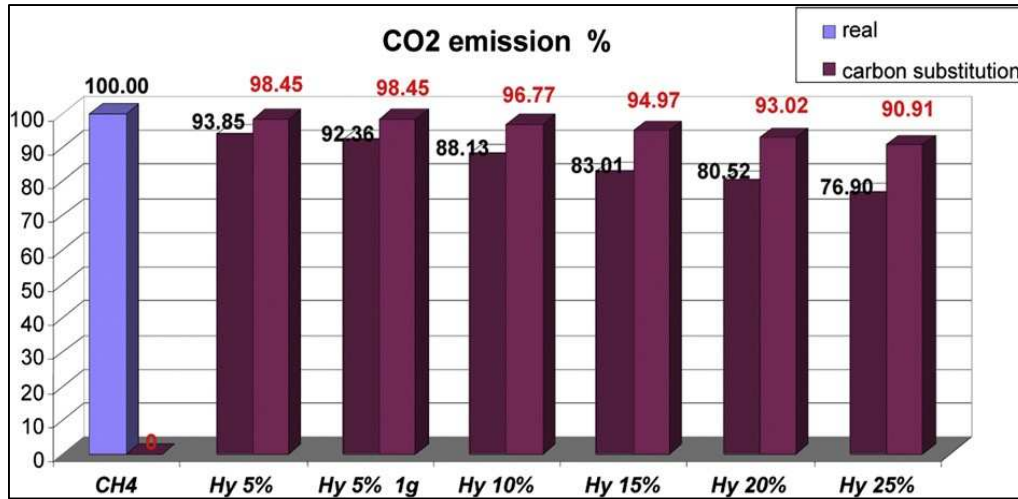


Figure 2.9: CO₂ Emission Percent^[13]

The theoretical CO₂ emissions, taking only carbon reduction into account, were calculated considering same energy input with different blends. Tables 1 and 2 in appendix list the measured and theoretical CO₂ emissions respectively for the various percentages of H₂. Figure 2.9, thus, shows the difference between these theoretical and experimental values. This difference is due to the improved engine efficiency that results in a lower fuel consumption and, consequently, in a further decrease in CO₂ emissions.

On the CFR, Bauer and Forest^[15] noted that for hydrogen addition up to 60%, decrease in BSCO₂ up to 26% (from $\phi = 0.58$ to 1.0) was observed. Figure 2.10 compares CO₂ emissions for different percentages of hydrogen. It was seen that for a given equivalence ratio, increase in hydrogen resulted in decrease in CO₂ emissions. CO₂ emissions continue to decrease as mixtures get leaner.

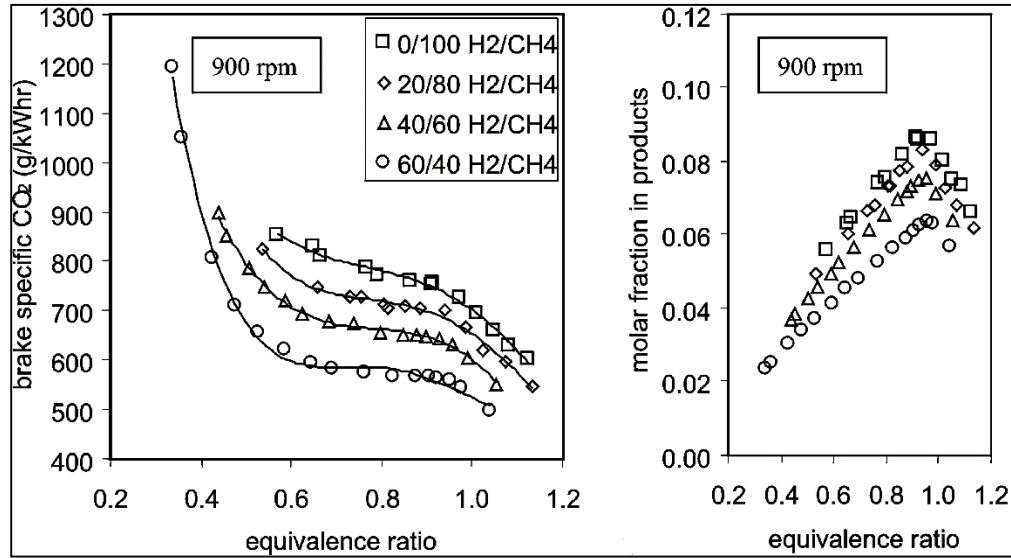


Figure 2.10: CO₂ vs Equivalence Ratio^[15]

The reason why BSCO₂ emissions increase at lean equivalence ratios is that the power reduction is proportionally greater than the reduction in CO₂ concentration in the exhaust.

2.1.2 Impact on Combustion Characteristics

Huang et al^[17] investigated the combustion characteristics and heat release analysis of a three-cylinder automotive spark-ignited engine fueled with 10%, 20% and 26% by volume H₂-NG blends. It was observed that, for lean mixtures, up to 10% hydrogen fraction, peak pressure and heat release rate increased with hydrogen enrichment, while the opposite was observed for higher fractions. This difference in behavior is attributed to the balance between 2 effects that come with hydrogen addition: For H₂<10%, the effect of increased flame propagation speed is dominant causing increase in peak pressure, whereas for higher percentages, effect of reduced volumetric heating values dominates.

On the other hand, Fanhua et al^[16] observed increase in peak cylinder pressure for as high as 55% hydrogen for $\lambda > 1.7$. For mixtures with $\lambda < 1.7$, however, peak pressure

actually decreased with hydrogen addition, which was thought to be an effect of CNG reaching its lean limit and hydrogen helping with combustion performance.

Xu et al^[11] tested the effects of excess air ratio and spark timing on an electronic controlled single cylinder engine with 15, 20 and 25% hydrogen in natural gas blends. For the same spark ignition timing, the maximum in-cylinder pressure averaged 11% and 22% higher at 25% hydrogen/CNG fueling than for the pure CNG for $\lambda = 1.2$ and 1.8 respectively. Fanhua et al^[12] also observed increase in peak pressure with increase in hydrogen fraction in their study (Figure 2.11).

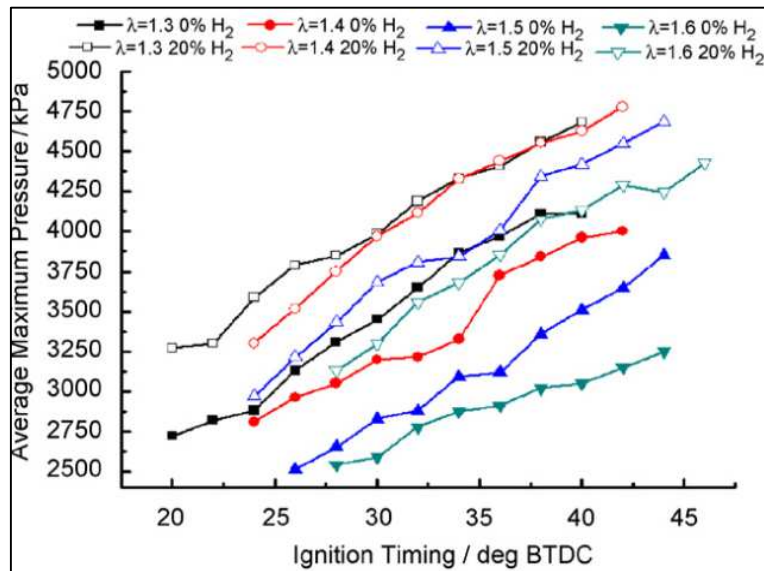


Figure 2.11: Average Peak Pressure vs Ignition Timing^[12]

2.1.3 Impact on Power and BMEP

Bauer and Forest observed a reduction in power with increase in hydrogen fraction at all equivalence ratios up to lean limit due to lower volumetric heating value of hydrogen (Figure 2.12). Hydrogen addition up to 60% by volume decreased the engine power by approximately 0.2 kW at $\phi=1.0$ ^[15].

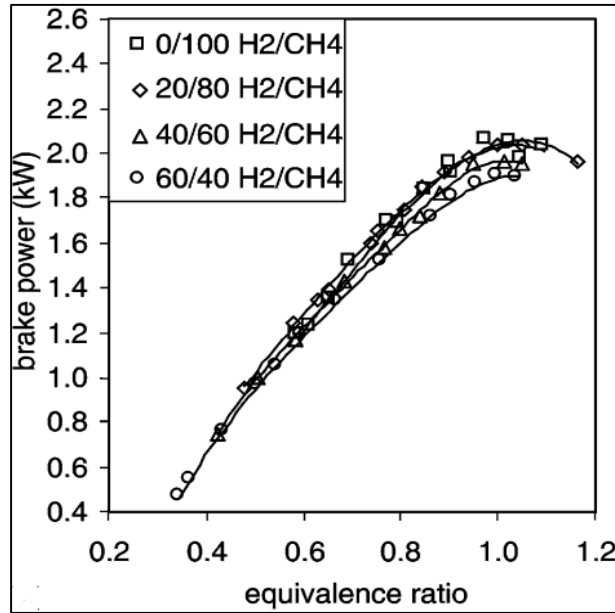


Figure 2.12: Brake Power vs Equivalence Ratio^[15]

However, similar to peak pressure, Fanhua et al observed λ greatly impacted what effect hydrogen enrichment had on the engine power^[16]. Although there was a slight reduction in power with increase in hydrogen fraction at stoichiometric to mixtures up to $\lambda = 1.7$, engine's power performance improved with hydrogen addition for leaner mixtures with $\lambda > 1.7$, which was thought to be an effect of CNG reaching its lean limit and hydrogen, thus, helping with combustion performance (Figure 2.13).

2.1.4 Impact on Efficiency and BSFC

The reduction of combustion duration promoted by hydrogen addition is thought to result in increased engine efficiency with respect to natural gas and enhance combustion stability, reducing cycle-to-cycle variation. Xu et al observed that brake thermal efficiency increased with increase in hydrogen percentage but only at leaner AFRs^[11]. Also, the effect was seen at H₂ > 20% only (Figure 2.14).

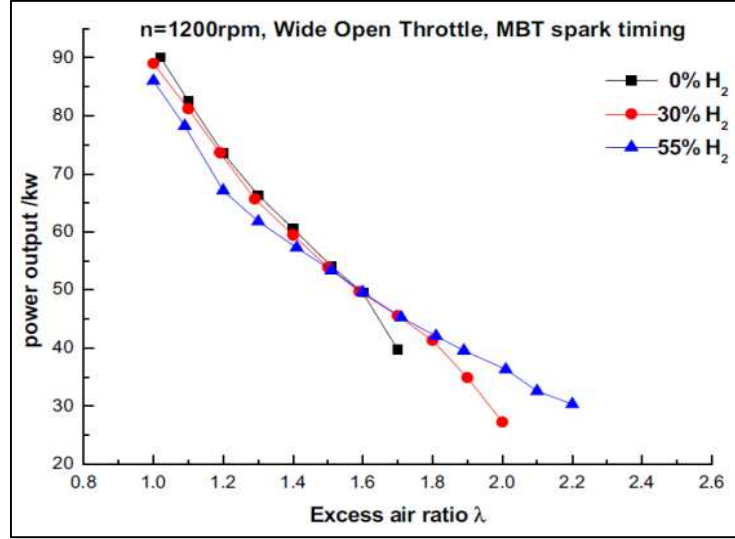


Figure 2.13: Power vs Excess Air Ratio^[16]

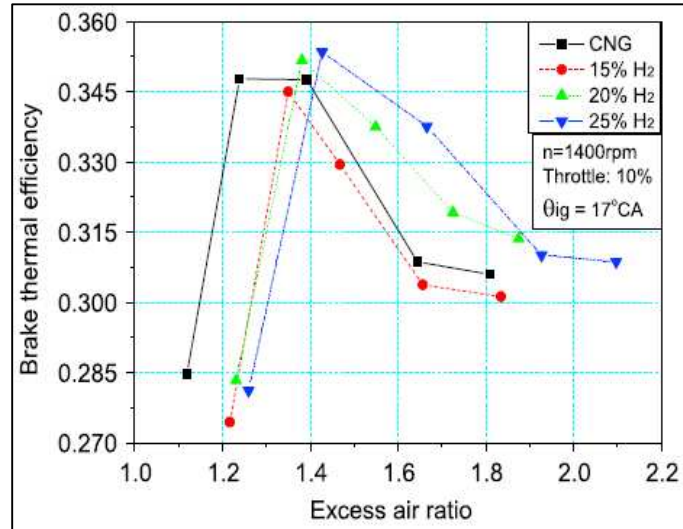


Figure 2.14: Brake Thermal Efficiency vs Excess Air Ratio^[11]

The energy consumption reduction depends on the increased engine efficiency derived from an improved combustion. This can be caused by the higher flame speed available at higher H_2 percentages. Genovese et al^[13] give a comparison of the energy consumption with the various H_2 -NG blends with respect to energy consumption with pure methane (Figure 2.15) (Refer Table 3 in appendix for operating parameters). It is seen that beyond 15%, not as much improvement is observed. 'Hy' denotes

'hydromethane' (another term for H₂-NG blend). It should be noted that the efficiencies are compared at the same engine power. So H₂-NG blends required more fuel to achieve the same engine power (possibly due to lower volumetric heating values). The first bar result with 5% H₂ has no advance in ignition timing while the second test has a 1 degree advance. This increase in energy consumption with a small change in ignition advance reinforces the role of the higher flame speed of H₂-NG blend and then the necessity to delay the ignition time. To quantify the improvement, Table 2.1 gives a comparison in terms of methane g/km equivalent at the various hydrogen fractions.

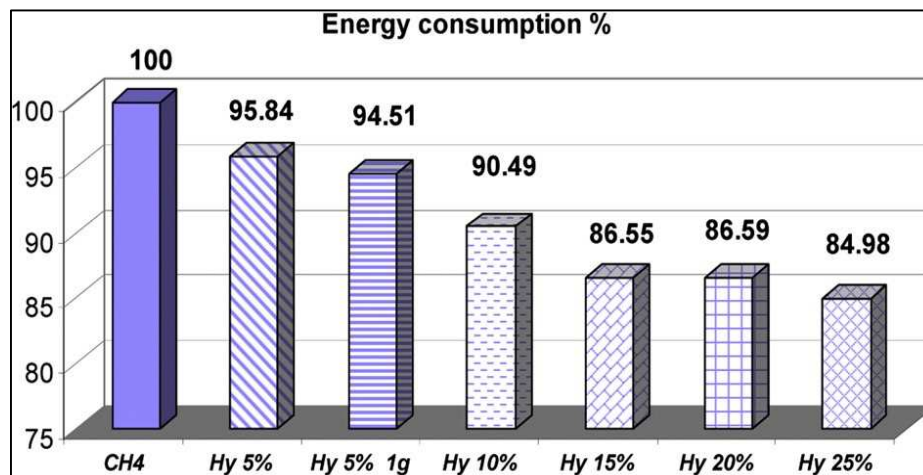


Figure 2.15: Energy Consumption Percent^[13]

Table 2.1: Improvement in Energy Consumption^[13]

	kWh/km	g/km CH ₄ equiv.	Δ%
CH ₄	4.29	309.18	0
Hy 5%	4.12	296.31	-4.2
Hy 5% 1 deg	4.06	292.20	-5.5
Hy 10%	3.89	279.76	-9.5
Hy 15%	3.72	267.58	-13.5
Hy 20%	3.72	267.73	-13.4
Hy 25%	3.65	262.73	-15.0

However, Bauer et al reported an unusual result: Indicated thermal efficiency drops by approximately 2% with the addition of 60% hydrogen due to an increase in the energy input of the fuel without an increase in power^[15] (Figure 2.16). It was supposed that the positive effects of fast burn speed of hydrogen and its greater ratio of specific heats may have been offset by the high flame temperature of hydrogen, and the research engine's cooling system (designed to run at constant temperature). It was found that the addition of hydrogen decreases BSFC on a mass basis, because of the higher energy content of the fuel. However, hydrogen addition to 60% by volume decreased brake efficiency by approximately 2%.

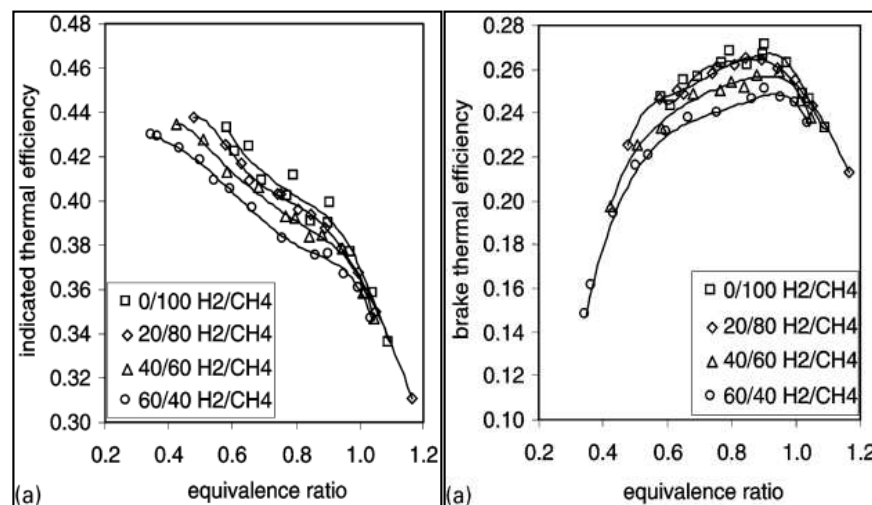


Figure 2.16: Thermal Efficiency vs Equivalence Ratio^[15]

2.2 STOICHIOMETRIC ENGINES

Although lean operation has many advantages, variation in λ with less lean mixtures is required for certain operating conditions like acceleration or low engine speeds. Saanum and Bysveen tested a Volvo TD100 bus stoichiometric engine equipped with EGR and a 3-way catalyst to compare stoichiometric operation with EGR to the lean burn approach^[18]. Experiments revealed that even with 25% H₂, lean burn NO_x emissions

(Figure 2.17) were much higher than that of stoichiometric operation with NSCR catalyst and EGR upstream of catalyst (Figure 2.18). EGR can provide the same advantage as dilution with air (although there has to be a compromise on efficiency) and AFR can remain stoichiometric, which is a requirement for NSCR catalyst operation. H₂ addition can help increase the achievable dilution with EGR due to its high reactivity and high laminar speed. It was seen that EGR decreases NO_x almost linearly, since less oxygen is available at stoichiometric condition with EGR. The post-catalyst NO_x emissions were further reduced (Figure 2.19).

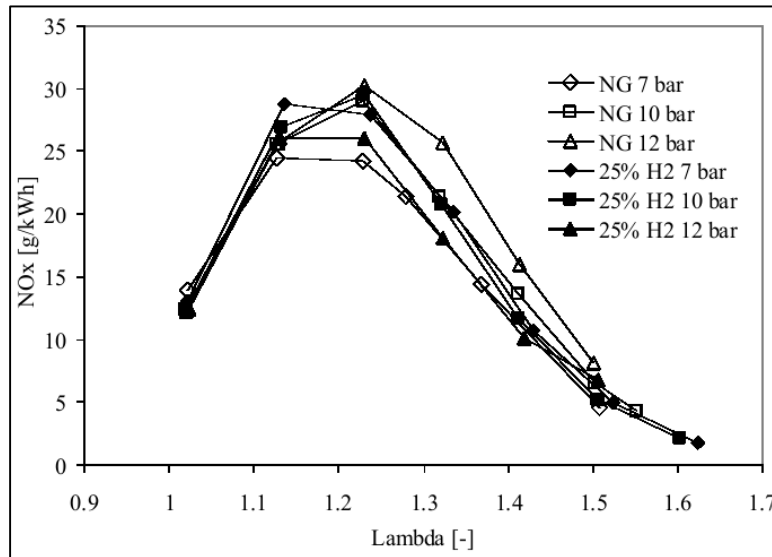


Figure 2.17: NO_x vs λ (lean burn)^[18]

Reduced HC emissions are seen not only due to less C atoms but also due to improved HC oxidation with H₂ addition owing to lower quenching distance of hydrogen. The catalyst was operated without dithering in these tests (dithering is usually very effective to create both oxidizing and reducing conditions in the catalyst). Nonetheless, NO_x and HC post-catalyst emissions were very low compared to lean burn at all loads.

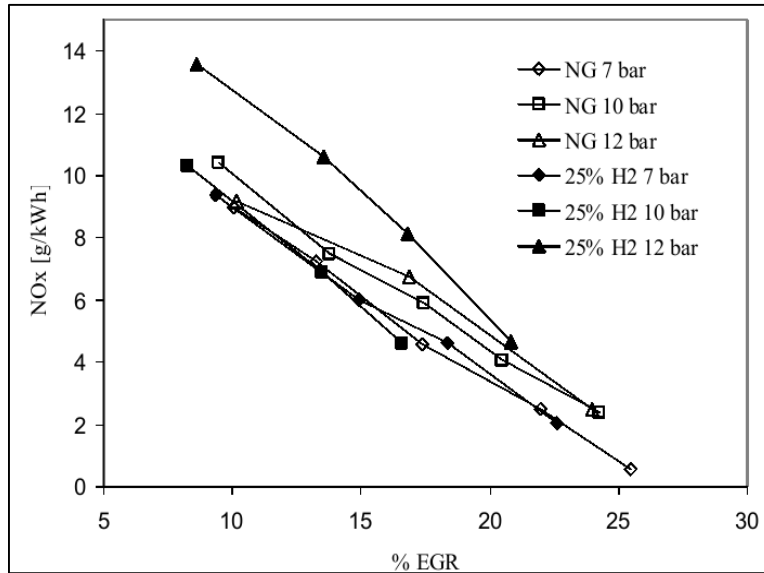


Figure 2.18: NOx vs Percent EGR – Pre-Catalyst (stoichiometric)^[18]

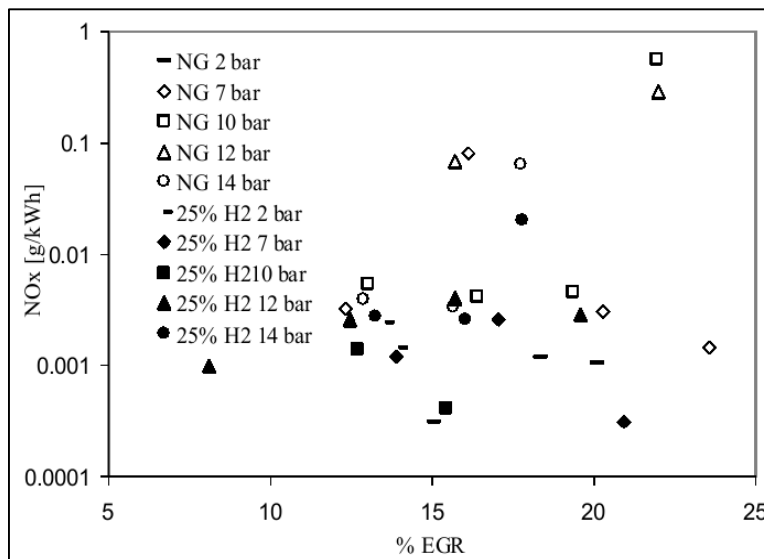


Figure 2.19: NOx vs Percent EGR - Post-Catalyst (stoichiometric)^[18]

Owing to absence of dithering, λ was, in fact, adjusted to reduce NOx and HC post-catalyst. Therefore, CO emissions (Figure 2.20 – pre-catalyst) were comparatively higher. Despite this, for most cases, CO post-catalyst emissions were still lower (Figure 2.21) than lean burn emissions (Figure 2.22).

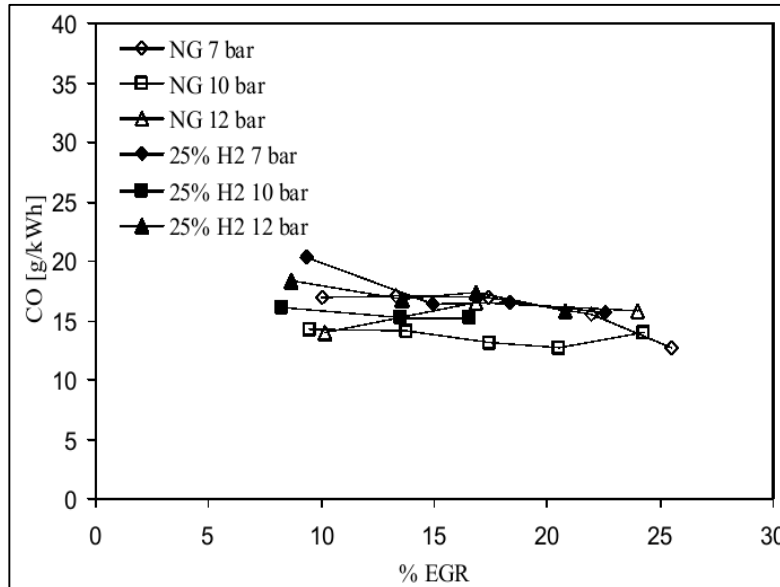


Figure 2.20: CO vs Percent EGR – Pre-Catalyst (stoichiometric)^[18]

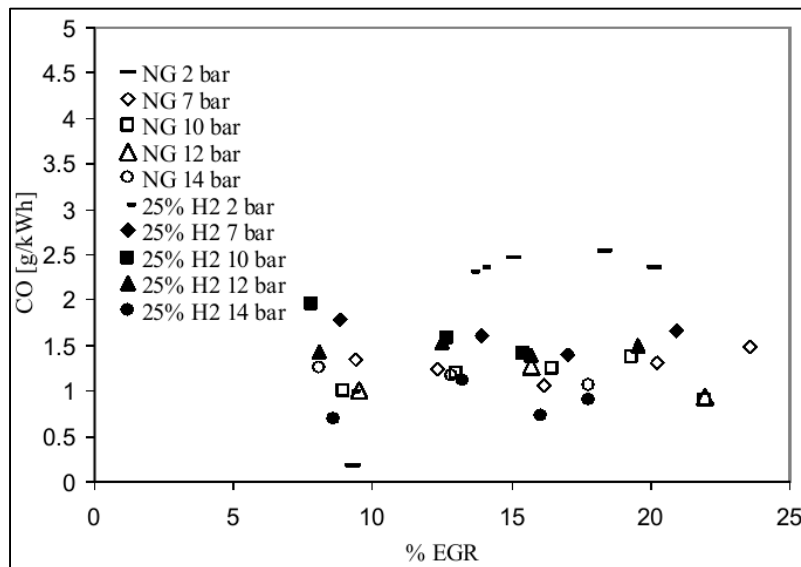


Figure 2.21: CO vs Percent EGR - Post-Catalyst (stoichiometric)^[18]

Thus, results showed that the stoichiometric operation with EGR and 3-way catalyst was able to meet Euro 5 emissions limit, unlike the lean burn operation. However, lean burn operation can improve efficiency, as discussed in the previous section.

Ortenzi et al^[14] made a similar observation when testing the 15% H₂-NG blend: a spark advance reduction of only 3 degrees (which meant a little retard compared to the case of

pure methane) resulted in a large decrease of NO_x emissions, without an adverse effect on torque (Figure 2.23). At stoichiometric conditions, using optimized maps for ignition timing, emission levels at 10% H₂ were lower than pure CNG. Stoichiometric NO_x values were found to be better than the values observed during lean burn testing.

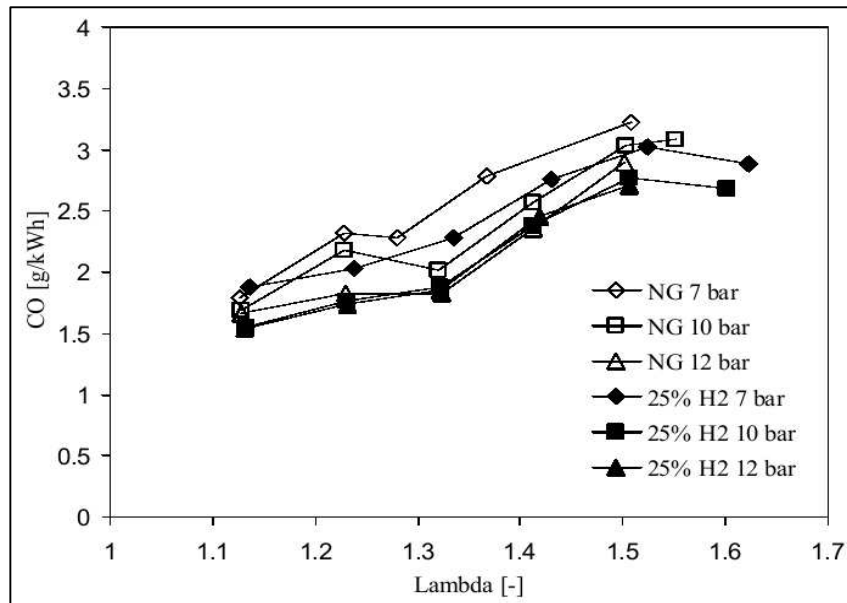


Figure 2.22: CO vs λ (lean burn)^[18]

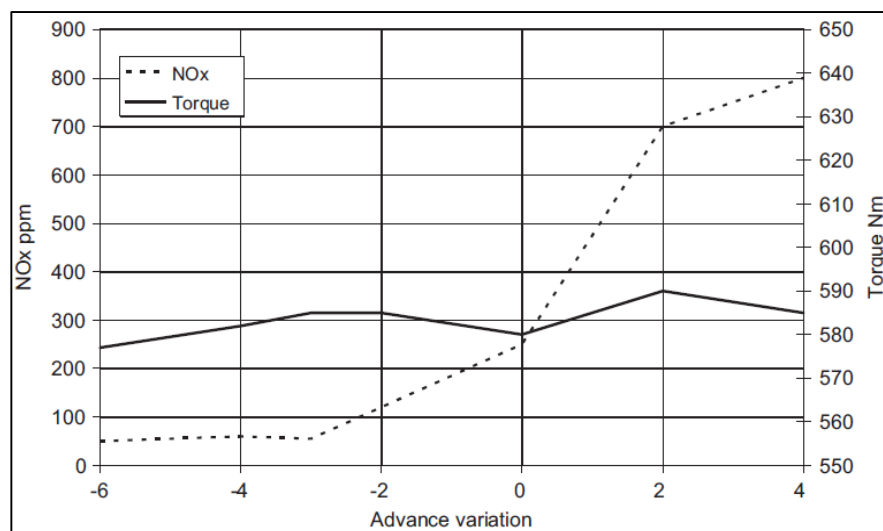


Figure 2.23: NO_x vs Spark Advance Variation^[14]

Thus, H₂-NG blends at stoichiometric operation with a 3-way catalyst may be another viable option, besides lean burn operation. However, changes such as modifications in spark ignition timing may be required to achieve emissions comparable to lean operation. Not much literature is available looking at H₂-NG blends for stoichiometric operation. The improvement seen in emissions may be a catalyst performance and/or air fuel ratio controller effect rather than changes in combustion caused by hydrogen.

3. EXPERIMENTAL SETUP AND PROCEDURES

3.1 CUMMINS ONAN GENSET ENGINE

The platform used for stoichiometric engine testing is a Cummins-Onan Generator Set (Genset), model GGHD 60Hz. It houses an industrial 4-stroke, V8 spark-ignited (SI) internal combustion engine manufactured by Ford, model LSG-875, which can operate on various gaseous fuels including natural gas. The engine has a displacement of 7.5 liters. Engine parameters are provided in Table 3.1^[19]

Table 3.1: Cummins-Onan Genset Engine Specifications^[19]

Sr. No.	Parameter	Description
1	Base Engine	LSG-875
2	Configuration	4 stroke, turbocharged
3	No. of cylinders	8
4	Displacement [lit]	7.5
5	Gross Power Output [bHP]	173
6	BMEP [kPa]	1034.2
7	Bore [mm]	110.7
8	Stroke [mm]	97.8
9	Compression Ratio	8.6:1
10	Piston Speed [m/s]	5.9
11	Lube Oil Capacity [lit]	9.5

The engine is equipped with a non wastegated turbocharger by Holset. An aftermarket water-to-air intercooler, manufactured by Frozen Boost, has been added to the setup, located downstream of the compressor. The reason for this was that previous testing had revealed that temperature fluctuations in the ambient air (mass air flow)

around the intake filter due to radiator and engine heat were resulting in inconsistent engine exhaust emissions^[20]. The intercooler also compensates for slow changes in air properties throughout the day.

Natural gas was supplied to the engine through the laboratory supply system. A separate hydrogen blending system was designed and added to the setup, which introduces hydrogen into the natural gas main stream, upstream of the carburetor. Hydrogen flow was metered and measured using a rotameter model FL3840C with 150mm flowtube from Omega (specifications provided in appendix). The rotameter works on the principle of force balance. The float reaches an equilibrium position when the upward force exerted by the fluid in proportion to its flowrate is balanced by gravitational force. A needle valve at the inlet is controlled by a knob to meter the flow. The FL3840C flowmeter had a minimum flowrate of 8012 std ml/min and maximum flowrate of 224353 std ml/min with a measurement accuracy of $\pm 2\%$ of full scale. A measurement flowmeter (without control valve) model FL1504A from Omega (specifications provided in appendix) was used for NG flowrate measurement. The FL1504A had a minimum flowrate of 5.76 scfm to 57.6 scfm natural gas.

The engine is coupled to an electric generator. Although the engine is rated at 148HP for natural gas, at the elevation of 5000 feet, the maximum power output from the genset was derated to 80kWe. This output can be supplied to a load bank or an electrical grid. The generator was operated at 480 V, 60 Hz, with a power factor of 1. Figure 3.1 shows the engine setup.

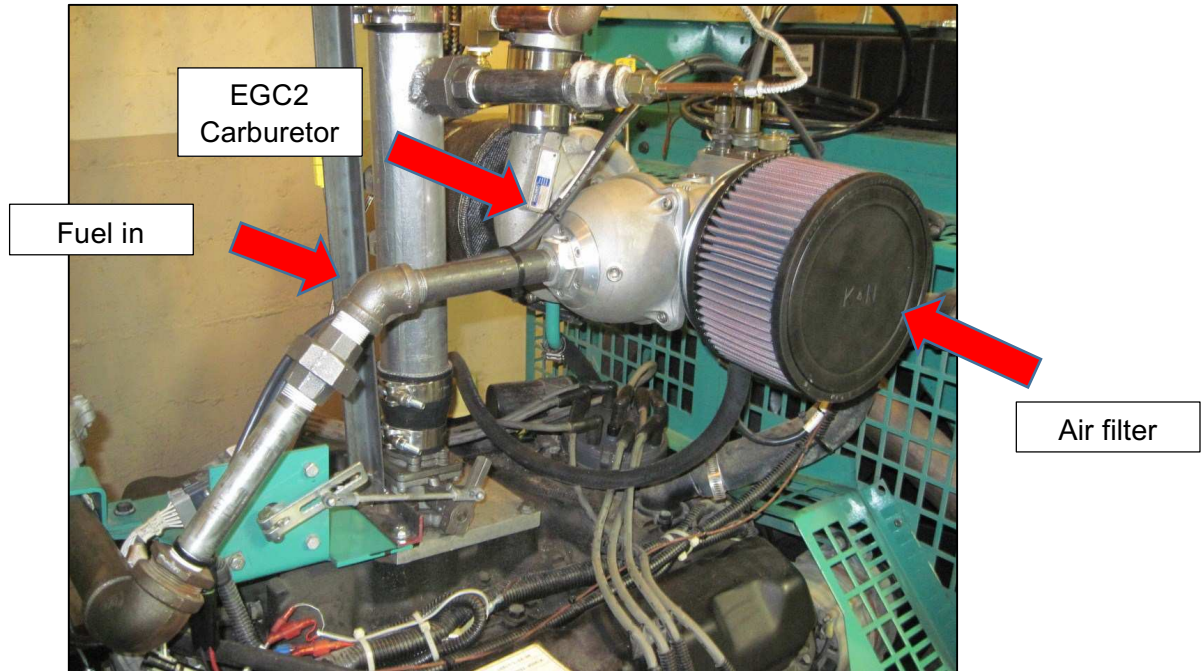


Figure 3.1: Cummins Onan Genset Engine Setup

3.2 CONTINENTAL CONTROLS EGC2 CARBURETOR

Although the engine was originally equipped with a mechanical carburetor manufactured by IMPCO, it was replaced with the electronically controlled carburetor EGC2, manufactured by CCC, for the first round of stoichiometric engine testing. The EGC2 operates based on feedback received from the λ sensor in exhaust. A drawing of the EGC2 from the manufacturer is provided in the Appendix. The EGC2 was installed at the compressor inlet, in place of the mechanical carburetor.

The EGC2^[21] (Electronic Gas Carburetor) utilizes wide band λ sensor for feedback and is specifically designed for small gas engines. It receives natural gas at a pressure of approximately 15 inches of water column and employs a patented technique to precisely control the AFR using variable pressure control combined with an advanced venturi mixer. The shape of the venturi throat creates a low pressure used to draw in a precise amount of fuel through the injection ports into the air stream for stoichiometric

operation. Additionally, the gas pressure transducer measures pressure at the injection holes, which is matched to the system set point by the controller, based on the exhaust oxygen content feedback from the λ sensor. This system coupled with a 3-way catalyst (NSCR catalyst) is very effective at reducing emissions. The EGC2 can be seen mounted on the engine in Figure 3.1. Further details are available in appendix.

Additionally, Continental Controls also provided the Valve Viewer software with the EGC2, which monitors and logs various parameters, with an option to view the data live. It offers a graphical user interface (GUI) with the ability to log and adjust parameters through the use of a laptop that communicates with both the CCC EGC2 and the λ sensor. The EGC2 parameters including O2 sensor set point, fuel pressure range limits, dithering options, initial cranking conditions, O2 sensor and fuel pressure gain values can be set utilizing the “Valve Viewer” software. When the carburetor is in operation and connected to a laptop via the serial communications connector, the software provides a GUI feedback that updates at a rate of 1 Hz. Data logging can be enabled within the software as well. A screen shot of the Valve Viewer software is provided in appendix.

For this project, the EGC2 was tested with a wide band λ sensor from Bosch. The working of a λ sensor and the difference between a wide band and a narrow band λ sensor are discussed at length later in section 3.5.

3.3 CONTINENTAL CONTROLS GV1 CARBURETOR

For the second round of testing on this engine setup, the EGC2 carburetor was replaced with a simpler design CCC GV1 carburetor, which utilizes a narrow band λ sensor. Figure 3.2 shows the CCC GV1 carburetor.

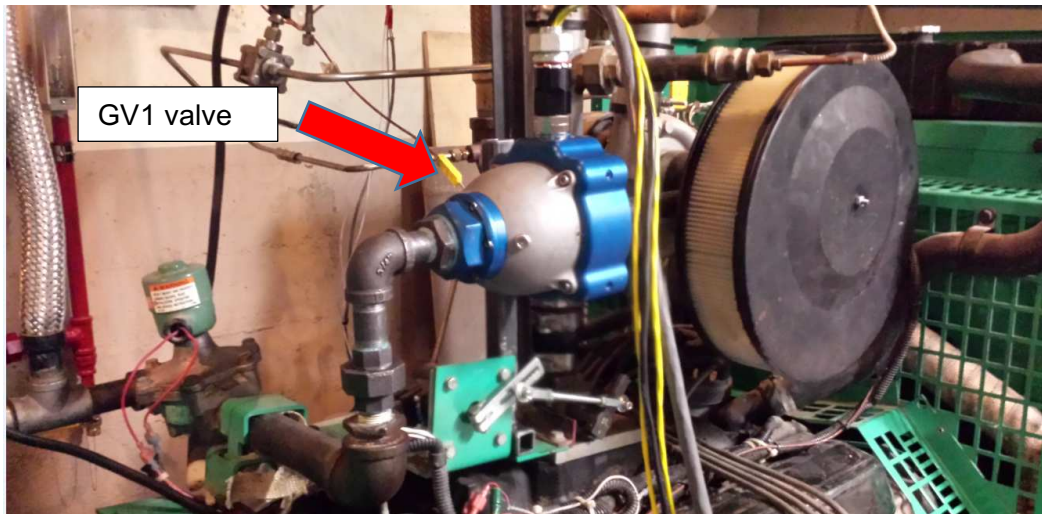


Figure 3.2: GV1 setup

The CCC GV1^[22] is a gas valve with a built-in differential pressure transducer measuring fuel over air pressure. One side of the transducer measures fuel pressure at the valve outlet while the other is connected to the turbocharger outlet. The GV1 gets exhaust oxygen feedback from the λ sensor and varies the fuel pressure to control AFR to match with the AFR set point. For this project, the GV1 was tested with a narrow band λ sensor from Bosch.

The GV1 also comes with its own Valve Viewer Software, similar to the EGC2. While the dithering control settings are available to the user for the EGC2, the GV1 comes with set dithering parameters, which cannot be modified. Another difference is that the air/fuel ratio (AFR) set point is set in terms of its voltage, instead of the AFR/ ϕ value on the EGC2. This voltage set point corresponds to a specific AFR value.

3.4 NSCR CATALYST

Stoichiometric SI engines require exhaust treatment in the form of an NSCR catalyst (also called 3-way catalyst) primarily to reduce NO_x emissions due to high temperatures. The term '3-way' catalyst (TWC) refers to the ability of the NSCR catalyst

to simultaneously reduce NO_x and oxidize THC and CO. A TWC is made of multi-component material, typically containing the precious metals rhodium, platinum and palladium, ceria (CeO₂), γ -alumina (Al₂O₃), and other metal oxides^[23]. Rhodium is generally the most efficient reduction catalyst. Platinum and palladium are used for oxidation.

The NSCR, however, requires precise AFR control near (or slightly rich of) stoichiometric ratio ($\lambda = 1$) for efficient operation. This is because the reduction of NO_x requires an oxygen-depleted environment. CO and HC get oxidized with whatever oxygen is available in the exhaust stream, which aids NO_x reduction. The water-gas shift reaction finally converts HC and CO to CO₂ and H₂, which further helps in NO_x reduction. Figure 3.3^[24] depicts the 'operating window' for NSCR catalyst to efficiently convert all the 3 main exhaust species. Here X axis gives the ϕ value, while Y axis depicts the conversion efficiencies.

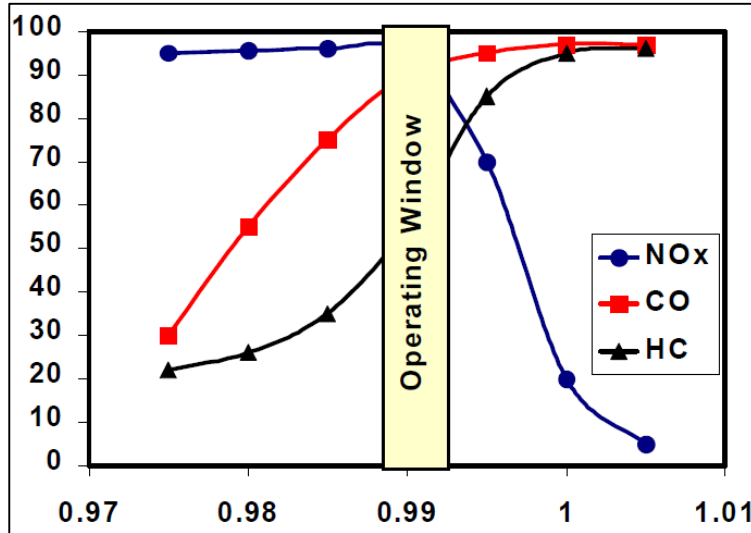


Figure 3.3: NSCR Catalyst Operation^[24]

Catalyst efficiency for a given species 'i' is calculated as:

$$\eta_{catalyst} = 1 - \frac{m_{i_{out}}}{m_{i_{in}}} \quad \text{Eqn (3.1)}$$

$m_{i_{out}}$: post-catalyst emissions measurement for species 'i'

$m_{i_{in}}$: pre-catalyst emissions measurement for species 'i'

It can be clearly seen that the conversion efficiency for NOx drops dramatically in the lean regime, while CO and HC conversion efficiencies decline in the rich regime. This is because, in the lean region, CO and THC are consumed by the excess oxygen, instead of removing NOx by reduction. On the other hand, CO and THC conversion efficiencies are limited by the lack of oxygen available. Thus precise control of the AFR in this narrow range is essential. Electronic carburetors with λ sensor feedback are usually employed for effective control of the AFR. Another control strategy that helps widen this operating window is called 'dithering', which is purposeful oscillation of the AFR by the AFR controller. This essentially creates an 'oxygen buffer'. When dithering on the rich side of mean, cerium oxide in the catalyst wash coat releases oxygen, creating a leaner environment promoting oxidation of HC and CO; as AFR begins to go lean, the cerium oxide now begins to consume oxygen, effectively creating a richer environment for NOx reduction.

The catalyst used for this project was MINE-X model provided by DCL International, sized for the engine specifications. The manufacturer guarantees a reduction efficiency of 90-99% for NOx and CO, and 50-90% for THC. Figure 3.4 shows the catalyst installed on the engine.

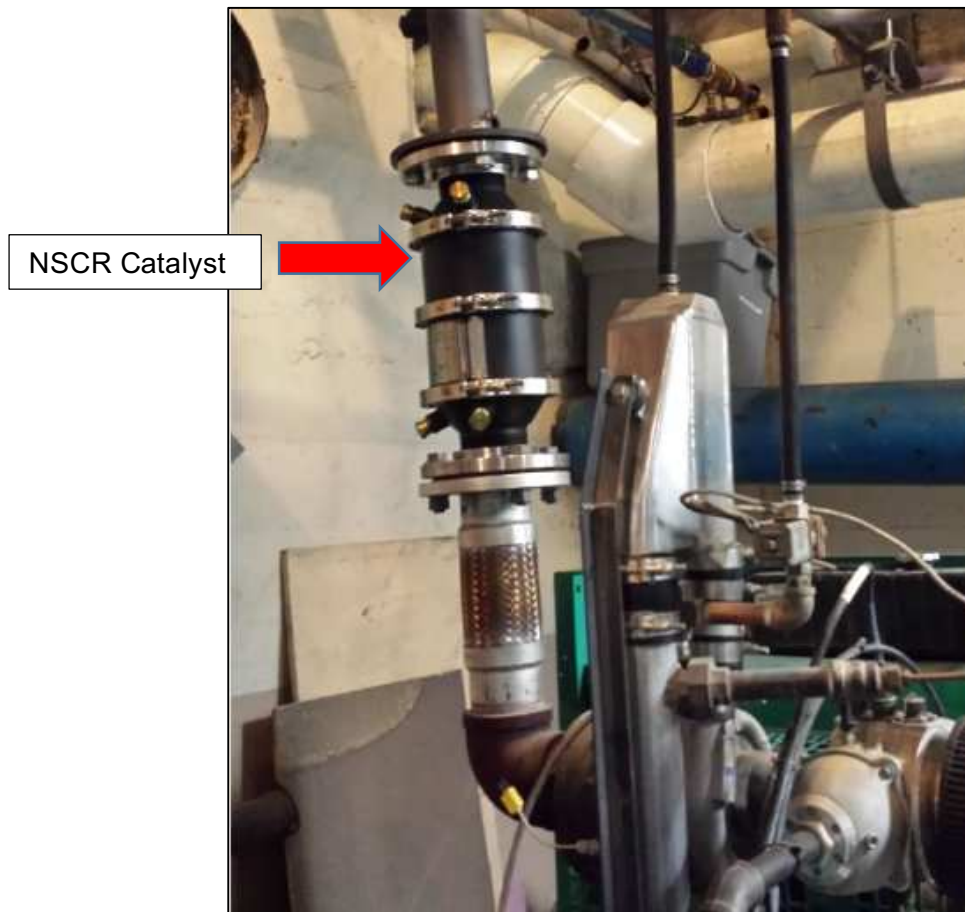


Figure 3.4: NSCR Catalyst

3.5 LAMBDA (λ) SENSOR

Lambda sensor (or oxygen sensor) is a key component to reduce pollutant emissions for stoichiometric operation with NSCR catalyst. This sensor, upstream of the catalyst, gives a feedback to the carburetor controller to control AFR to a given set point in order to achieve the best 3-way emissions reduction efficiency at the catalyst. Lambda sensors are of two types.

3.5.1 Heated Exhaust Gas Oxygen (HEGO) / Narrow Band Lambda Sensor

This typical λ sensor consists of 2 platinum electrodes, separated by the electrolyte. These electrodes serve as a catalyst that responds to the chemical

composition of the exhaust gases. Left electrode (in contact with the exhaust gases) acts as anode, which releases electrons that migrate to the other electrode (cathode) subjected to atmospheric oxygen. The sensor output voltage is driven by the difference in partial pressure of oxygen (O_2) at the two electrodes. Figure 3.5 depicts a typical response of the narrow band sensor^[25].

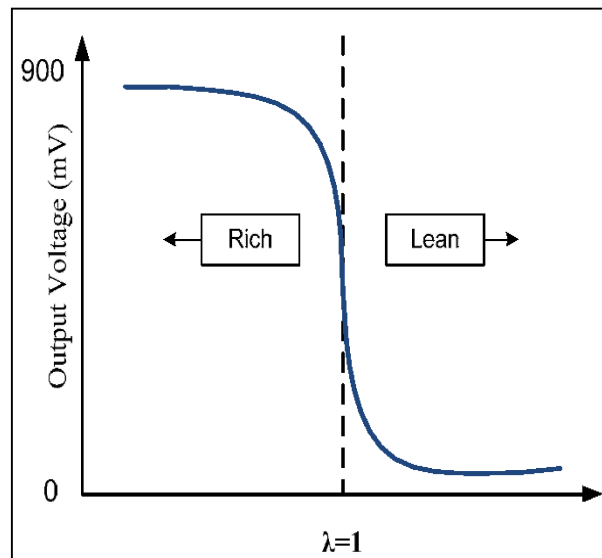


Figure 3.5: Narrow Band Lambda Sensor Operation^[25]

Thus, the output from this sensor is in the form of a switch. Rich mixture produces a higher output voltage corresponding to the higher difference in O_2 concentrations between the two electrodes. Conversely, larger λ values indicating higher oxygen concentration create a lower output voltage.

3.5.2 Universal Exhaust Gas Oxygen Sensor (UEGO) / Wide Band Lambda Sensor

Another type of λ sensor is the UEGO sensor (also called AFR sensor). As the name suggests, this sensor operates in a 'wider' band compared to the narrow band λ sensor. Instead of the switching action seen on the narrow band sensor, the signal changes in direct proportion to the amount of oxygen in the exhaust and outputs a precise

AFR value. The UEGO sensor is more linear and can provide a more accurate O₂ measurement, compared to the HEGO sensor. Typical UEGO sensor consists of three basic components:

1. Cavity separated from the exhaust by a diffusion passage
2. Heated Exhaust Gas Oxygen (HEGO) sensor that detects the presence of oxygen
3. Pumping cell that can pump oxygen into or out of the cavity based on the polarity of current applied to the pump.

The sensor determines the air/fuel ratio by how much oxygen needs to be pumped into or out of the cavity, as determined by the magnitude of the current applied, to maintain a stoichiometric condition inside the cavity.

Although the λ sensor is based on this simple principle, in reality, its results may be affected by the presence of other gases in the exhaust besides oxygen. According to Toema and Chapman, the inconsistency of the sensor output is due to difference in mass transfer diffusion rate of various exhaust species through the sensor protective layer^[25]. There is also an impact of the catalytic reactions of the reducing species on the sensor electrodes. The existence of reducing species like hydrogen affects the thermodynamic equilibrium concentration of oxygen at the sensor. Presence of hydrogen in exhaust causes a lean shift in the response of the sensor. At stoichiometric point, the sensor perceives H₂ in excess of reality and so continues to register a high voltage, which deceives the controller causing a lean shift. Only under a leaner mixture does the sensor perceive an equal balance between H₂ and O₂ and consequently switches from high voltage to low voltage. Thus the switching point is shifted to the leaner side. This is thought to be caused due to higher diffusion velocity of H₂ as compared to O₂. This H₂

deception is more pronounced as the sensor ages. However, as per Buglass et al^[26], there is a possibility that the sensor may be affected in the opposite direction by other gases in the exhaust, thus counteracting the effect of hydrogen.

3.6 COOPERATIVE FUEL RESEARCH (CFR) ENGINE

The CFR engine is an F-2 model, manufactured by Waukesha Engine, Dresser Industries. It is a single cylinder, 4-stroke, SI engine with a constant speed of 940rpm, which can be run at various compression ratios (CR) from 4:1 to 18:1. A threaded worm-gear engagement is constructed on the cylinder head to increase or decrease the clearance volume (volume enclosed between the cylinder head, wall and top of piston at TDC), to adjust the compression ratio. The compression ratio can be adjusted while the engine is running. The engine is operated through a belt-driven synchronous motor. During motoring operation (no fuel injected/power produced), the engine is rotated by the motor, and when fueled to produce power, the motor acts as an electric generator. Figure-3.6 shows the CFR engine setup.

The knock measurement system consists of a piezoelectric, water-cooled pressure transducer (Kistler model 6061A), connected to a charge amplifier, for measuring in-cylinder pressures. An incremental encoder is connected to the crankshaft to provide crankshaft position and instantaneous engine RPM. The signal from the pressure transducer and the crankshaft position from encoder together provide a detailed pressure trace for further analysis of combustion data. Knock analysis is done by FFT (Fast Fourier Transform) method^[27] using this data.



Figure 3.6: CFR Engine Setup

3.7 EXHAUST MEASUREMENT SYSTEM

For both test platforms, Rosemount 5-gas emissions bench with Siemens instruments was used to measure CO, CO₂, THC, NO_x and O₂ concentrations. VOCs, ammonia and formaldehyde were measured with the Nicolet 6700 FTIR spectrometer. The building natural gas supply was used for the Cummins-Onan Genset testing and a Varian CP-4900 Micro GC was used to analyze fuel composition.

Figure 3.7 shows the Rosemount 5-gas emissions rack. The 5-gas emissions measurements are typically dry measurements because analyzers are not heated and if

water is not removed, this will result in poor measurement accuracy. A Peltier-type condenser removes water from the exhaust sample before it enters the analyzers.

Oxides of nitrogen (NO_x) are measured using Chemi-Luminescence Detector (CLD). Chemi-luminescence consists of photon emission during a chemical reaction. NO_2 is reduced to NO across the catalyst and this NO reacts with generated ozone (O_3) inside the reactor, forming an electronically excited NO_2 molecule. The molecule transitions back to ground state, emitting photons in the process, which are measured by a photodiode. The intensity of chemi-luminescence is directly proportional to the NO_x concentration.



Figure 3.7: Rosemount 5-gas Analyzer Bench

Non-Dispersive Infrared (NDIR) analyzers are used, one each, for the measurement of CO and CO₂ concentrations. In this technique, IR radiation is incident on two cells, where one cell is the reference cell without any CO or CO₂, while the other cell contains the sample exhaust gas. These cells have windows on either side, allowing the IR radiation to pass through, to be received by the detector on the other side. The detectors are sensitive to key regions of IR radiation absorbance, and can detect the dip in the transmittance level of incoming radiation at these specific wavelengths. This dip is directly proportional to the amount of CO/CO₂ in the sample exhaust gas.

Total Hydrocarbons (THC) measurement is based on the Flame Ionization Detection (FID) method. Sample exhaust gas is introduced into an H₂-air flame, where it undergoes complex ionization to generate ions and electrons. These positive ions and electrons are collected at the electrodes, which creates a current through the circuit. The presence of HCs significantly increase this ion current generated at the detector. This current response is proportional to the number of C atoms in the sample and its molecular structure.

Oxygen concentration is determined by measuring magnetic susceptibility of the sample. This method is called Paramagnetic Detection. Oxygen is strongly paramagnetic and accounts for almost all of the exhaust gas magnetic susceptibility. The analyzer detects magnetic susceptibility of the gas sample, which is proportional to oxygen concentration. Table 3.2 summarizes the 5-gas measurement.

Gas Chromatograph (GC) is the method used to determine fuel composition. Figure 3.8 gives a schematic of a gas chromatograph.

Table 3.2: 5-Gas Measurement

	Device	Measurement Technology	Minimum Concentration Range	Maximum Concentration Range	Linearity
CO	Ultramat 6	IR	0 – 10.0 ppm	0 – 10000 ppm	< 0.5% of full-scale value
CO₂	Ultramat 6	IR	0 – 5.0 ppm	0 – 30 %	< 0.5% of full-scale value
THC	Fidamat 6	FID	0 – 10 ppm	0 – 99999 ppm	< +/- 1% of full scale
NO_x	NOx MAT 600	Chemi-luminescence	0 – 1.0 ppm	0 – 3000 ppm	< 0.5% of full-scale value
O₂	OXYMAT6E	Paramagnetic	0 – 5 %	0 – 100 %	+/- 0.1% of full scale

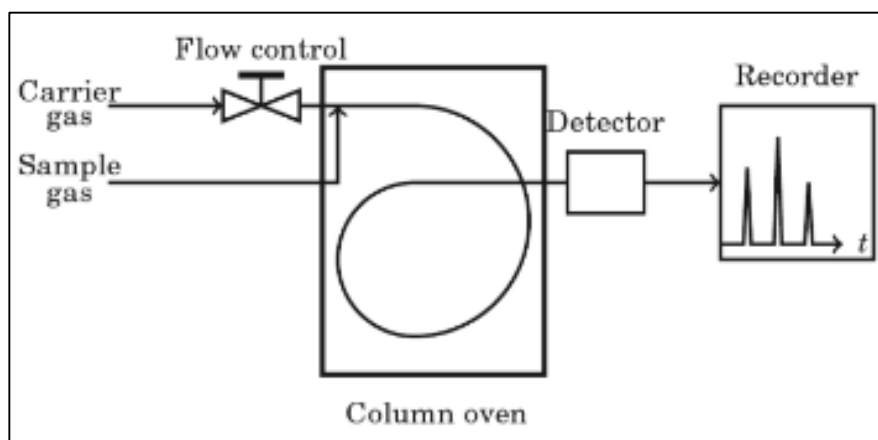


Figure 3.8: Schematic of Gas Chromatograph

It consists of a capillary GC column, in conjunction with TCD (Thermal Conductivity Detector) to measure the concentration of the constituent gases. The column is in the form of coil of a capillary whose inside surface is coated with a suitable adsorbent. The

column is maintained at a constant temperature by placing it inside an oven. As the gas mixture, transported with a carrier gas like Helium, moves through the column, different constituents are adsorbed and released at different rates, thus separating out. Generally, molecules with smaller diameter or simpler structure come out first.

VOCs, ammonia and formaldehyde are measured by Fourier Transform Infrared (FTIR) Spectroscopy. Figure 3.9 shows the Nicolet 6700 FTIR spectrometer.



Figure 3.9: FTIR Spectrometer

The concept is similar to NDIR, except that NDIR is tuned only for one particular species detection, while FTIR can detect a number of species. An IR beam containing many frequencies enters a Michelson Interferometer, which allows the IR beam wavelengths to be analyzed separately. The beam passes through a gas cell and into a detector. Each exhaust species has a unique IR absorption spectra. The absorbance spectra (absorbance versus wavelength) is analyzed with a special software to evaluate

gas composition. The FTIR detects any polar molecule below a molecular weight of approximately 45g/mol. For higher molecular weights, wavelength absorption bands are too close together and cannot be resolved.

Exhaust air/fuel ratio (AFR) feedback from lambda sensor is recorded with an AFRecorder ECM (Engine Control and Monitoring) 4800R. The fuel gas composition is entered into the analyzer, which enables accurate AFR measurement. Figure 3.10 shows the AFRecorder ECM4800R.



Figure 3.10: AFRecorder ECM 4800R

3.8 TEST PROCEDURE

The objective of testing on the Cummins Onan genset was to estimate the amount of hydrogen that can be blended into natural gas as fuel to a stoichiometric SI engine/NSCR catalyst system for different controller/sensor combinations, without significant impact on engine performance, and while still complying with emissions norms. A hydrogen blending system was setup consisting of compressed hydrogen tank, pressure regulator, plumbing to bring hydrogen up to the natural gas fuel line and a rotameter for metering and measuring flow rate. Hydrogen was added to the natural gas line upstream of the carburetor. A measurement rotameter was also installed in the natural gas line, just upstream of engine, for measuring natural gas flow.

The engine was tested at 60kWe (75% of maximum de-rated load of 80kWe) with H₂ blended at various percentages (by volume). The EGC2 utilized a wide-band λ sensor while the GV1 was used in combination with a narrow-band λ sensor. Dithering for EGC2 testing was set at an amplitude of 600 and a dithering period of 667 (~1 sec), which was determined as optimal for this setup in a previous testing^[20]. Dithering for GV1 testing could not be set by user and the factory-set default values had to be used instead.

A ϕ sweep was carried out with the base fuel (natural gas), before blending in hydrogen, to determine the optimum set point for this testing. Hydrogen was then added at increasing percentages (by volume), while maintaining this optimum ϕ set point, with the help of the carburetor controller. Each test point was recorded at steady state for a duration of 5 minutes. Two runs were carried out, once while measuring the post-catalyst emissions and again while measuring the pre-catalyst emissions, to determine the NSCR catalyst efficiency. A 3-way valve installed in the exhaust was used for this purpose. Sample of natural gas was taken by a GC line installed just upstream of the engine, to be analyzed by the Varian CP 4900 Micron GC.

The CFR engine was used for both stoichiometric as well as lean burn engine testing. The objective of stoichiometric testing was to assess impact of increasing hydrogen in fuel on engine combustion in terms of critical compression ratio as well as ignition timing. An in-cylinder pressure transducer (Kistler model 6061A) was installed for recording detailed in-cylinder pressure data, which was used to analyze engine knock. To determine the critical compression ratio, engine was set at a constant ignition timing equal to the MBT (maximum brake torque) timing at baseline (0% H₂). Base fuel was taken as a blend of 90% methane and 10% ethane to simulate natural gas. Two test

points were recorded at each blend. Each test point consisted of 1410 cycles, each cycle recorded with a resolution of 0.1 degrees. FFT method^[27] was used to analyze the pressure data so obtained to quantify knock. The calculations are discussed in the results section. A moving summation of 100 consecutive cycles was computed and monitored in real time. Knock was noticeable at a magnitude of 20, which was defined as the threshold value to determine critical compression ratio.

Lean burn testing was also performed on the CFR engine in an attempt to determine the impact of various percentages of H₂-NG blend on the lean burn limit as well as emissions. Lean burn limit was defined as the point beyond which engine was not able to maintain an NMEP of 1000kPa. For the emissions testing, spark ignition timing was adjusted for each blend to keep location of peak pressure constant, equal to the location of peak pressure for MBT at baseline.

Results from these tests are presented in the subsequent sections.

4. RESULTS AND DISCUSSION – STOICHIOMETRIC TESTING

One of the major objectives of this project was to evaluate impact of blending hydrogen with natural gas on engines operating at stoichiometric conditions. Specifically, this section attempts to assess impact on emissions by testing different carburetor/sensor combinations with the Cummins-Onan genset engine. This is followed by evaluation of impact on critical compression ratio and engine susceptibility to knock, as well as impact on ignition timing, based on results from the CFR engine testing.

4.1 IMPACT ON POLLUTANT EMISSIONS - EGC2 TESTING

First round of testing consisted of testing the EGC2 carburetor with UEGO (wide band) λ sensor. Dithering was enabled for this testing with an amplitude of 600 and a dithering period of 667. Dithering refers to the steady oscillation of the air/fuel ratio (AFR) above and below a target AFR set point at a given amplitude and frequency. It helps widen the NSCR catalyst operating window, thus improving performance^[24]. The dithering amplitude value of 600 corresponds to the ten-thousandth fraction of the ϕ value, calculated as a ratio of the range of ϕ values over average, for a given period. Dithering period of 667 means the dither will go above and below the target AFR set point in that period of time. The EGC2 settings for this testing are specified in Table 4.1. These settings were found to be optimal for this setup based on a previous study^[20].

The first step for this testing was to obtain an optimum AFR set point for this setup. An AFR sweep was carried out with the base fuel (natural gas) while monitoring post-catalyst emissions and an AFR of 16.925 was determined to be optimal. Figure 4.1 shows the results from this sweep. As mixtures got leaner (higher AFR), CO and THC values

decreased. Here the vertical lines show the range within which both NO_x and CO were compliant (Limits as per AQMD norms: NO_x = 11ppmd @ 15% O₂, CO = 250 ppmd @ 15% O₂)^[8]. The optimal AFR value was chosen biased to the rich side of the compliance window, with a large margin for NO_x and no margin for CO. Since adding hydrogen tends to move the operating point to the lean side of the compliance window, this set point determined the maximum H₂ that could be added.

Table 4.1: EGC2 Settings

Parameter	Value
Target AFR	16.925
O ₂ Sensor Gain	700
Pressure Proportional Gain	1600
Pressure Integral Gain	200
Dithering Amplitude	600
Dithering Period	667

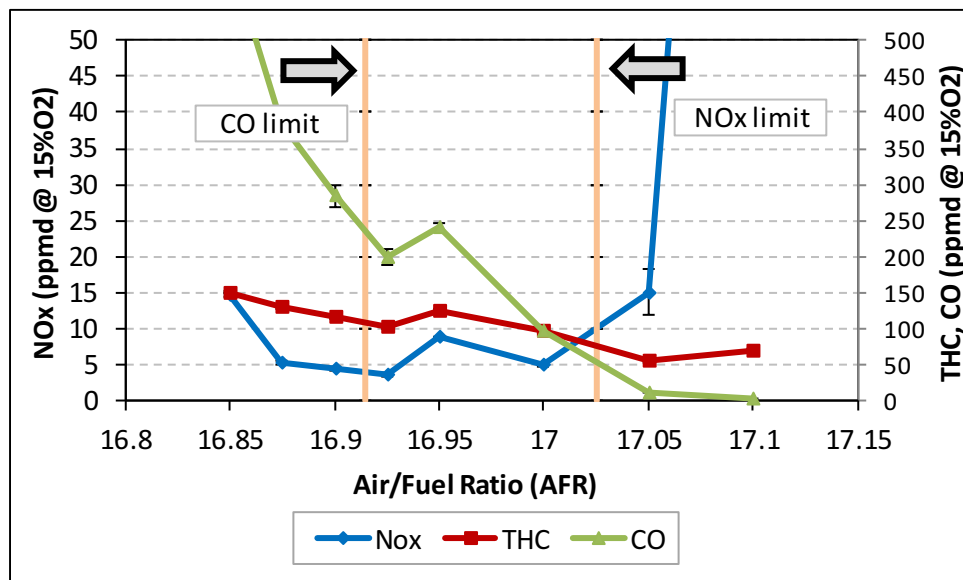


Figure 4.1: EGC2 AFR Sweep Post-Catalyst Emissions

Throughout the test, each data point was taken for a duration of 5 minutes and uncertainty was evaluated with a confidence interval of 95%. The maximum uncertainty values were $\pm 1.26\%$ for THC, $\pm 1.49\%$ for NOx and $\pm 1.31\%$ for CO. Due to time constraints, AFR sweep with pre-catalyst emissions' measurement was not carried out. Instead, the post-catalyst emissions from this testing were compared with pre-catalyst emissions (refer appendix) from a previous testing (for the same operating parameters) to estimate approximate catalyst efficiencies (Figure 4.2). The pre-catalyst and post-catalyst temperatures were relatively constant throughout the sweep at an average of 1105 deg F and 1189 deg F respectively. The data tables can be referred in the appendix.

Hydrogen sweep was then performed twice at the optimal AFR of 16.925 to record both post-catalyst and pre-catalyst emissions. Figure 4.3 gives the post-catalyst emissions from the H₂ sweep, in terms of ppm_d (parts per million, dry) calculated at 15% oxygen.

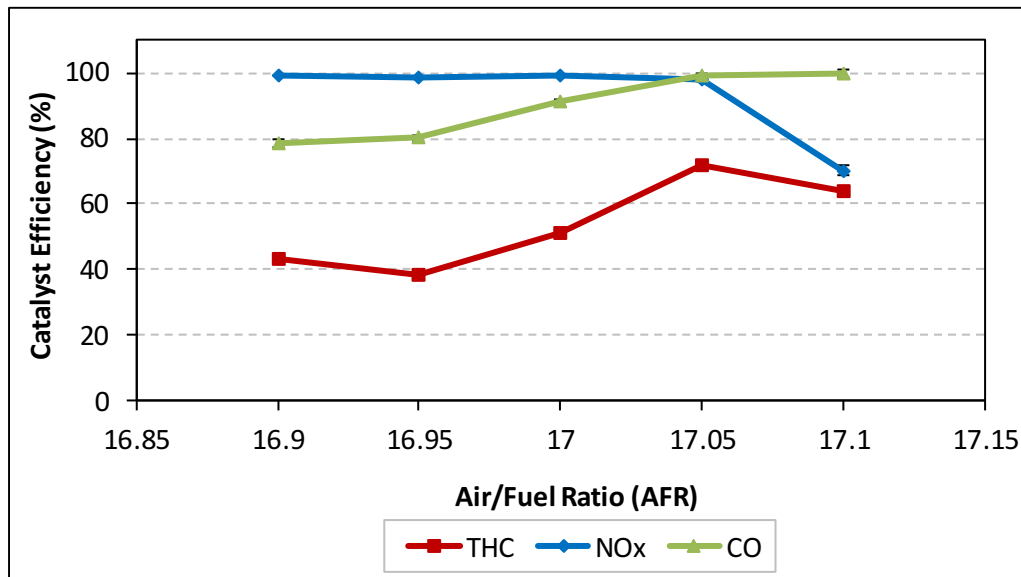


Figure 4.2: EGC2 AFR Sweep Catalyst Efficiency

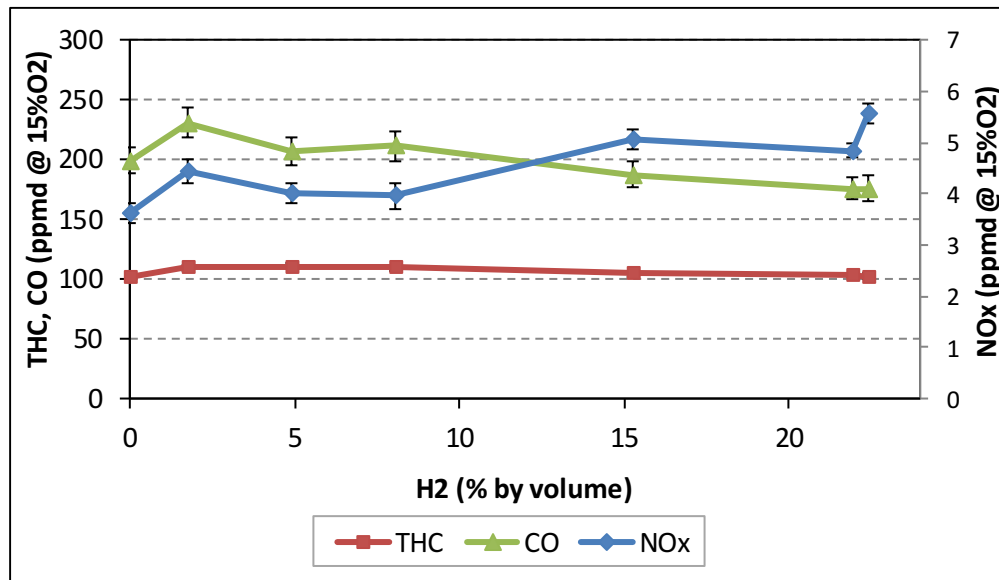


Figure 4.3: EGC2 H2 Sweep Post-Catalyst Emissions – NOx, CO, THC

Both NOx and CO remained within compliance up to approximately 22% (Limits as per AQMD norms: NOx = 11ppmd @ 15% O₂, CO = 250 ppmd @ 15% O₂). This could be attributed to the fact that the optimal AFR set point was on the richer side, and hence NOx values did not show any significant rise and stayed within compliance. Although this represented the best case for determining the maximum hydrogen percentage that could be blended in with natural gas, while still remaining compliant, it would not be practical in practice to select an AFR with almost zero CO margin. THC values, too, remained relatively constant, while CO values showed a gradual decline at H₂ values higher than 5%. The slight jump for CO value at approximately 2% H₂ may have been a result of controller drift to the rich side, creating a temporary oxygen deficient environment. Figure 4.4 shows the calculated stoichiometric and actual AFR values. Fuel composition and exhaust composition were used for calculating the stoichiometric and actual AFR values.

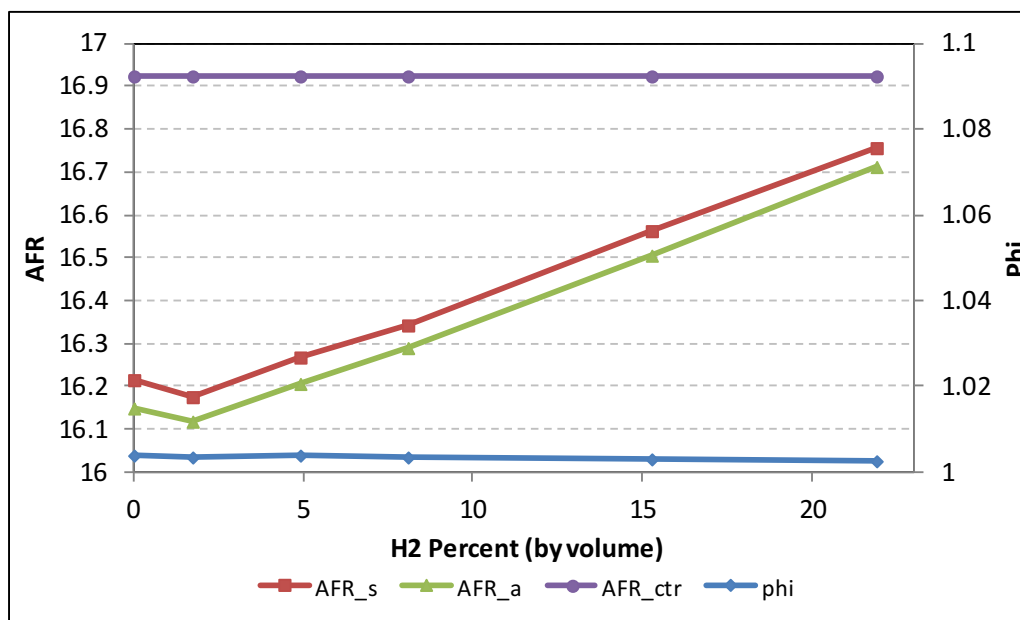


Figure 4.4: EGC2 Calculated AFR vs H2

There was a slight drop in the actual AFR value at 2% before increasing again at 5% hydrogen data point. However, this was accompanied by a reduction in stoichiometric AFR as well. Looking at the fuel composition, it was found that methane concentration in natural gas had dropped by 0.3%, while concentration of higher hydrocarbons had increased slightly. This could be a reason why the stoichiometric AFR dropped at this point, causing the controller to reduce actual AFR too in order to maintain constant ϕ . It is likely that the actual AFR dropped more than required momentarily in the process of reaching a stable ϕ value, causing slightly higher CO emissions.

This anomaly at 2% hydrogen is reflected in slightly reduced catalyst efficiency for both CO and THC as well (Figure 4.5). Uncertainty values, calculated with a confidence interval of 95%, revealed more or less consistent values with a maximum error of less than ± 1 ppm for NO_x, less than ± 3 ppm for THC and about ± 12 ppm for CO. The CO and THC pre-catalyst emissions reduced gradually, while NO_x increased with increasing hydrogen. This is most likely due to reduced C/H ratio of the fuel as well as more

complete, higher temperature combustion (Figure 4.6). The catalyst was very effective at reducing NO_x (efficiency more than 99% at all data points), even with increasing hydrogen, while simultaneously oxidizing CO with an efficiency between 80 to 85%.

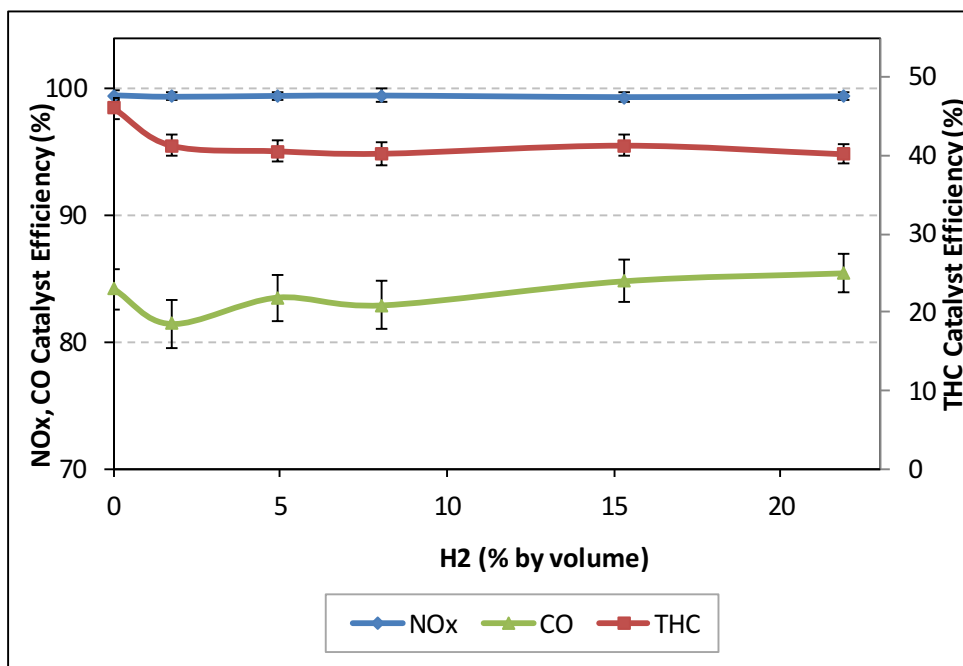


Figure 4.5: EGC2 H2 Sweep Catalyst Efficiency – NO_x, CO, THC

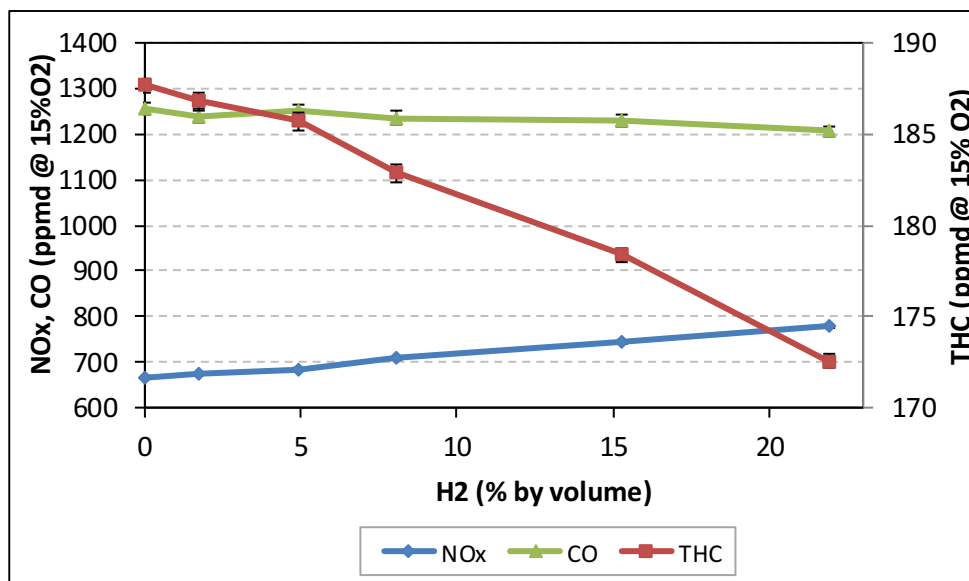


Figure 4.6: EGC2 H2 Sweep Pre-Catalyst Emissions – NO_x, CO, THC

The increase in NO_x post-catalyst is then primarily due to corresponding increase in pre-catalyst emissions, which may be a result of higher combustion temperatures with increased hydrogen.

Apart from the criteria pollutants discussed above, Volatile Organic Compounds (VOCs), formaldehyde (CH₂O) and ammonia (NH₃) were measured by the FTIR. VOCs are defined as all hydrocarbons excluding methane, ethane and formaldehyde. Figures 4.7, 4.8, 4.9 show these results.

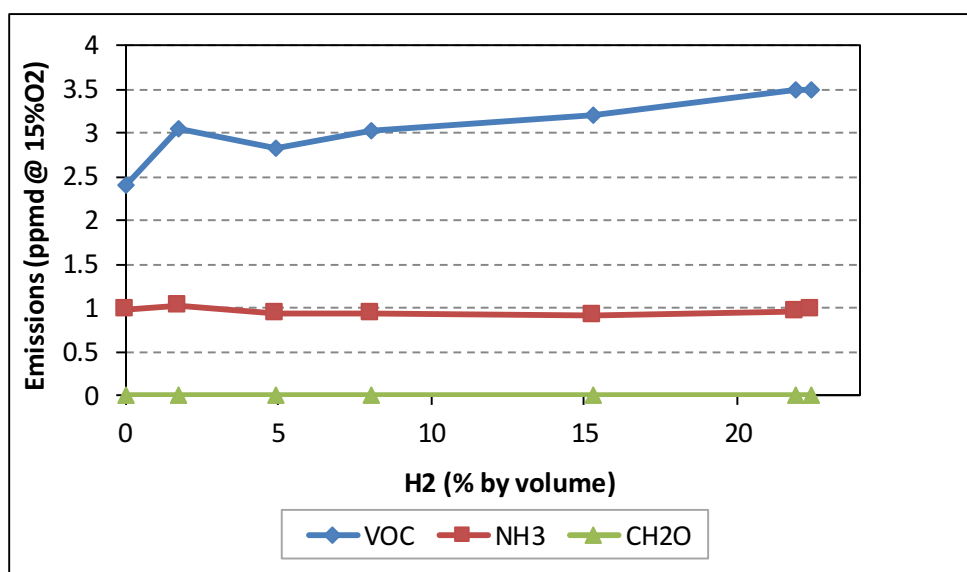


Figure 4.7: EGC2 H₂ Sweep Post-Catalyst Emissions – VOCs, NH₃, CH₂O

Figure 4.7 shows the post-catalyst emissions for these pollutants. As per AQMD norms, which were considered as the emissions limits for this testing, limit defined for VOCs is 30 ppmd at 15% oxygen in exhaust^[8]. It was observed that VOCs' emissions measured were compliant and well below this limit.

Catalyst efficiency for VOCs showed a slight downward trend with increasing H₂%. The average value was observed to be lower than expected. Ammonia values post-catalyst are higher than pre-catalyst. This is expected since ammonia is produced in the

NSCR catalyst for rich mixtures. However, results showed ammonia production to be insignificant. CH₂O was completely eliminated in the catalyst.

Another important observation was no knock was detected even at these higher percentages of H₂ blending, although that may be expected since the engine has a relatively low compression ratio of 8.6.

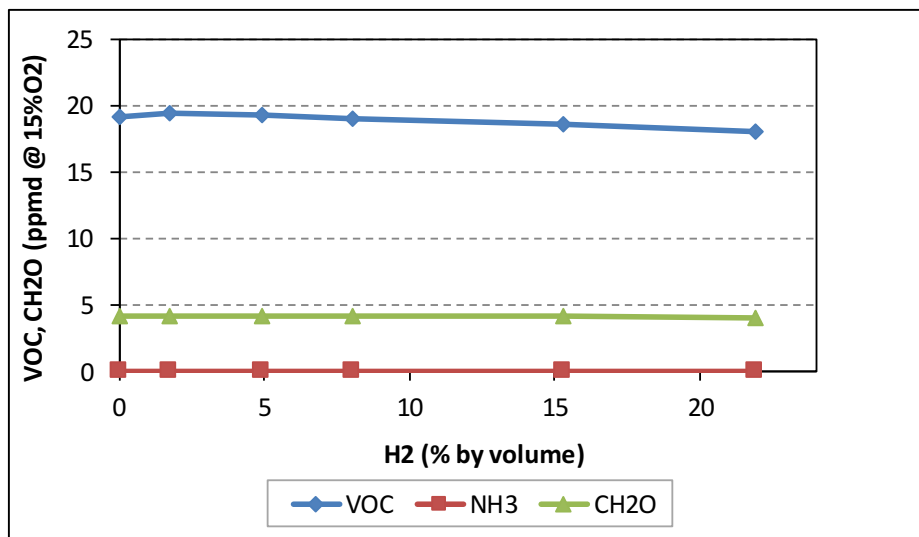


Figure 4.8: EGC2 H₂ Sweep Pre-Catalyst Emissions – VOCs, NH₃, CH₂O

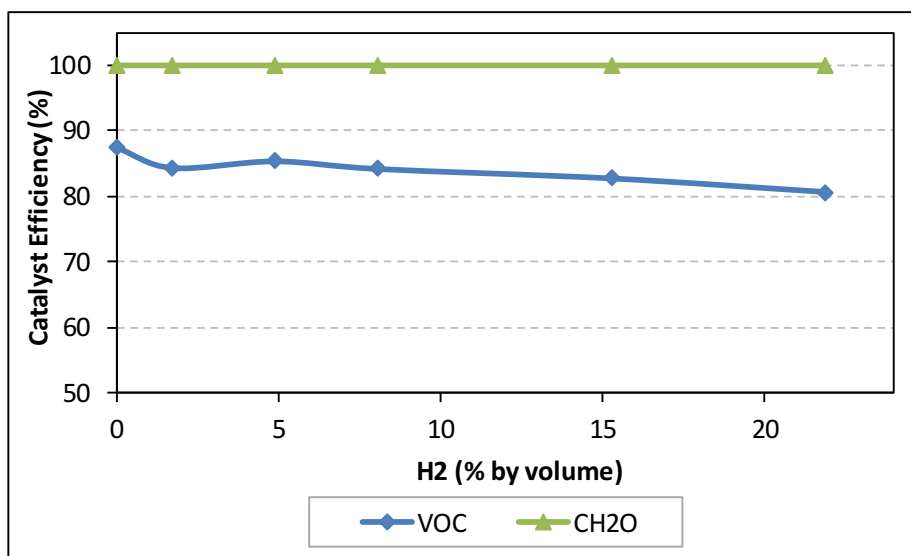


Figure 4.9: EGC2 H₂ Sweep Catalyst Efficiency – VOCs, CH₂O

4.2 IMPACT ON POLLUTANT EMISSIONS - GV1 TESTING

In order to compare the engine behavior with respect to λ sensor control type, the engine was next tested with a narrow band λ sensor (HEGO sensor) along with the GV1 electronic carburetor. This sensor acts like a switch, primarily giving output in terms of high or low voltage corresponding to rich or lean exhaust mixture respectively. To determine an optimum voltage set point, a sweep was performed from 0.1V (lean) to 0.8V (rich) (Figure 4.10).

The catalyst removed CO very effectively in the lean regime as seen from the post-catalyst emissions, while NO_x values remained low on the richer side, barring the one outlier at 0.8 V set point. It is unclear as to why NO_x value increased on this point in spite of pre-catalyst emissions continuing to reduce and no apparent reason for the catalyst efficiency to decrease. THC emissions also showed a gradual rise as the mixtures got richer. The reduction in THC values at the set point of 0.7 V is thought to be a reason of increase in dithering witnessed at this point, which signified that we were approaching the 'switching' point from lean to rich, expected with a narrow band λ sensor. This was accompanied by an increase in uncertainty from ± 0.7 to ± 2.7 ppm for a confidence interval of 95%. It was observed that NO_x values shot up dramatically at voltages below 0.71 V, which was then designated as the lean limit. CO values exceeded the emissions limit at 0.74 V, which was the rich limit of the operating window. The centroid of this range in which NO_x and CO both were within emissions limits was then determined as the optimum sensor set point. Figure 4.11 gives the pre-catalyst emissions.

In order to get an idea of how these λ sensor set point values compared to mixture composition, catalyst efficiencies were plotted against ϕ values corresponding to the λ

sensor set points. The ϕ calculations were made at each data point based on exhaust and fuel compositions. ϕ values computed in this way are not reliant on λ sensor response and are expected to be closer to the true equivalence ratio. These results can be seen in Figure 4.12.

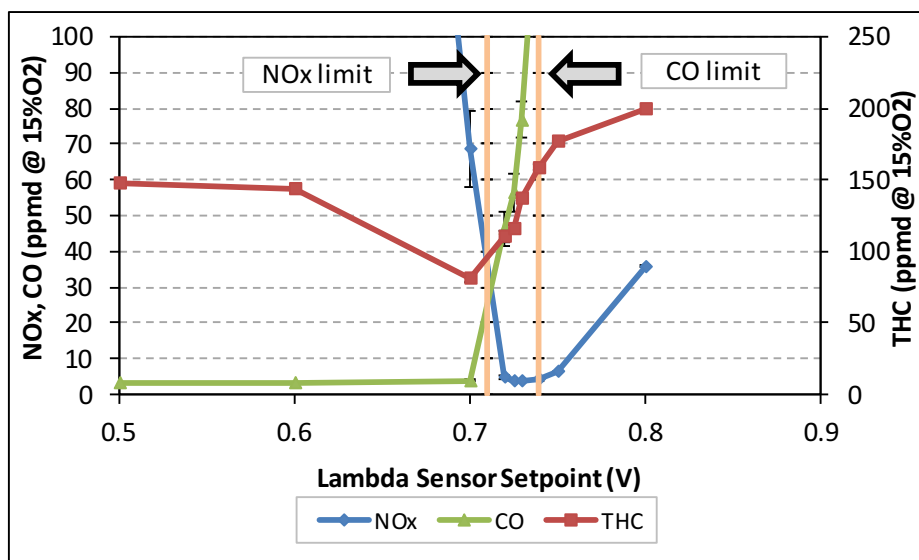


Figure 4.10: GV1 ϕ Sweep Post-Catalyst Emissions

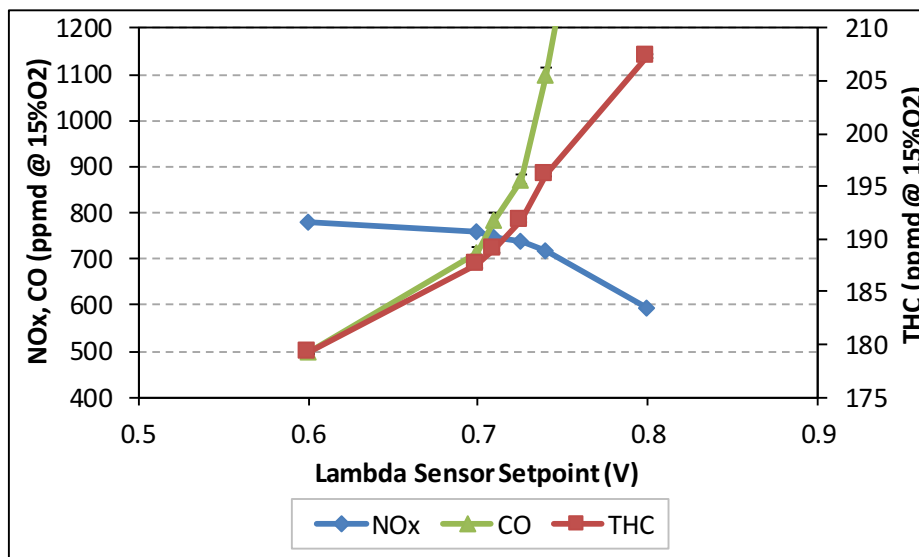


Figure 4.11: GV1 ϕ Sweep Pre-Catalyst Emissions

The optimum sensor set point of 0.725 V corresponds to a ϕ value of 1. NOx reducing efficiency of the catalyst at this point was 99% while CO oxidizing efficiency was 93%.

Hydrogen blend sweeps were then carried out at this optimum point. Results revealed that NOx exceeded limits beyond 10% H2 blended into NG (Figure 4.13).

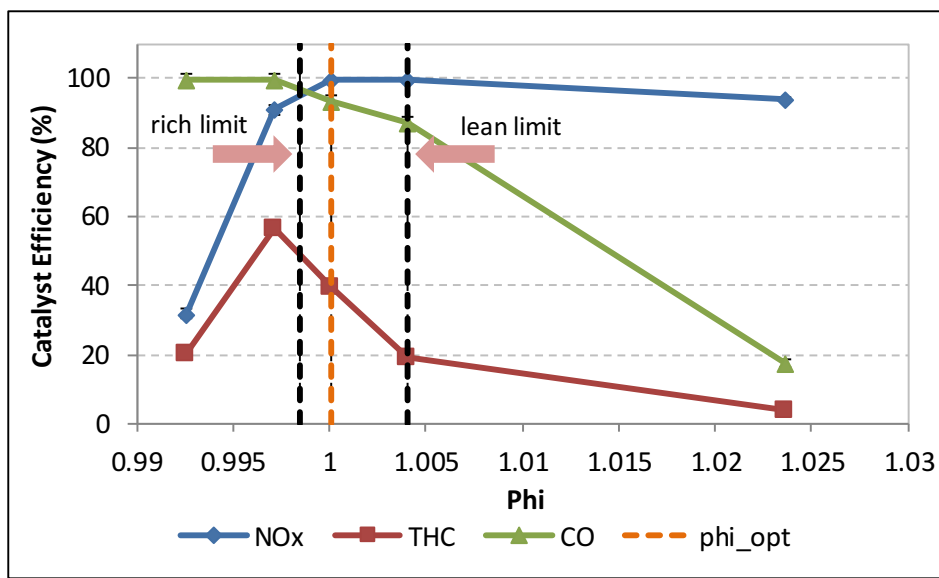


Figure 4.12: GV1 ϕ Sweep Catalyst Efficiency

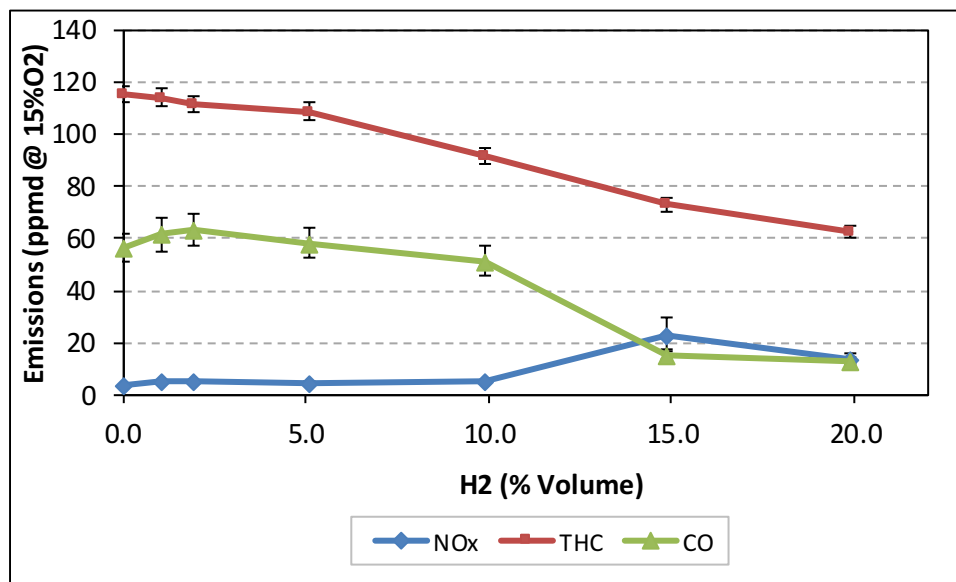


Figure 4.13: GV1 H2 Sweep Post-Catalyst Emissions – NOx, CO, THC

NOx values remained low until 10% beyond which a significant rise was observed. This is thought to be a combined effect of increase in pre-catalyst emissions as well as reduction in catalyst efficiency. Similarly CO values remained approximately constant before experiencing a sudden drop at the 15% H2 data point. This suggests that below 10% H2, not significant impact was seen on these emissions. Higher NOx values at 15% H2 compared to 20% H2 are most likely erroneous, which is reflected in the higher error value associated with the 15% data point. Data shows that NOx values were recorded significantly higher at the start of this data point, giving rise to higher average and standard deviation values. This suggests the point may have been recorded before allowing it to reach steady state.

THC values showed a steady decline with increasing hydrogen percentage. This is thought to be a combination of reduced C/H ratio and more complete combustion, which is reflected in the steady decrease of pre-catalyst values as well. Figure 4.14 shows the pre-catalyst emissions data.

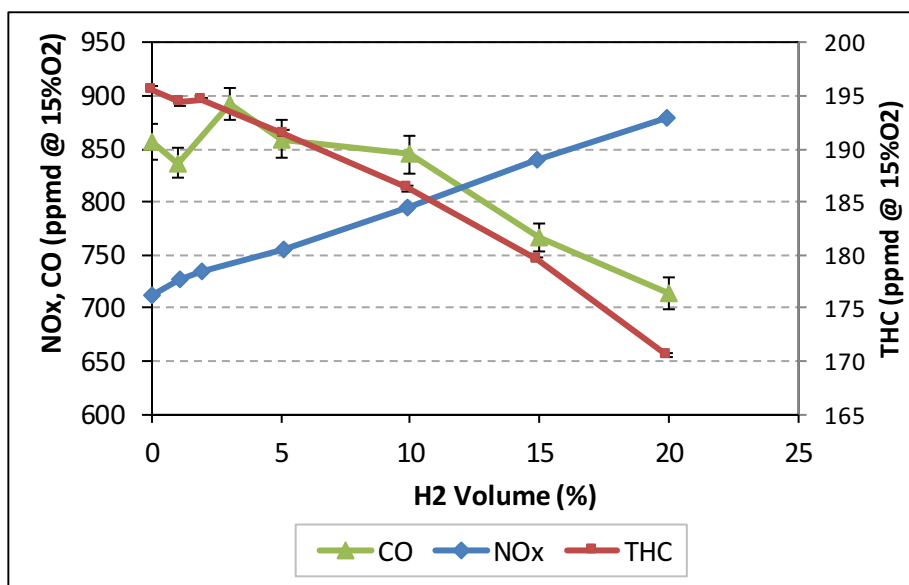


Figure 4.14: GV1 H2 Sweep Pre-Catalyst Emissions – NOx, CO, THC

Increased hydrogen in fuel led to increased engine out NO_x emissions and reduced CO and THC emissions. CO emissions increased temporarily at 3% hydrogen before gradually decreasing again. This seems to be a result of an extended dithering on the rich side at this data point due to controller instability.

Increase in NO_x emissions is most likely due to higher combustion temperatures associated with hydrogen. The pronounced effect of hydrogen at 15% was also reflected in the catalyst efficiencies. In line with the shift in NO_x and CO emissions, crossover of CO and NO_x reduction efficiencies was also seen at this point. Catalyst efficiency for oxidizing THC also improved at higher percentages of hydrogen. (Figure 4.15)

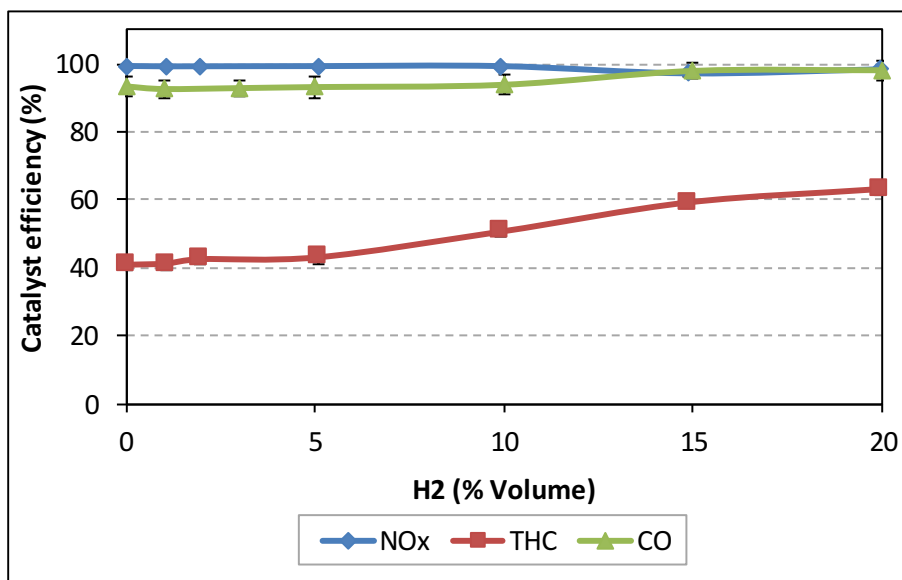


Figure 4.15: GV1 H₂ Sweep Catalyst Efficiency – NO_x, CO, THC

Thus, change in catalyst efficiency also plays a role in the shift in post-catalyst emissions. The reason for this could be a noticeable increase in oxygen in the exhaust beyond 15% hydrogen, indicating a shift in average equivalence ratio. Calculated actual and stoichiometric AFR and ϕ values are presented in Figure 4.16. Fuel composition and exhaust composition data was used for these calculations.

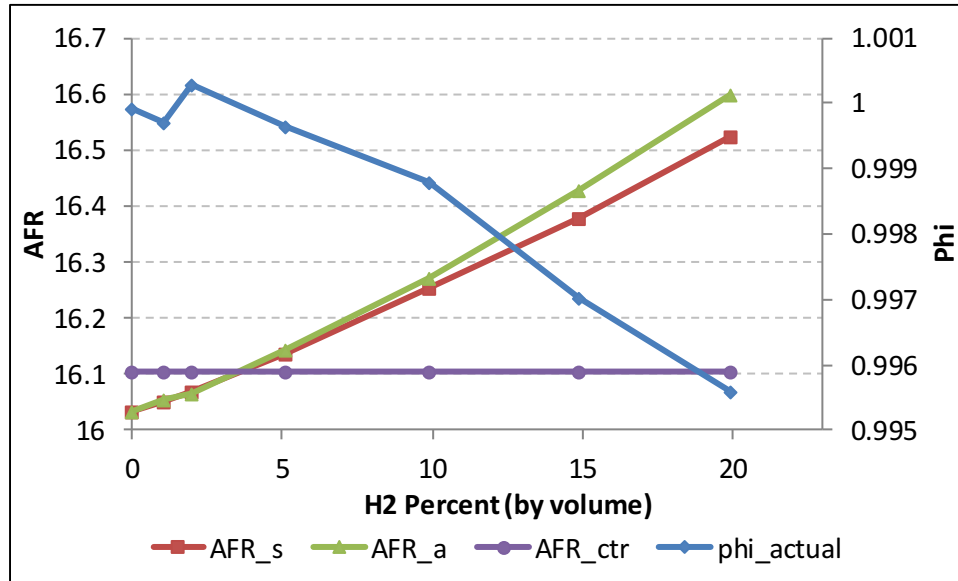


Figure 4.16: GV1 AFR vs H2

It was observed that actual AFR increased faster than the stoichiometric AFR. This gap is especially noticeable at higher percentages of hydrogen. This is thought to be an effect of the λ sensor response. Presence of hydrogen in exhaust can affect the λ sensor to read richer, thus causing a lean shift by the controller (Refer section 3.5). Increasing percentage of hydrogen in fuel may have caused an increase in hydrogen in exhaust, in turn, causing the controller to shift lean, thus increasing oxygen in exhaust and decreasing the equivalence ratio.

Unlike the GV1, the post-catalyst emissions obtained with the EGC2 were mostly driven by changes in pre-catalyst emissions, with approximately constant catalyst efficiencies throughout the range of H2-NG blend tested (up to 20% H2). This is most likely due to the AFR set point. For the GV1, the AFR set point was centered, whereas the AFR set point for the EGC2 was skewed towards the rich side of the AFR control window. Another interesting observation was that the post-catalyst temperatures for GV1 hydrogen sweep were lower than those observed for EGC2, with comparable pre-catalyst

as well as turbine in temperatures. For example, at 0 % hydrogen, for a pre-catalyst temperature of approximately 1108 deg F, post-catalyst temperature for GV1 was 1181 deg F, while that for the EGC2 was 1192 deg F. (Detailed temperature data can be found in the appendix). This may again be due to the different AFR set point causing different reactions to dominate in the catalyst. Another possible reason may be a difference in control algorithms for the two carburetors.

Looking at the non-criteria pollutants namely Volatile Organic Compounds (VOCs), ammonia (NH₃) and formaldehyde (CH₂O) in Figures 4.17 (post-catalyst) and 4.18 (pre-catalyst), it was observed that ammonia values were higher both post-catalyst as well as pre-catalyst, compared to data with EGC2. A possible reason may be that this setup was not as stable as the EGC2 and the engine may be running richer occasionally while trying to converge on to the set point.

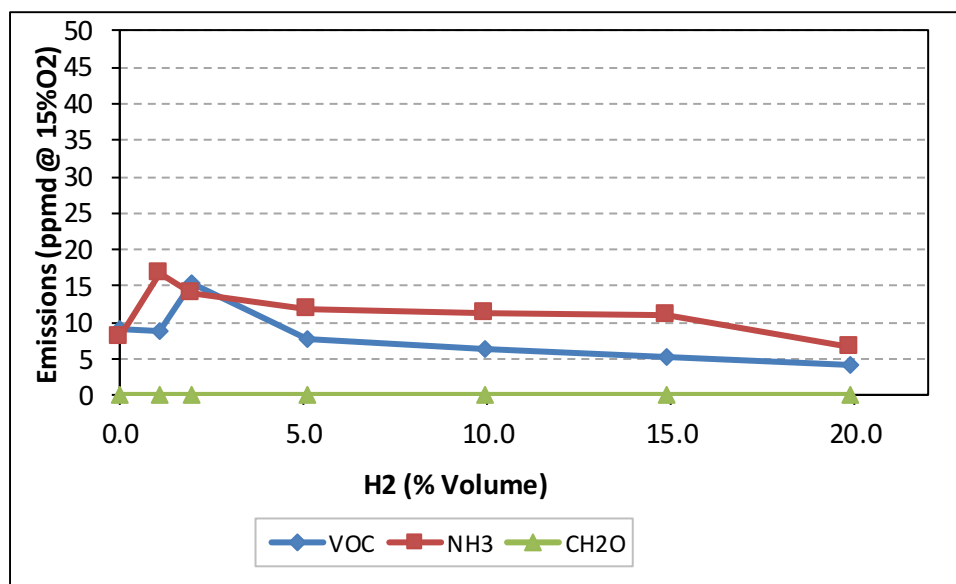


Figure 4.17: GV1 H2 Sweep Post-Catalyst Emissions – VOCs, NH₃, CH₂O

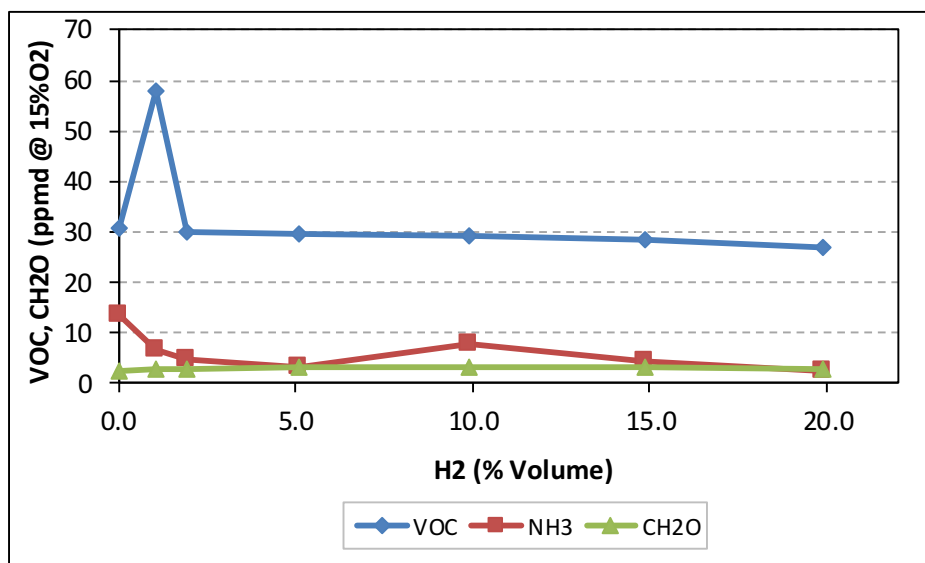


Figure 4.18: GV1 H2 Sweep Pre-Catalyst Emissions – VOCs, NH3, CH2O

Post-catalyst VOC emissions remained low and averaged at approximately 8 ppmd at 15% oxygen in exhaust. This was well within the limit of 30 ppmd (@ 15% O2) as defined by AQMD emissions norms.

Another unusual trend that was observed was the slightly decreasing trend of post-catalyst ammonia with increase in H2 percentage. However, the drop is small and the values may be considered as constant. The VOC pre-catalyst value at 1% hydrogen seems to be an outlier and is most likely a measurement error or related to controller instability. CH2O was reduced completely post-catalyst and VOC saw an average catalyst efficiency of 80%. (Figure 4.19)

4.3 KNOCK ANALYSIS AND IMPACT ON CRITICAL COMPRESSION RATIO

Knock analysis was carried out on the Cooperative Fuel Research (CFR) Engine. Knock is the name given to the noise which is transmitted through the engine structure when essentially spontaneous ignition of a portion of the end-gas – the fuel, air, residual gas, mixture ahead of the propagating flame – occurs^[9].

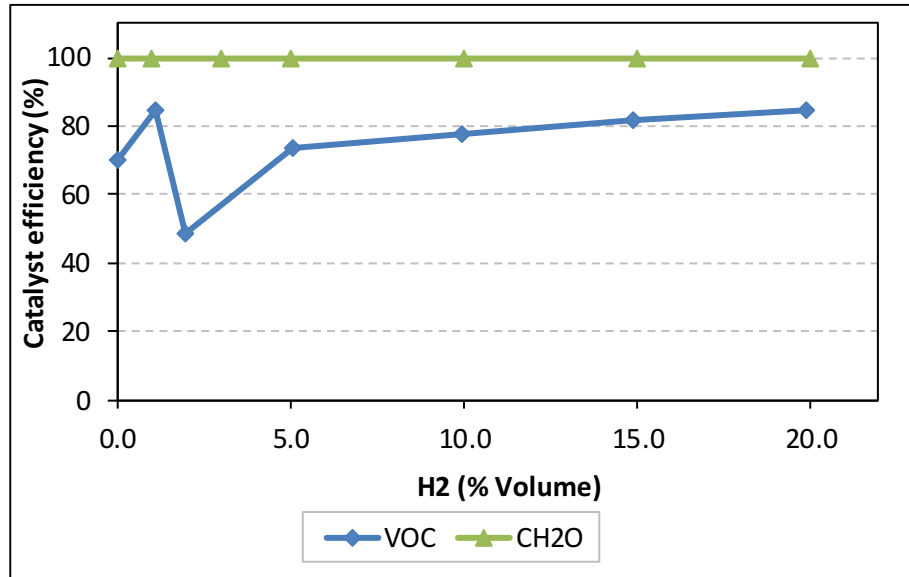


Figure 4.19: GV1 H2 Sweep Catalyst Efficiency – VOCs, CH₂O

During normal combustion, flame formed at the spark travels through the combustion chamber. This flame front consumes all of the unburned mass rapidly raising temperature and pressure inside the chamber. If, however, the high temperature and pressure around causes the unburned charge to self-ignite before the flame front reaches it, this gives rise to engine knock. Knock is characterized by dramatic fluctuations in pressure and temperature inside the combustion chamber, causing accelerated mechanical wear of bearings and other parts as well as pitting of cylinder walls and piston surfaces.

For this project, all of the knock analysis testing was carried out on the Cooperative Fuel Research (CFR) Engine at a constant ignition timing set to the MBT (maximum brake torque) timing at baseline (0% H₂). Base fuel was taken as a blend of 90% methane and 10% ethane to simulate natural gas. The MBT timing was determined to be 21 degrees BTDC by initially doing an ignition timing sweep at 0% H₂.

Two test points were recorded at each blend. Each test point consisted of 1410 cycles, each cycle recorded with a resolution of 0.1 degree i.e. 7200 instantaneous values

were available for a detailed in cylinder pressure trace. FFT analysis was performed on the pressure trace to calculate the knock index value^[27]. The FFT knock detection method utilizes a fast Fourier transform to measure the knock frequency. The period of the knock event is the time required for the pressure wave to travel the diameter of the cylinder and back and knock frequency is then the inverse of this period. The anticipated knocking frequency for the CFR engine is 5850 Hz^[27]. A bandpass filter is applied to the pressure data to remove operating pressure trace corresponding to fundamental engine frequency, and bounds of the filter are set to 0.8x to 2x the expected knock frequency. An FFT is calculated of the resulting pressure data, producing discrete amplitude versus frequency data. This data reveals the frequency at which knock occurs and the amplitude corresponds to the intensity of knock. A knock integral is computed by adding the knock amplitude from each cycle.

A moving summation of 100 consecutive cycles is computed and monitored in real time. Knock was noticeable at a magnitude of 20, which was defined as the point of onset of knock. To determine the critical compression ratio (R_c) for each blend, hydrogen was added in increasing percentages at a constant ignition timing set to the MBT timing for baseline fuel (0% H₂). Critical compression ratio is defined as the compression ratio at which engine starts knocking. These results are presented in Figure 4.20.

Critical compression ratio reduced with increasing hydrogen in the fuel, due to increased susceptibility to knock. Hydrogen is very prone to knocking due to its high reactivity resulting in high in-cylinder pressures and temperatures. Hence, at the same ignition timing as base fuel, hydrogen in the fuel caused engine to knock at a lower compression ratio compared to baseline.

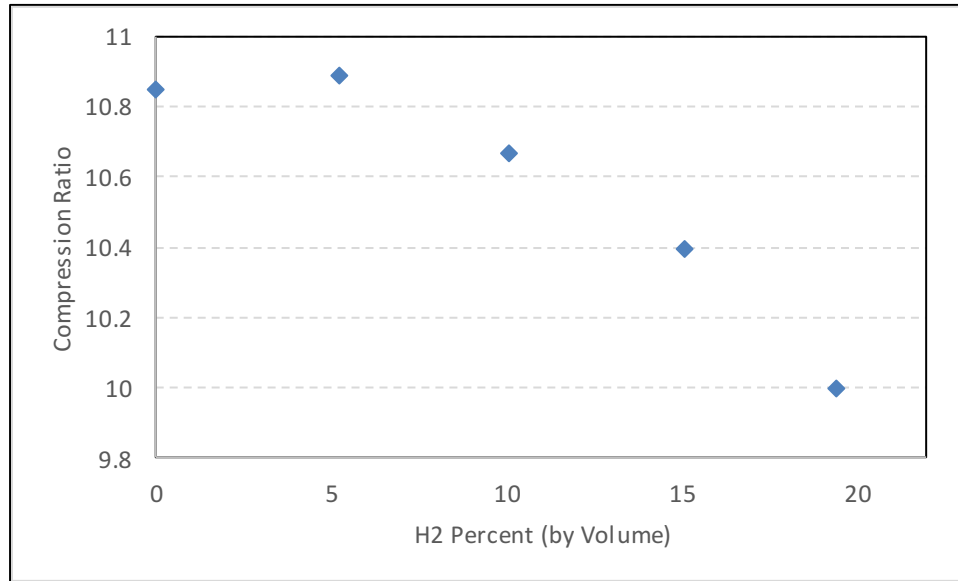


Figure 4.20: Effect of H2 on Critical Compression Ratio

As H2 percentage was increased from 0 to 20, critical compression ratio reduced from 10.8 to 10.0. This is a reduction of approximately one compression ratio unit per 20% H2, or approximately 0.05 compression ratio units per 1% H2 added.

The higher critical compression ratio at 5% hydrogen, when compared to baseline, is thought to be an error, since it was difficult to control hydrogen flow at this low level. This is reflected in error calculated for volume measurement (95% confidence interval), which shows an error of $\pm 0.04\%$ for 5% which is one order of magnitude higher than $\pm 0.002\%$ for 10% hydrogen.

Although the number of cycles (approximately 25% of total) with a knock integral greater than 20 did not change with change in amount of hydrogen blended in base fuel, it was observed that the frequency of higher intensity knock events increased at higher percentages. Figure 4.21 shows the impact of increasing hydrogen on the average number of cycles between a high intensity knock event where knock integral value is greater than 100.

The frequency of these events increased at higher percentages of hydrogen. Figure 4.22 gives a graphical illustration of how the frequency of high intensity knock events changes with hydrogen percentage. It was observed that for 15% hydrogen, many of these events occurred in the first 400 cycles. Also, for each blend, it was observed that the maximum knock integral for the first run was higher than the maximum knock integral for the second run.

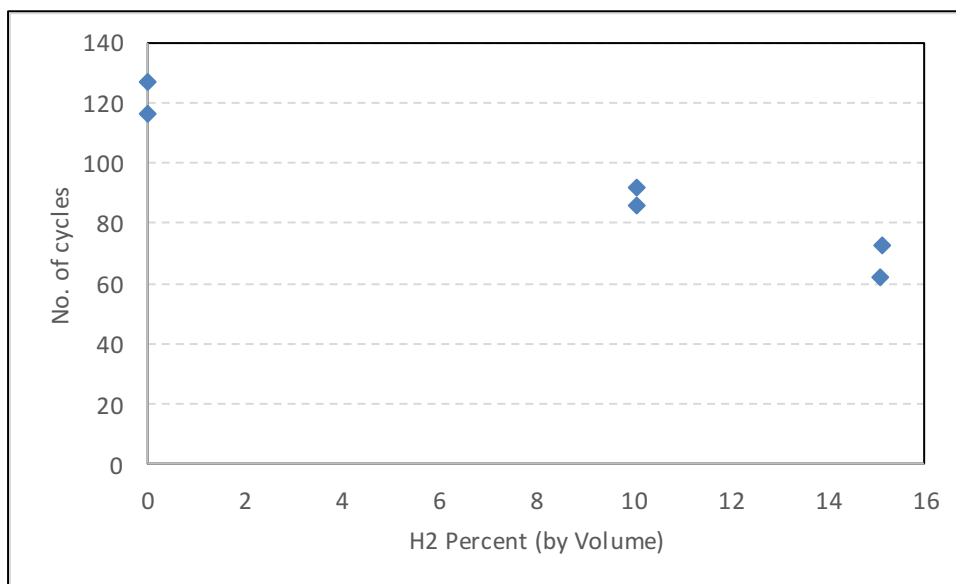


Figure 4.21: Average Number of Cycles between Events with knock intensity > 100

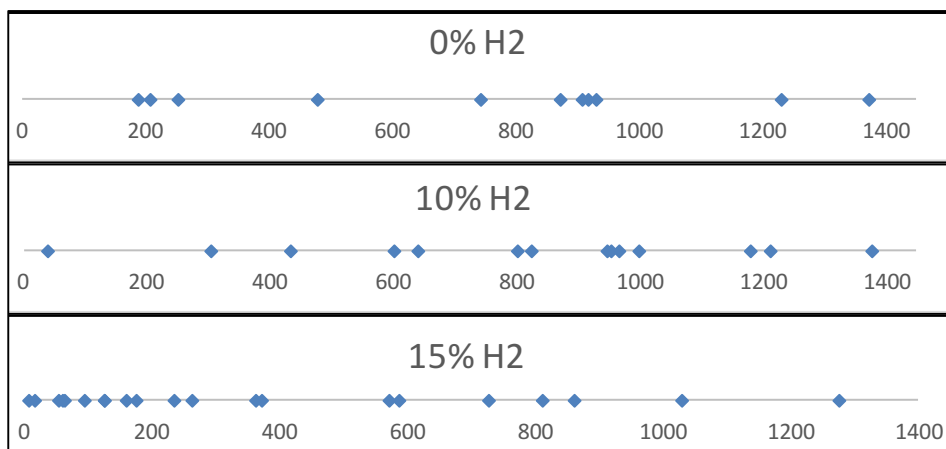


Figure 4.22: Frequency of Higher Intensity Knock Events

Another important observation was that, in general, the location of peak pressure advanced and its amplitude increased at higher percentages of hydrogen. This was also accompanied by more fluctuations observed in the pressure trace, which was a result of engine knocking (Figure 4.23).

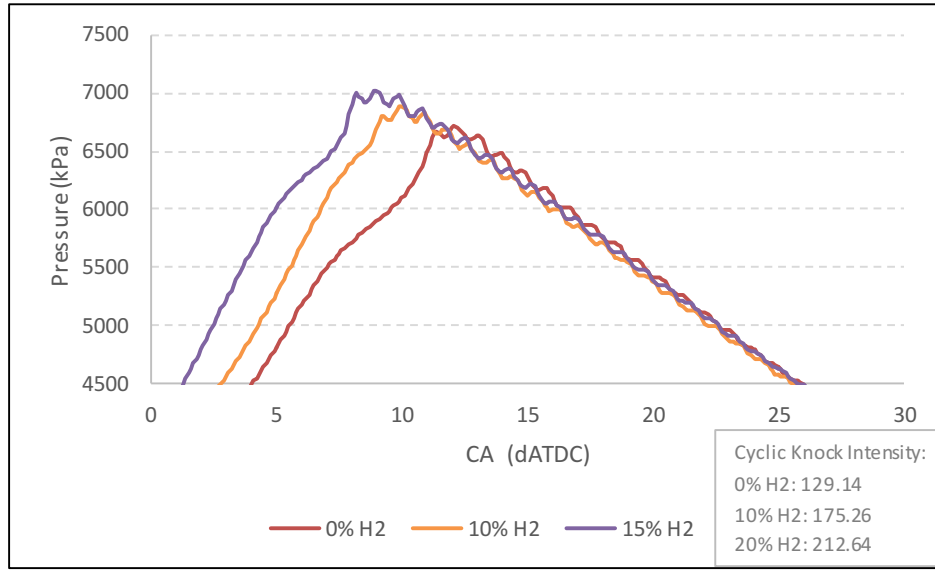


Figure 4.23: Pressure Trace Comparison for Different H2 Percent Blends

Owing to the lower ignition energy and higher flame speed for hydrogen, ignition delay was expected to reduce with higher percentages of hydrogen. Ignition delay is defined as the time required in terms of crank angle (CA) duration from spark ignition to 10% MFB. However, this effect was not very significant up to 15% hydrogen. Figure 4.25 below shows the ignition delay at the critical compression ratio data points for each blend.

On the other hand, increased combustion rate for higher percentages of hydrogen was observed, which was indicated by an advance in the location of 50% MFB (mass fuel burned). These results can be seen in Figure 4.24. The 50% burn location is a measure of overall combustion phasing, which is related to ignition delay, laminar flame speed, and turbulence level.

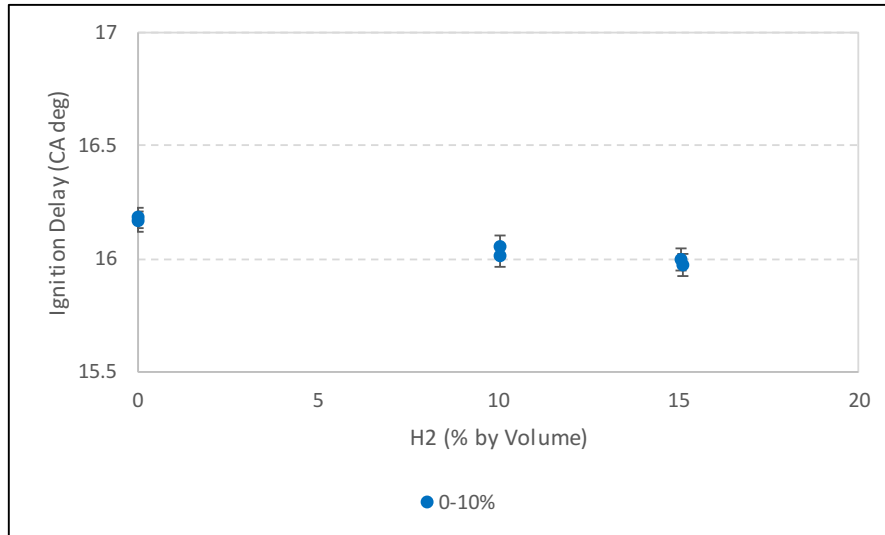


Figure 4.24: Impact of Hydrogen on Ignition Delay

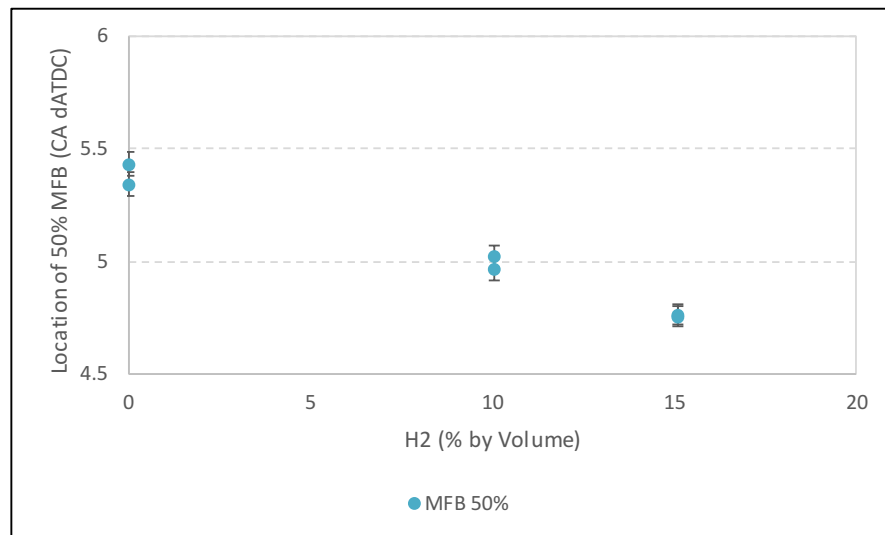


Figure 4.25: Impact of Hydrogen on Location of 50% Mass Fraction Burnt

It was observed that the effect on combustion rate was more pronounced for later part of combustion (50-90% MFB), compared to 0-50% MFB (Figure 4.26). Also, this impact was observed only for 15% hydrogen, while combustion duration did not show much of an effect for hydrogen up to 10%. This improvement in combustion rate for higher H2 percentages was observed only at higher compression ratios.

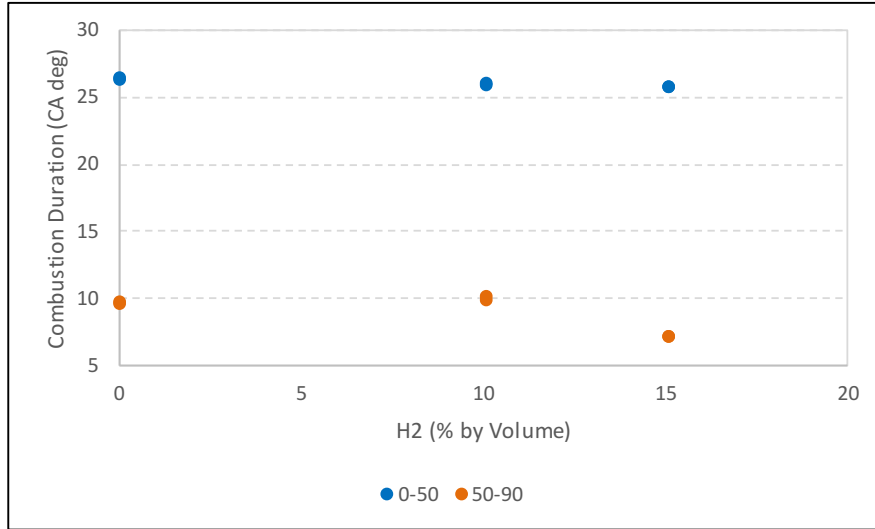


Figure 4.26: Impact of H2 on Combustion Rate at Stoichiometric Operation

4.4 IMPACT ON IGNITION TIMING

In order to understand the effect of increasing hydrogen on the ignition timing, different blends were tested keeping location of peak pressure constant (Figure 4.27).

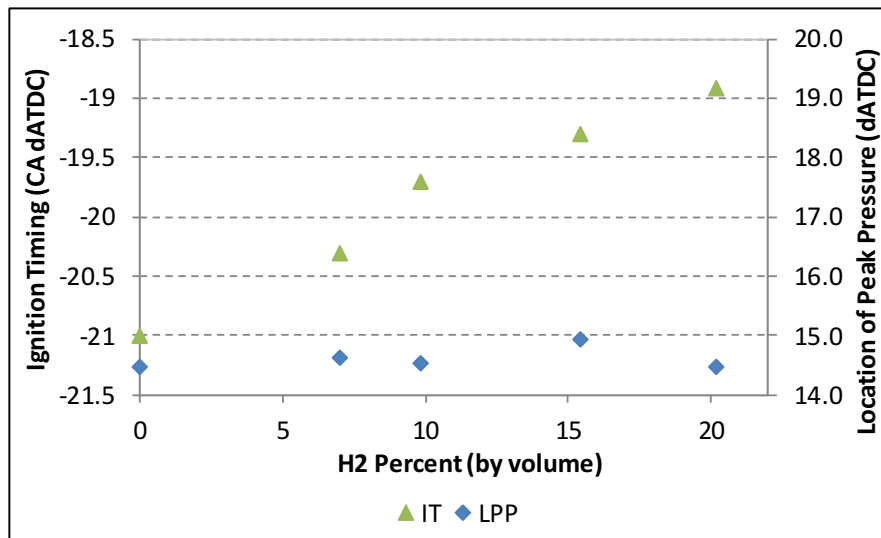


Figure 4.27: Impact of Hydrogen on Ignition Timing

In contrast with the results obtained for ignition delay with constant ignition timing tests, this round of testing showed a significant impact on ignition timing with increasing percentages of hydrogen. This can be attributed to the higher flame speed of hydrogen.

Increasing H₂ percent in fuel speeds up combustion, requiring retarded spark timing to achieve same location of peak pressure as baseline. These results are presented in Figure 4.26. Spark timing had to be retarded by over 2 degrees for 20% hydrogen compared to 0% hydrogen to achieve comparable location of peak pressure.

To summarize, it was observed that pre-catalyst or engine-out NO_x emissions increase with increasing hydrogen percentage in fuel mainly due to higher flame temperatures. Pre-catalyst CO and THC emissions reduce with increase in hydrogen percent due to reduced C/H ratio of fuel as well as more complete combustion. The data shows that post-catalyst NO_x and CO emissions also change (increase in NO_x and decrease in CO) as hydrogen is added to the fuel. This is due primarily to changes in pre-catalyst emissions. However, there is evidence that H₂ addition also impacts catalyst efficiencies, but this is dependent on the AFR control technique and the AFR set point.

For EGC2 testing, the AFR set point was chosen towards the rich limit of the compliance range, which resulted in much reduced NO_x emissions and showed that both NO_x and CO remained within compliance up to approximately 22%. Assuming AFR set point is centered in the control window, hydrogen up to 10% by volume may be blended in with natural gas while staying within emissions limits. This was seen from results on the GV1. With the AFR set point centered, an improvement is seen in catalyst efficiency for both CO and THC, without adversely affecting the efficiency for NO_x. The catalyst was very effective at reducing NO_x with an efficiency more than 99% at all data point, even with increasing hydrogen percent. Formaldehyde was eliminated completely post-catalyst. It was observed that below 10% hydrogen in fuel, not significant impact was seen on emissions. For higher percentages, NO_x values rose dramatically, along with

considerable reduction in CO and THC emissions. VOCs were very low and well within emissions limits throughout the testing.

Although NO_x emissions tend to increase with increase in hydrogen percentage in fuel, this effect can be offset by retarded ignition timing. This was observed in the results from the CFR testing. Results showed that spark timing had to be retarded by over 2 degrees for 20% hydrogen compared to 0% hydrogen to achieve comparable location of peak pressure. Retarding ignition timing with increasing hydrogen helps achieve similar location of peak pressures due to faster flame speed of hydrogen, which aids in controlling NO_x emissions, without adversely affecting CO and THC emissions.

Critical compression ratio reduces with increasing hydrogen in the fuel, due to increased susceptibility to knock. The critical compression ratio decreased approximately 0.05 compression ratio units per 1% hydrogen. It was observed that the frequency of high intensity knock events increases at higher percentages of hydrogen.

5. RESULTS AND DISCUSSION – LEAN BURN TESTING

To assess impact of hydrogen on lean burn engine operation, testing was performed on the CFR engine. In addition to analyzing impact on emissions for lean burn conditions, this section also talks about how hydrogen impacts ignition timing and lean burn limit of engine operation.

5.1 IMPACT ON LEAN LIMIT

Hydrogen has wider flammability limits compared to natural gas, which can allow the engine to operate at leaner air/fuel ratios. Operating at the lean limit can help control NO_x emissions and may increase overall efficiency. This testing was carried out to evaluate impact of hydrogen in extending the lean limit operation. Lean limit was defined as the point where engine was not able to maintain an NMEP of 1000kPa. Engine was tested at a constant speed of 940 rpm with a blend of 90% methane (CH₄) and 10% ethane (C₂H₆) as the base fuel. ϕ sweep was carried out at 0%, 10% and 20% hydrogen blended in base fuel to determine lean limit for various blends.

It was seen that the lean limit improved from $\phi = 0.57$ at 0% hydrogen to $\phi = 0.56$ at 10% hydrogen and $\phi = 0.54$ at 20% hydrogen. This was a 5% extension to the lean limit at 20% H₂, which is seen by the 20% data points extending further to the left on the plot. Peak pressure COV (coefficient of variation) for 0% hydrogen rose sharply at a ϕ of 0.57. This sharp rise in COV indicates misfire and partial combustion events causing substantial pressure fluctuations.

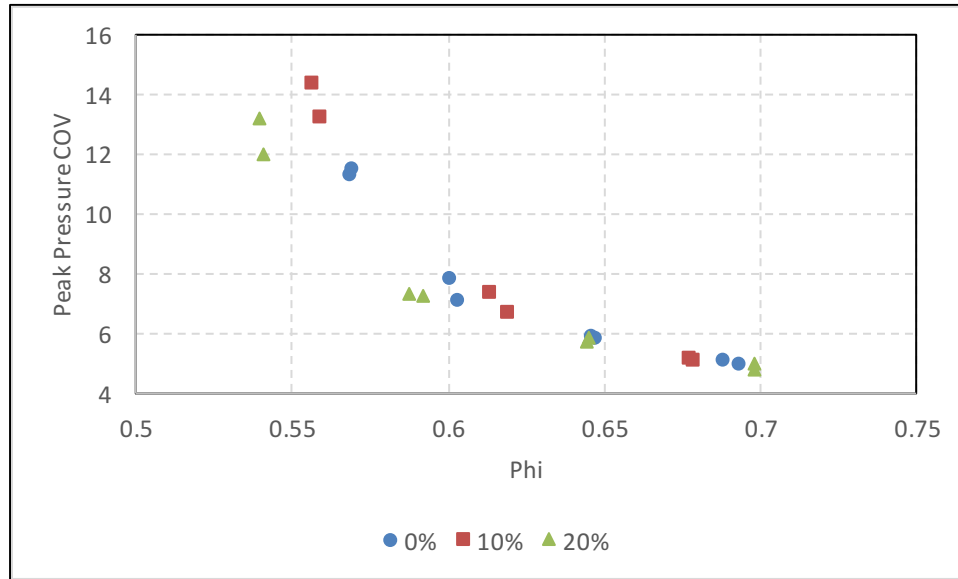


Figure 5.1: Impact of Hydrogen on Lean Limit

Looking at the trend of 20% hydrogen, COV for 20% hydrogen seems to be much lower at $\phi = 0.57$. It is difficult to compare this with the results for 10% hydrogen due to insufficient data for that blend. The ϕ values measured by the lambda sensor and calculated from the exhaust composition are compared in Figure 5.2. There were three different ways of determining ϕ for this testing:

- 1) ϕ calculation from exhaust composition ($\phi_{\text{calculated}}$)
- 2) ϕ calculation based on flow rates (ϕ_{intake})
- 3) ϕ based on AFR measured by the λ sensor in exhaust (ϕ_{measured})

AFR measurement (3) from λ sensor was recorded with an ECM AFRRecorder 4800R. Figures 5.2 and 5.3 give a comparison of these ϕ values for 0% and 20% hydrogen. A comparison for 10% hydrogen can be found in appendix. The sensor measured consistently higher than calculated values for ϕ . However, results from this testing can still be used for H2 blends' comparison since ϕ values from each measurement technique

show similar trends, when compared for different hydrogen blends. ϕ values calculated from the exhaust composition are used to present the rest of the results in this section.

Although there was improvement in the lean operation limit of the engine with higher hydrogen percentages, as seen in Figure 5.1, not much effect was seen on power or efficiency values.

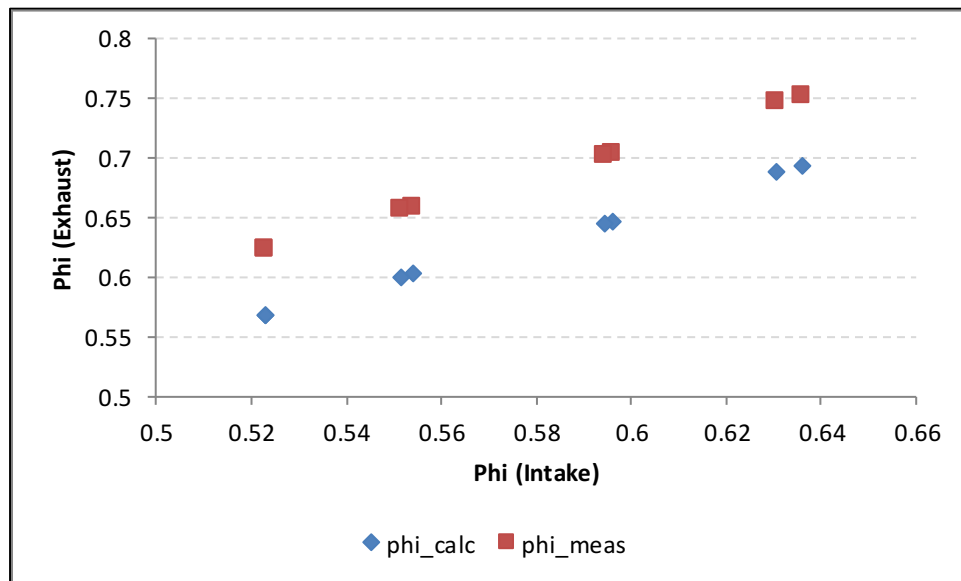


Figure 5.2: ϕ Values Comparison for 0% Hydrogen

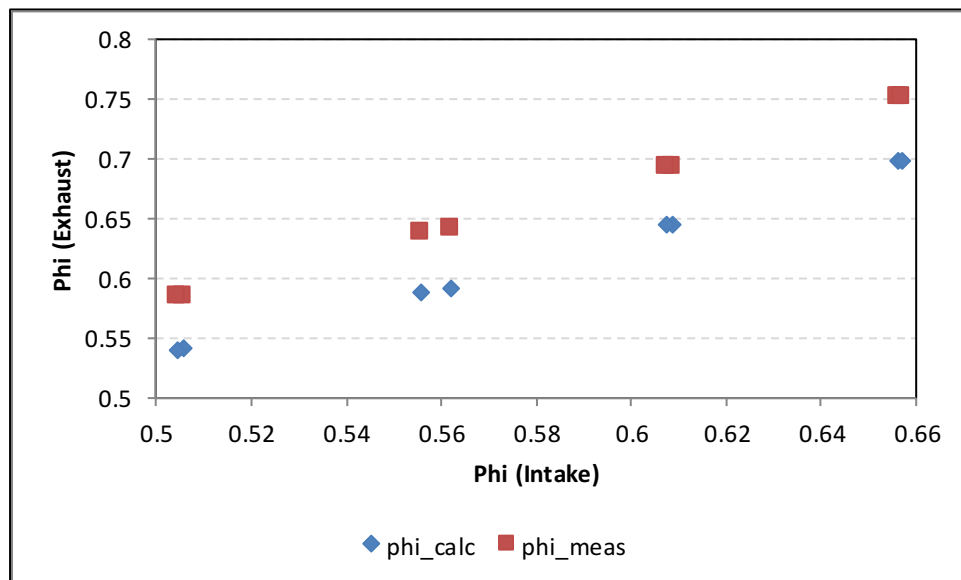


Figure 5.3: ϕ Values Comparison for 20% Hydrogen

Thermal efficiency was calculated using the following equation:

$$\eta = \frac{Power}{LHV_{fuel}} * 100 \quad \text{Eqn (5.1)}$$

η : Thermal efficiency

LHV: Lower Heating Value

Throughout the test, power was relatively constant at approximately 2.3kW with a maximum error of ± 9 W for a 95% confidence interval. This was expected since a constant NMEP of 1000 kPa was maintained for this testing. Brake thermal efficiency also remained relatively constant at approximately 26.6% with a maximum error of $\pm 0.1\%$ and no specific impact of increasing hydrogen percentage was seen (Figure 5.4).

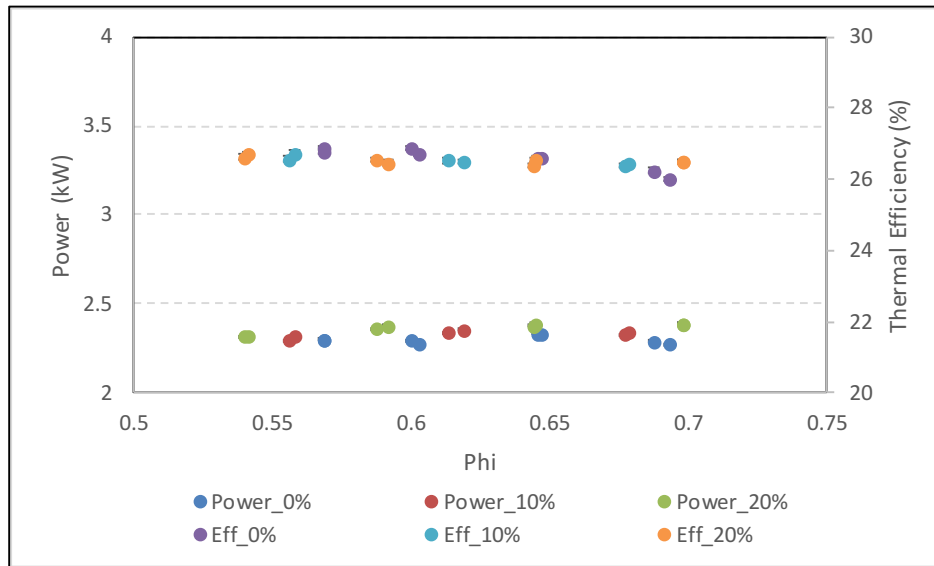


Figure 5.4: Effect of Hydrogen on Power and Efficiency

5.2 IMPACT ON EMISSIONS

It was observed from the results of constant spark ignition timing on the Cummins-Onan genset engine that NOx increased with increase in hydrogen percent, which was attributed to higher flame temperatures and faster flame speeds associated with

hydrogen. Hence, for this testing, it was decided to maintain location of peak pressure (LPP) constant by adjusting the spark ignition timing for higher percentages of hydrogen in an attempt to assess the impact on emissions.

Figure 5.5 shows the comparison of NO_x vs ϕ for different hydrogen blends. While NO_x values increased for all blends as air/fuel mixtures got richer due to increase in combustion temperatures, when comparing results for the different H₂-NG blends, reduced NO_x emissions were observed even at 20% hydrogen. The error calculations revealed reliable values with a maximum error of less than 10 ppm.

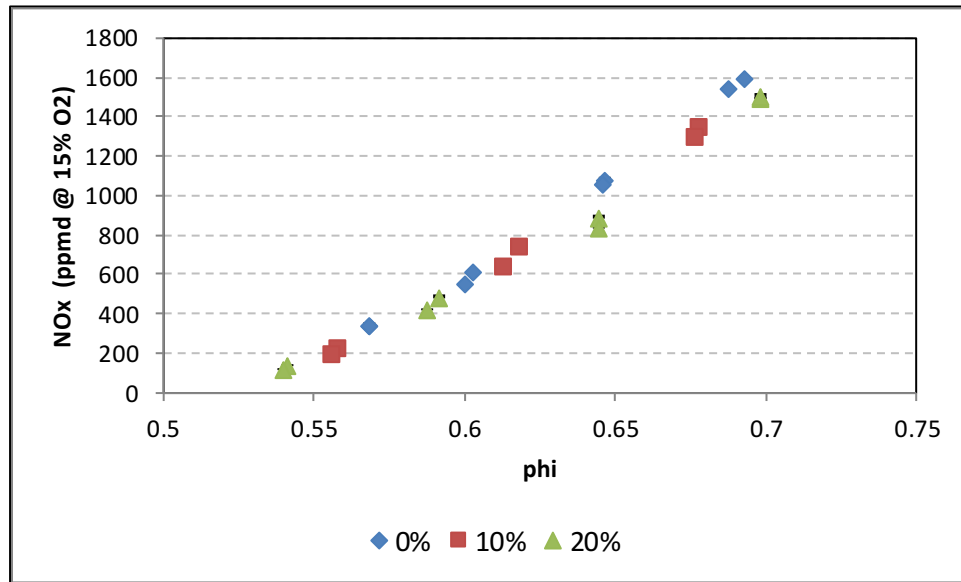


Figure 5.5: NO_x vs ϕ for different H₂ Blends

Thus, retarding spark ignition timing to achieve same location of peak pressure successfully offset the adverse effect of faster flame speeds and higher combustion temperatures of hydrogen, which can otherwise cause increased NO_x emissions. When comparing NO_x values at the lean limit for each blend, it was observed that NO_x emissions lower than the baseline could be achieved for 20% hydrogen. This is most likely a result of lower lean limit made possible by higher percentage of hydrogen, where

reduced NOx emissions are observed due to lower temperatures. An improvement of 35% over baseline when operating at the lean limit of 10% while a dramatic improvement of 60% over baseline when operating at the lean limit of 20% was observed in NOx emissions at 15% O₂ in exhaust. This can be seen in Figure 5.6.

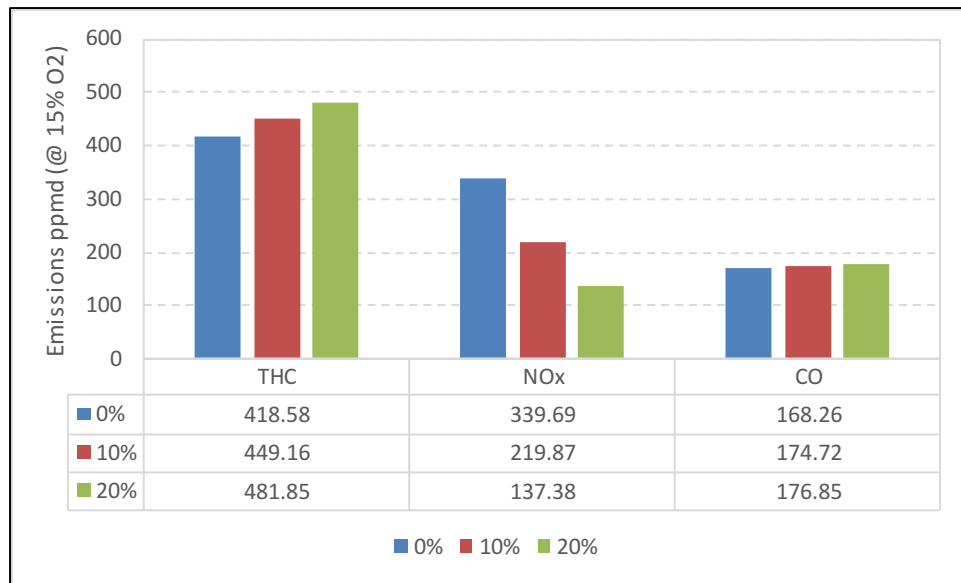


Figure 5.6: Comparison of Emissions at the Lean Limit:

Although CO and THC emissions increased as a result of operating at the lean limit due to combustion instability, this increase was not considerable, and was only observed when compared at the absolute lean limit operation with each blend. When compared with respect to same equivalence ratio, CO emissions were actually lower with 20% hydrogen blend for leaner mixtures despite the retarded spark ignition timing (Figure-5.7). This effect is possibly due to more misfire or incomplete combustion instances for 0% hydrogen at lean ϕ values, as indicated by higher COV. Results were comparable for higher ϕ values. Similar to NOx data, error values were low for CO data as well with a maximum error of 1 ppmd.

THC results also showed lower values for leaner mixtures at 20% hydrogen blend. Overall values tend to increase as air/fuel mixtures get leaner, same as CO, for all blends. This is most likely due to combustion instability and misfire typically observed in lean operation.

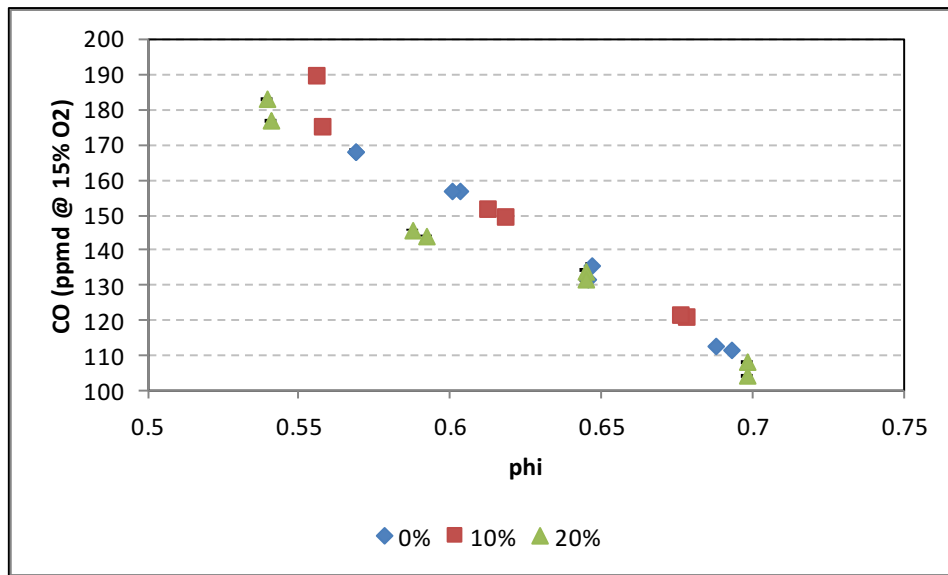


Figure 5.7: CO vs ϕ for different H₂ Blends

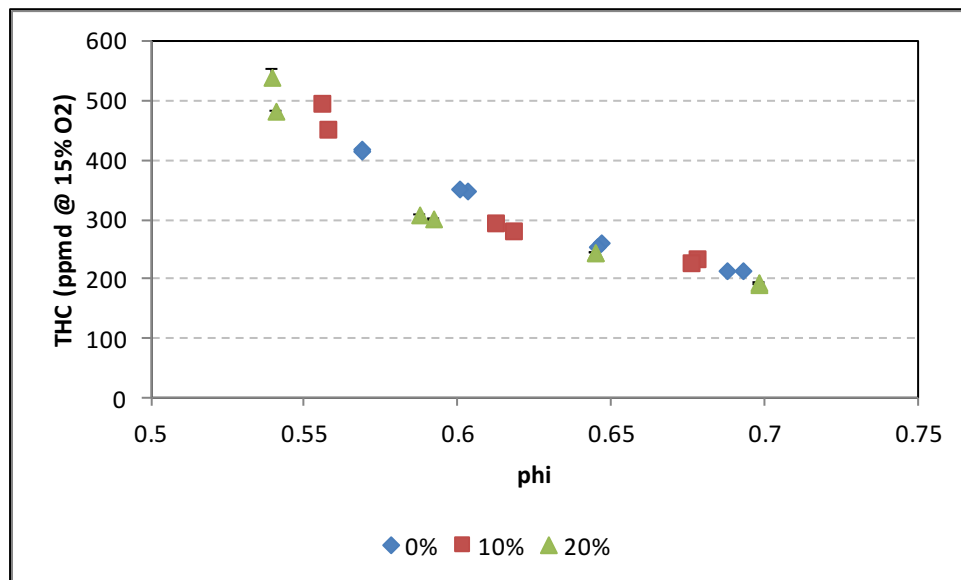


Figure 5.8: THC vs ϕ for different H₂ Blends

Presence of hydrogen may have helped with combustion at these lean mixtures, which is reflected in an improvement in CO and THC emissions. Additionally, as H₂ is added, carbon in the fuel decreases as CH₄ and C₂H₆ are displaced, which tends to decrease THC and CO emissions. Figure 5.8 presents THC values for the different blends.

5.3 IMPACT ON IGNITION TIMING

With location of peak pressure constant, for a given hydrogen blend, spark ignition timing had to be advanced as the air/fuel mixtures got leaner. This is because of increase in combustion duration expected with lean operation. Figure 5.9 shows the impact on ignition timing (IT).

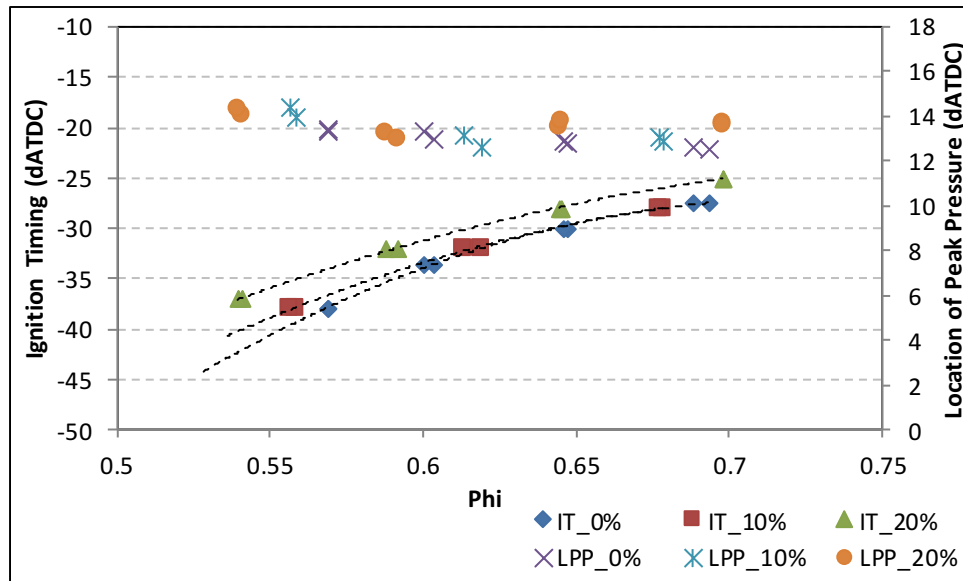


Figure 5.9: Impact of Hydrogen on Ignition Timing at Lean Operation

When comparing the different H₂-NG blends, it is observed that at a given ϕ , 20% hydrogen requires less spark advance compared to baseline (0% H₂). This can be attributed to faster flame speed of hydrogen. The effect is not as significant at 10%

hydrogen, although the trends do seem to diverge towards leaner mixtures, indicating impact of hydrogen becomes more pronounced for leaner mixtures. Location of peak pressure (LPP) was relatively constant at 13.35 ± 0.14 degrees ATDC, uncertainty calculated with a confidence interval of 95%.

Increase in combustion duration for leaner mixtures can also be seen in Figure 5.10, which presents ignition delay for the ϕ sweeps at different hydrogen percentages.

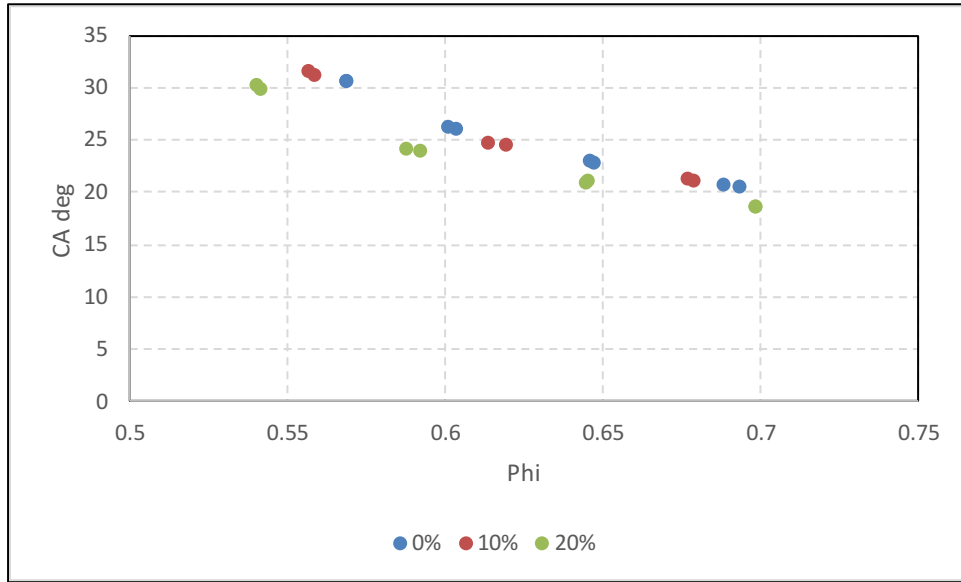


Figure 5.10: Ignition Delay vs ϕ for Different Hydrogen Blends

Ignition delay is calculated as the crank angle duration in degrees from start of ignition to 10% MFB (mass fraction burned). As can be seen in Figure 5.10, ignition delay increased for all hydrogen blends as the engine approached lean limit. Ignition delay for 20% hydrogen was found to be slightly lower at each ϕ value compared to baseline. This can be attributed to lower ignition energy required by hydrogen. Results for 10% H₂-NG blend and baseline, however, were similar.

Impact of faster flame speeds of hydrogen was also observed on the combustion rates, when comparing the different H₂-NG blends tested. Figures 5.11 and 5.12 compare

this impact of 20% H₂-NG blend on 0-50% MFB (mass fuel burned) and 50-90% MFB respectively. A clear improvement was observed for 20% hydrogen at all equivalence ratios in the 0-50% MFB combustion phase (Figure 5.11).

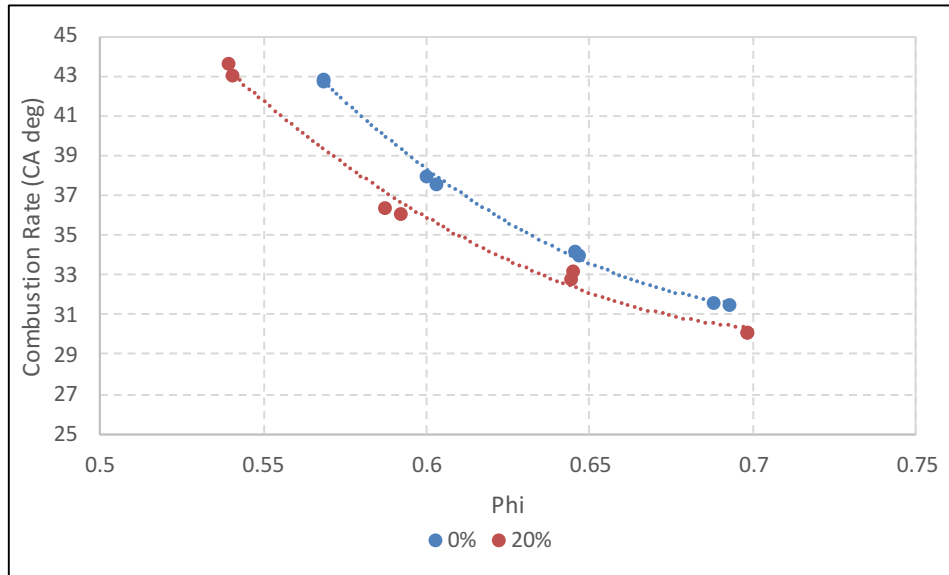


Figure 5.11: Impact of Hydrogen on 0-50% MFB

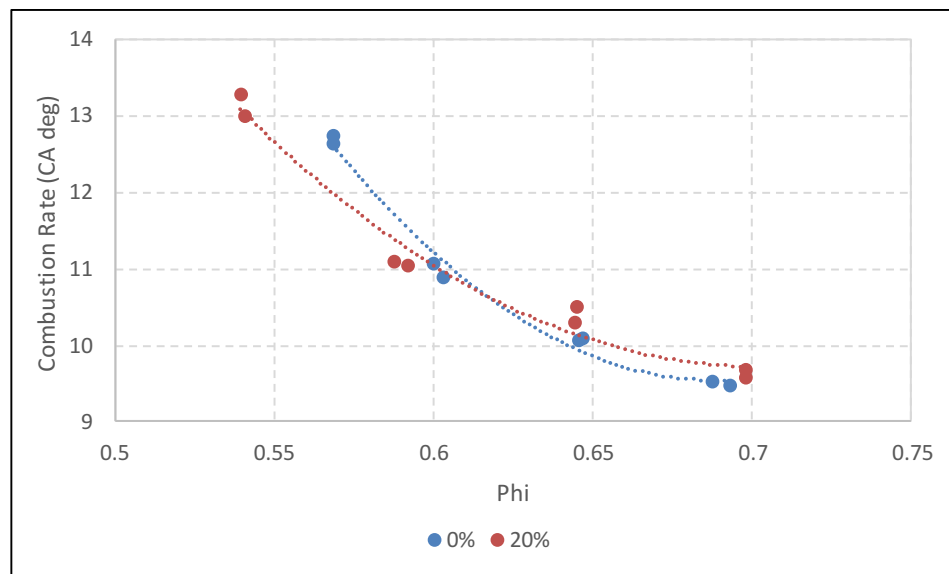


Figure 5.12: Impact of Hydrogen on 50-90% MFB

Results for impact on 50-90% MFB showed an interesting trend. While the results were comparable for higher equivalence ratios, the trends seemed to diverge towards the leaner limit, likely a result of improved combustion stability (Figure 5.12).

Thus, overall it was observed that higher percentage of hydrogen in the H₂-NG blend improved combustion when engine was operating in the leaner regime. The lean limit of the engine also improved by 5% when hydrogen percentage by volume was increased from 0 to 20%. This ability of the engine to operate at leaner equivalence ratios aids in reducing NO_x emissions. It was found that an improvement as high as 60% can be achieved over baseline when operating at a 20% hydrogen by volume H₂-NG blend.

6. SUMMARY AND CONCLUSIONS

The main objective of this work was to evaluate impact of blending hydrogen with natural gas for stoichiometric and lean burn spark ignited natural gas engines. Stoichiometric operation was evaluated on the 7.5 liter Cummins Onan genset engine equipped with exhaust treatment in the form of Non-Selective Catalytic Reduction (NSCR) catalyst. Two different combinations of carburetor/lambda sensor were tested. First the Electronic Gas Carburetor (EGC2) was tested with the wide band (UEGO) λ sensor, followed by GV1 (Gas Valve 1) carburetor testing with the narrow band (HEGO) λ sensor. Lambda sensor was installed upstream of the catalyst. Feedback of oxygen in the exhaust was given to the carburetor by the λ sensor. The carburetor then controlled the intake air/fuel ratio (AFR) to a given set point. Pre-catalyst and post-catalyst emissions were measured to evaluate effectiveness of the NSCR catalyst and carburetor control system.

Results show that engine-out NO_x emissions increase with increasing hydrogen percentage in fuel mainly due to higher flame temperatures. On the other hand, pre-catalyst CO and THC emissions reduce with increase in hydrogen percent due to reduced C/H ratio of fuel as well as more complete combustion. Impact of hydrogen is also seen on the post-catalyst NO_x and CO emissions, where NO_x increases while CO and THC decrease, primarily due to changes in pre-catalyst emissions. H₂ addition may also impact catalyst efficiencies, depending on the AFR control technique and the AFR set point.

Results from EGC2 testing showed that both NO_x and CO remained within compliance up to approximately 22%. Criteria for emissions considered for this testing

was South Coast Air Quality Management District Rule 1110.2 limits of 11 ppmd NO_x, 250 ppmd CO and 30 ppmd VOCs, corrected to 15% oxygen. This was because the AFR set point was chosen towards the rich limit of the compliance range. Assuming AFR set point is centered in the control window, hydrogen up to 10% by volume may be blended in with natural gas while staying within emissions limits. Below 10%, no significant impact is seen on emissions; however at higher percentages of hydrogen, NO_x values climb dramatically. This was seen from results on the GV1. With an AFR set point at the center of the rich and lean ends of the compliance window, an improvement is seen in catalyst efficiency for both CO and THC, without adversely affecting the efficiency for NO_x. NO_x reducing efficiency was more than 99% even at higher hydrogen levels. Formaldehyde was eliminated completely post-catalyst. VOCs were very low and well within emissions limits throughout the testing.

Impact of hydrogen on critical compression ratio and spark ignition timing was tested with the Cooperative Fuel Research (CFR) engine. The CFR can be run at various compression ratios (CR) from 4:1 to 18:1. The compression ratio can be adjusted while the engine is running. Knock measurement was done at different hydrogen blends by analyzing the combustion data for each blend. The signal from the in-cylinder pressure transducer and the crankshaft position from encoder together provide a detailed pressure trace for further analysis of combustion data. Knock analysis is done by FFT (Fast Fourier Transform) method using this data.

Results showed that critical compression ratio reduces with increasing hydrogen in the fuel, due to increased susceptibility to knock. The critical compression ratio decreased approximately 0.05 compression ratio units per 1% hydrogen. It was observed

that the frequency of high intensity knock events increases at higher percentages of hydrogen.

Although NO_x emissions tend to increase with increase in hydrogen percentage in fuel, this effect can be offset by retarded ignition timing. Impact of hydrogen on spark ignition timing was also tested on the CFR engine. Over 2 degrees retard in spark ignition timing was observed for 20% hydrogen compared to baseline, in order to achieve comparable location of peak pressure. Retarding ignition timing with increasing hydrogen helps achieve similar location of peak pressures due to faster flame speed of hydrogen, which aids in controlling NO_x emissions, without adversely affecting CO and THC emissions.

Apart from impact of H₂-NG blends on stoichiometric engine operation, lean burn engine testing was also performed to assess impact of increasing hydrogen levels on the lean limit of engine operation as well as emissions. It was observed that higher percentage of hydrogen in the H₂-NG blend improved combustion when engine was operating in the leaner regime. The lean limit of the engine improved by 5% when hydrogen percentage by volume was increased from 0 to 20%. This ability of the engine to operate at leaner equivalence ratios aids in reducing NO_x emissions. It was found that an improvement as high as 60% can be achieved in NO_x emissions over baseline when operating at a 20% hydrogen by volume H₂-NG blend. Lastly, it was seen that, similar to stoichiometric operation, increasing hydrogen required retarded spark ignition timing even at lean burn operation, to achieve location of peak pressure comparable to baseline. To summarize answers to the research questions:

- a) It was observed that 10% hydrogen could be blended in with natural gas, while complying with emissions limits as per South Coast AQMD rule 1110.2 for this test setup.
- b) The critical compression ratio decreased approximately 0.05 compression ratio units per 1% hydrogen.
- c) An improvement of 5% was observed in lean limit when hydrogen percentage by volume was increased from 0 to 20%.
- d) Operating at lean limit with retarded spark ignition timing resulted in an improvement as high as 60% in NO_x emissions over baseline when operating at a 20% hydrogen by volume H₂-NG blend.

Thus, it is seen that overall blending hydrogen with natural gas may have significant benefits. There are a few concerns that need to be addressed in order to implement this in practice. Safety is one of the main concerns. Adding hydrogen to natural gas in pipelines increases the risk factor because of increased probability of ignition and subsequent damage. Another important consideration is leakage. Permeation rates for hydrogen are about 4 to 5 times than for methane for pipes used in US natural gas network^[4]. If these concerns are addressed, H₂-NG blends may prove to be a viable strategy for increasing use of renewable energy.

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APPENDIX I – EXPERIMENTAL SETUP

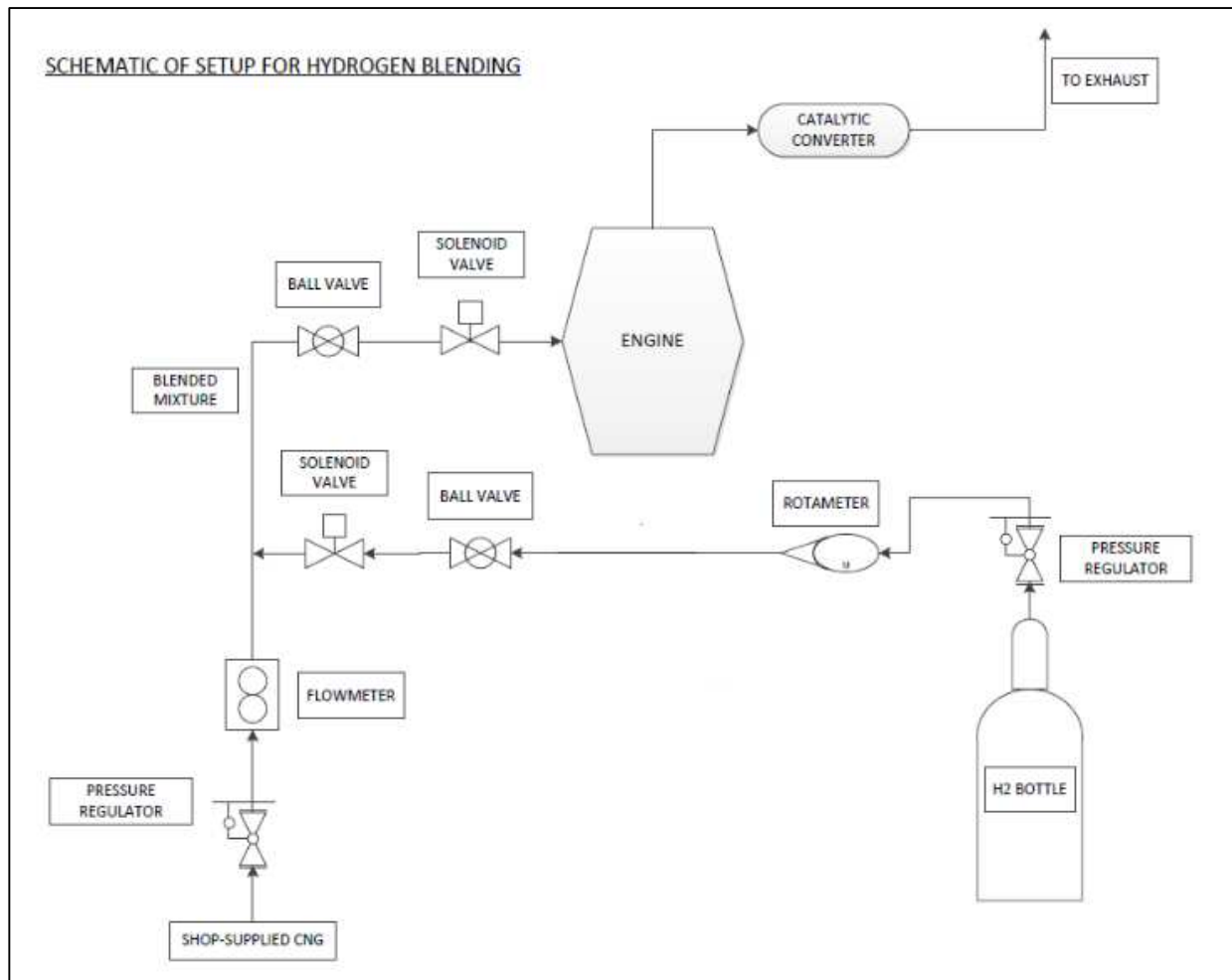


Figure 1: Schematic of Setup for Hydrogen Blending

APPENDIX II – EXPERIMENTAL HARDWARE

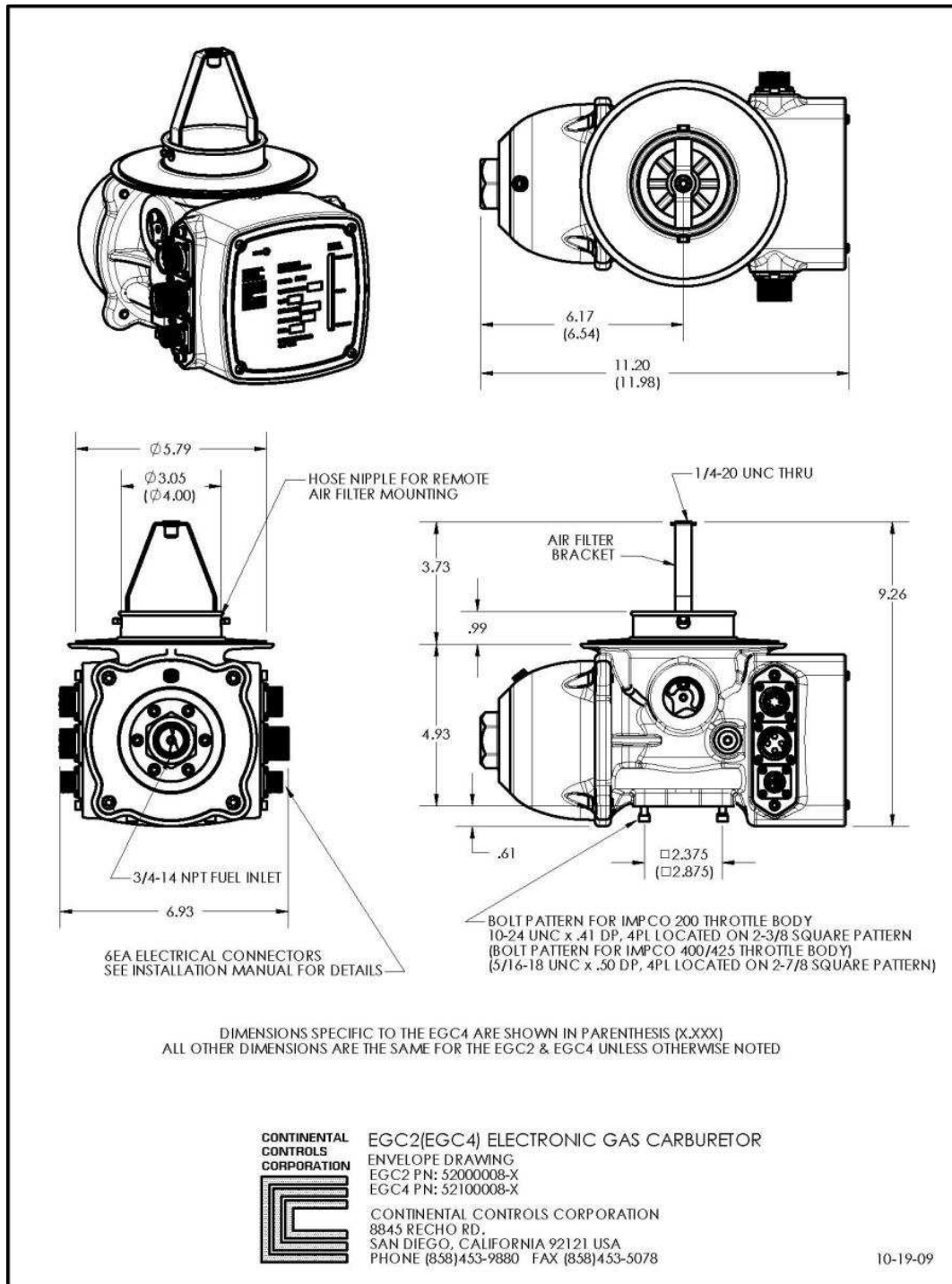
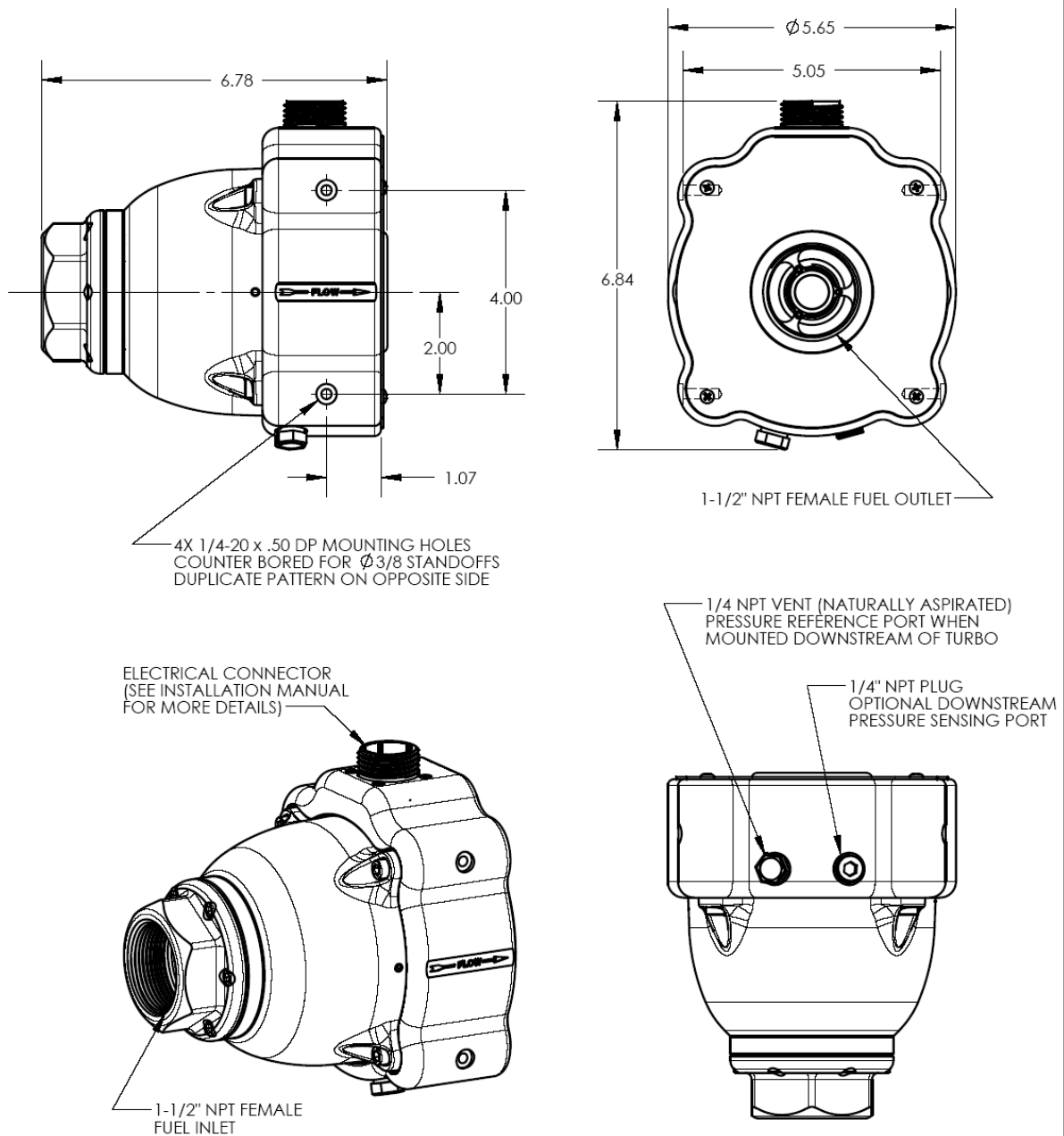
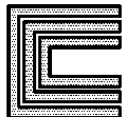


Figure 3: EGC2



CONTINENTAL
CONTROLS
CORPORATION



GV1 GAS VALVE
ENVELOPE DRAWING
PN: 52600008-XX

CONTINENTAL CONTROLS CORPORATION
8845 RECHO RD.
SAN DIEGO, CALIFORNIA 92121 USA
PHONE (858)453-9880 FAX (858)453-5078

10-11-11

Figure 4: GV1

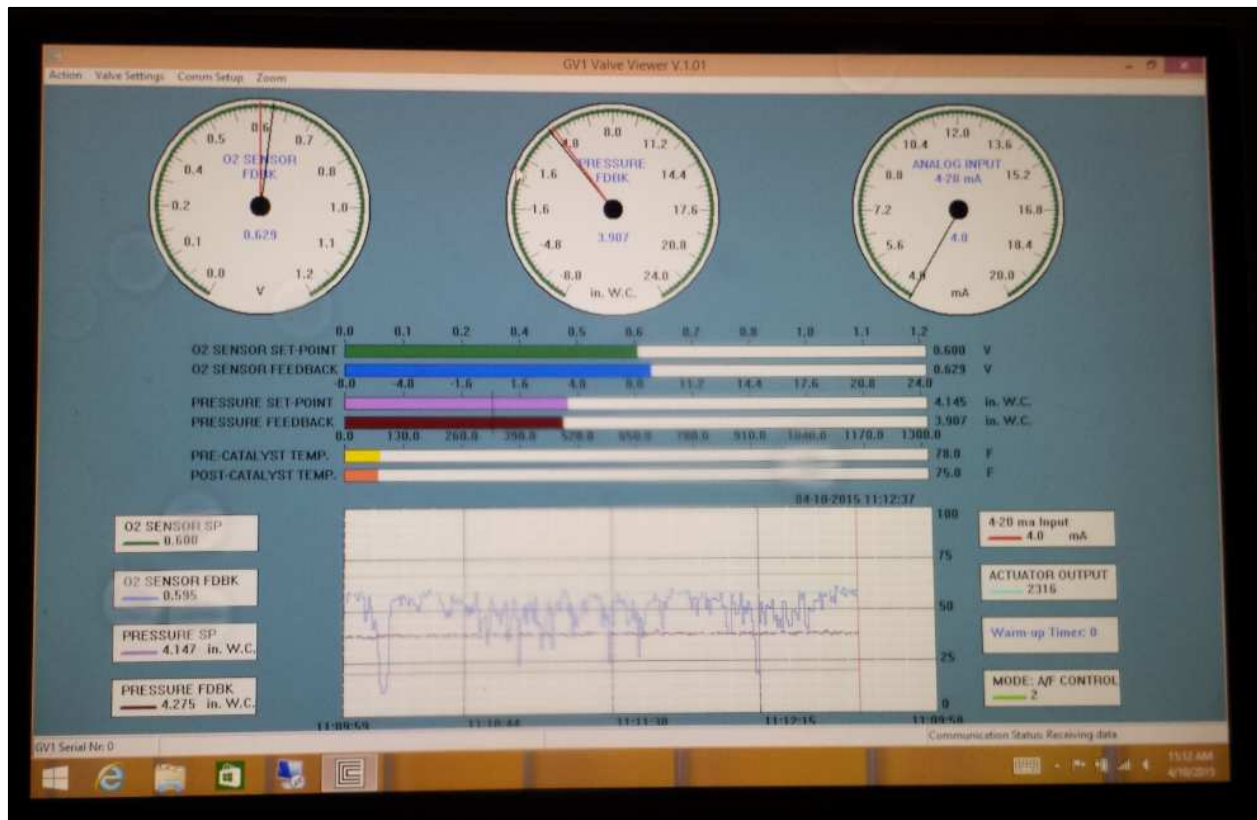


Figure 5: GV1 Valve Viewer Software

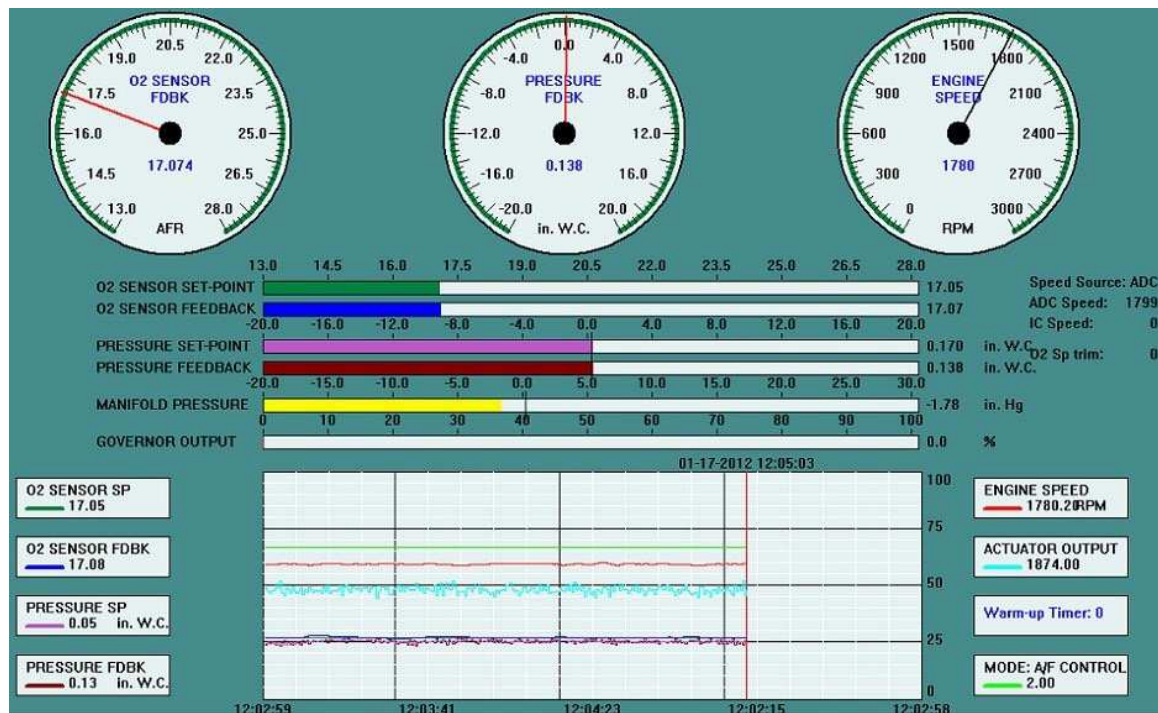


Figure 6: EGC2 Valve Viewer Software

Rotameters with 150 MM Flowtubes

Model No. Aluminum Frame	Price	Model No 316 SS Frame	Price	Max Flow Rate* (cc/min)	
				Air	Water*
FL-3845G	\$139	FL-3945G	\$249	25.3	.32
FL-3845ST	139	FL-3945ST	249	75.5	1.25
FL-3845C	139	FL-3945C	249	132.2	2.25
FL-3841G	139	FL-3941G	249	48.5	.53
FL-3841ST	139	FL-3941ST	249	141.5	2.45
FL-3841G	139	FL-3961G	249	92	.85
FL-3861SA	139	FL-3961SA	249	140	1.92
FL-3861ST	139	FL-3961ST	249	263	4.7
FL-3861C	139	FL-3961C	249	454	8.5
FL-3802G	139	FL-3902G	249	374	5.5
FL-3802ST	139	FL-3902ST	249	814	20.4
FL-3802C	139	FL-3902C	249	1222	33.7
FL-3803G	139	FL-3903G	249	825	16.5
FL-3803ST	139	FL-3903ST	249	1682	45.9
FL-3804G	139	FL-3904G	249	2313	53.5
FL-3804G	139	FL-3904ST	249	4562	130
FL-3805G	139	FL-3905G	249	3800	84
FL-3805ST	139	FL-3905ST	249	7590	215
FL-3839G	139	FL-3939G	249	9229	215
FL-3839ST	139	FL-3939ST	249	17,430	521
FL-3840G	149	FL-3940G	259	23,121	558
FL-3840ST	149	FL-3940ST	259	42,650	1319
FL-3840C	149	FL-3940C	259	63,024	1903

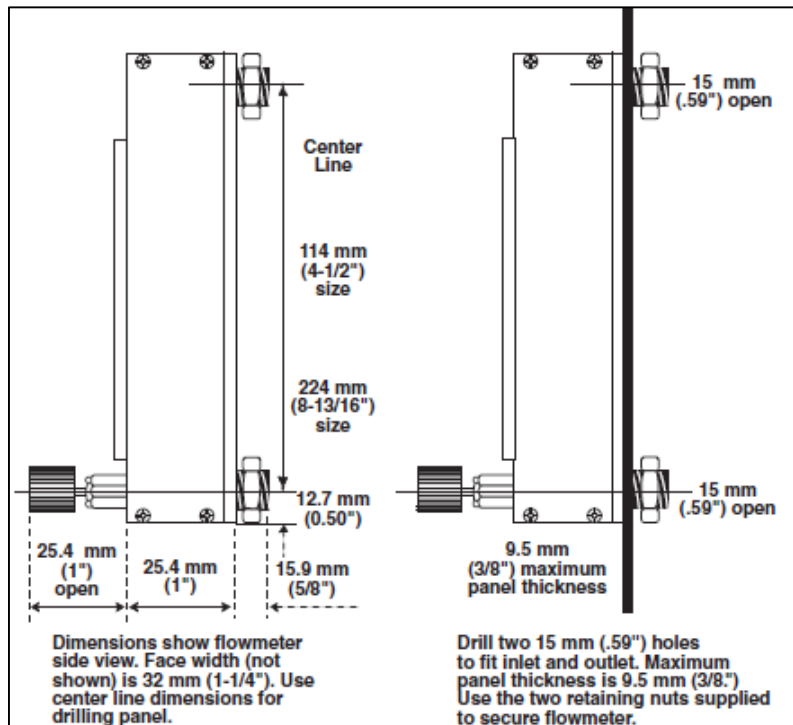


Figure 7: FL3840C - Rotameter for Hydrogen

Model No.	Range Air (SCFM)	Range Water (GPM)	Pressure Drop (H ₂ O)
FL-1501A	0.317 to 3.17	0.078 to 0.78	4"
FL-1502A	0.588 to 5.88	0.145 to 1.45	11"
FL-1503A	1.045 to 10.45	0.253 to 2.53	7"
FL-1504A	2.576 to 25.76	0.628 to 6.28	13"

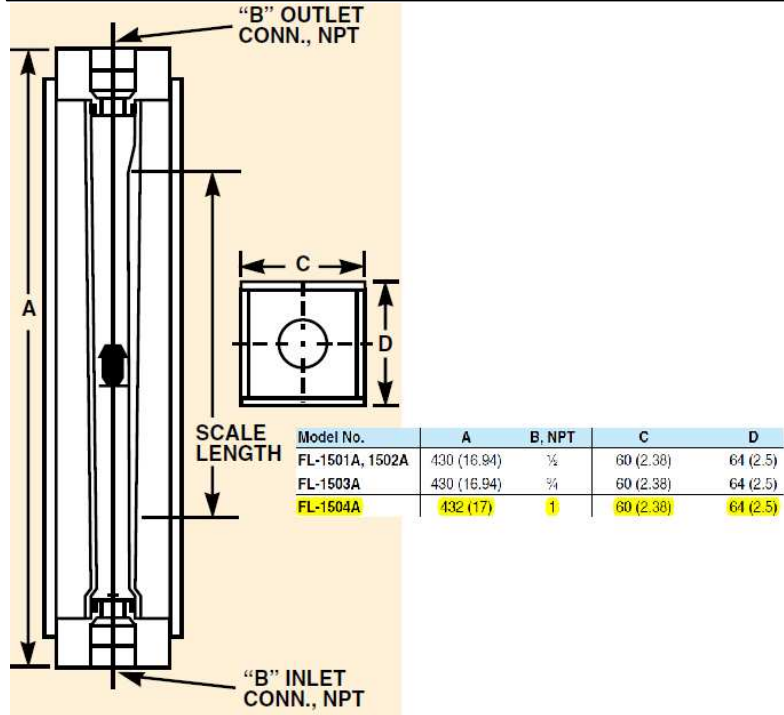


Figure 8: FL1504A - Flowmeter for NG

APPENDIX III – DATA

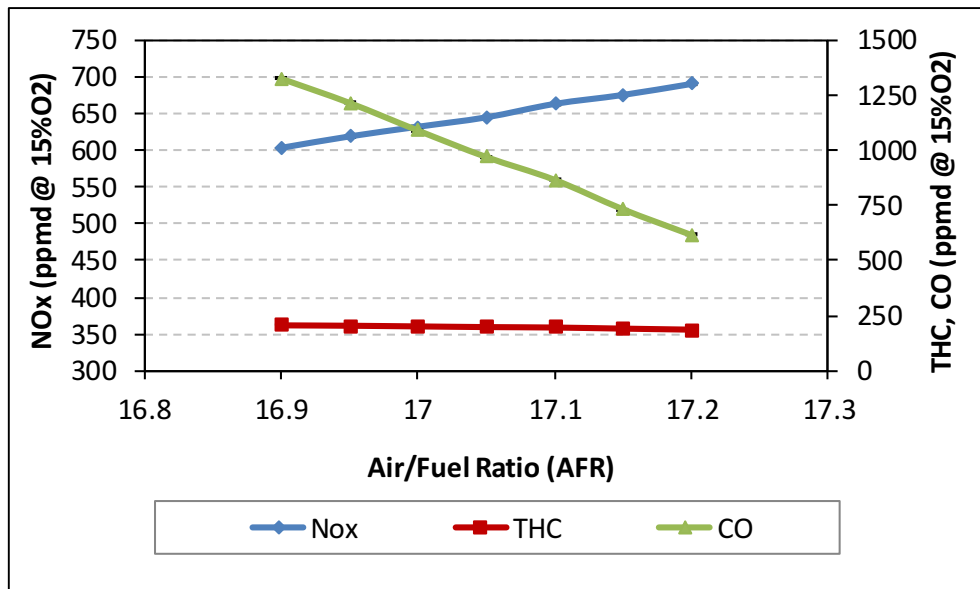


Figure 9: EGC2 AFR Sweep - Pre-Catalyst Emissions

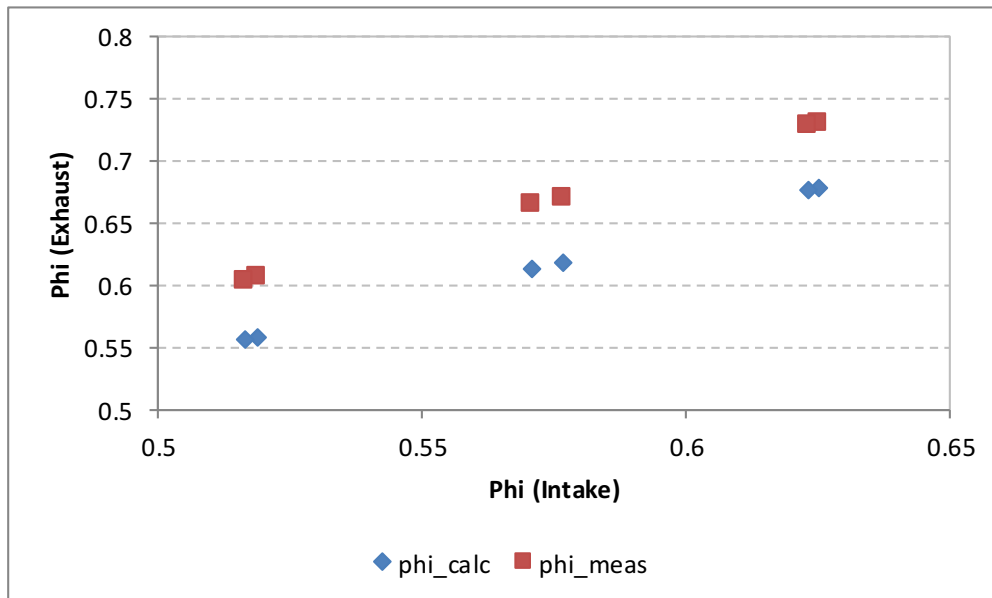


Figure 10: ϕ Values Comparison for 10% Hydrogen

EGC2 AFR SWEEP DATA								
POST-CATALYST								
AFR	16.85	16.875	16.9	16.925	16.95	17	17.05	17.1
THC	150.0193	128.9909	116.0577	101.4082	125.0876	98.03268	55.38416	70.13004
Nox	14.58035	5.369476	4.436789	3.605046	8.742909	4.86733	15.00123	197.2262
CO	620.058	384.5138	285.0065	198.8776	240.6296	97.80315	10.3611	2.4339
THC_err	1.114861	2.33695	2.576894	2.441962	1.217158	1.986227	1.705291	1.362748
Nox_err	0.261152	0.261526	0.27954	0.191544	0.195669	0.210727	3.19624	9.833599
CO_err	14.85095	16.99337	15.22867	11.13415	6.74979	4.673256	0.480025	0.015133
PRE-CATALYST								
AFR	16.9	16.95	17	17.05	17.1	17.15	17.2	
THC	205.527	203.8051	200.7471	197.6705	195.6744	190.7024	186.0009	
Nox	603.7476	619.3531	632.5325	645.4003	663.7044	675.9387	690.9316	
CO	1328.203	1217.688	1092.298	971.6887	867.8534	734.0015	617.1369	
THC_err	0.214349	0.202231	0.222032	0.245078	0.234587	0.245591	0.217646	
Nox_err	0.669336	0.671642	0.726574	0.790629	1.058121	0.681062	0.791267	
CO_err	6.634437	6.301379	6.303306	6.90723	7.926129	5.444497	5.273895	
CATALYST EFFICIENCY								
AFR	16.9	16.95	17	17.05	17.1			
THC	43.53165	38.62389	51.16607	71.98157	64.15984			
Nox	99.26513	98.58838	99.2305	97.67567	70.28402			
CO	78.54195	80.23881	91.04611	98.9337	99.71955			
THC_err	1.258947	0.606616	0.997188	0.876115	0.710854			
Nox_err	0.162927	0.155525	0.165217	0.524004	1.494383			
CO_err	1.310735	0.864562	0.889998	1.001165	1.289797			

AFR	Post Cat Temp	Pre Cat Temp
16.85	1182.991571	1105.412241
16.875	1188.012905	1106.353167
16.9	1188.499042	1106.677337
16.925	1191.830397	1107.388937
16.95	1190.716873	1107.29477
17	1193.637238	1107.486693
17.05	1184.992714	1092.902005
17.1	1187.562567	1105.808578

EGC2 H2 SWEEP DATA								
POST-CATALYST								
H2 %	Limits	0	1.720598	4.901765	8.060091	15.28725	21.90753	22.4
NOx	11	3.604722	4.431262	4.020832	3.955124	5.063077	4.837601	5.548812
THC		101.3991	109.8064	110.4713	109.3617	104.8525	103.3211	102.3842
CO	250	198.8597	230.3271	206.5544	211.5174	187.1717	175.922	175.8156
Nox_err		0.191527	0.242808	0.199951	0.239712	0.182456	0.131701	0.193366
THC_err		2.441743	2.416003	2.404391	2.572659	2.406498	1.990104	2.148357
CO_err		11.13315	12.41821	12.17817	12.42352	10.74309	8.913331	11.18713
VOC	30	2.412416	3.042014	2.827387	3.014424	3.209782	3.500963	3.487188
NH3		0.984487	1.01991	0.933289	0.934077	0.917115	0.957955	0.983159
CH2O		0	0	0	0	0	0	0
PRE-CATALYST								
NOx		665.7307	673.8577	683.841	707.7405	742.1181	777.9662	
THC		187.6796	186.8235	185.7014	182.8673	178.4076	172.5665	
CO		1256.302	1239.554	1251.774	1236.107	1230.231	1206.392	
Nox_err		1.961419	1.396308	1.555924	2.725727	2.047037	1.556497	
THC_err		0.379344	0.477931	0.462476	0.479073	0.391749	0.364538	
CO_err		12.73282	14.68323	14.96416	15.32361	13.40205	12.19726	
VOC		19.18426	19.39925	19.28526	19.04341	18.57588	18.09237	
NH3		0.070432	0.032931	0.023399	0.018985	0.014781	0.012479	
CH2O		4.217368	4.227882	4.189967	4.19271	4.106059	3.988355	
CATALYST EFFICIENCY								
NOx		99.45853	99.3424	99.41202	99.44116	99.31775	99.37817	
THC		45.97223	41.22451	40.51133	40.19612	41.22868	40.12681	
CO		84.17102	81.41854	83.49907	82.88843	84.78565	85.41751	
Nox_err		0.416533	0.294293	0.322157	0.544192	0.389541	0.282574	
THC_err		1.319899	1.322472	1.32235	1.434899	1.369627	1.175487	
CO_err		1.59383	1.826746	1.836275	1.898089	1.674062	1.521166	
VOC		87.42502	84.31891	85.33913	84.17078	82.7207	80.6495	
CH2O		100	100	100	100	100	100	

H2 %	Post Cat	Pre Cat
0	1191.83	1107.389
1.720598	1191.762	1108.152
4.901765	1191.141	1107.107
8.060091	1189.603	1105.463
15.28725	1187.307	1101.861
21.90753	1184.144	1098.77
22.4	1180.1	1094.495

		GV1 PHI SWEEP DATA												
POST-CATALYST														
O2 Setpoi	Limits	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.72	0.725	0.73	0.74	0.75	0.8
NOx	11	727.1362	694.9984	677.4388	661.6074	618.8627	531.2007	68.77735	4.634782	4.023291	3.742366	4.139476	6.426203	35.81643
THC		133.0866	140.3116	143.3176	146.5653	148.1683	143.363	81.58333	110.3892	115.5371	137.4706	158.5022	176.5667	199.5728
CO	250	2.111071	2.402471	2.606087	2.807927	3.048118	3.285332	4.043147	46.23454	56.471	76.78231	143.4476	323.4332	1872.578
Nox error		0.97829	0.882435	0.961287	1.301046	4.084539	10.53797	10.67813	0.539102	0.360972	0.118303	0.0893	0.078875	0.195637
THC error		0.351897	0.303881	0.259722	0.20049	0.157696	0.677004	2.609274	3.646478	3.072976	2.41291	1.822991	0.474721	0.222984
CO error		0.007943	0.009714	0.010402	0.010944	0.018403	0.021395	0.261861	4.743279	5.367161	5.149183	9.083864	16.07854	20.02226
VOC	30	6.756091	7.068635	7.233012	7.363654	7.35931	7.206987	4.806417	5.474684	6.488562	7.088438	8.007607	9.641987	15.5828
NH3		8.029459	5.072404	3.37923	2.552602	2.040498	1.652161	1.477078	19.02296	7.993229	30.87726	29.6278	30.63171	83.81812
HCHO		0	0	0	0	0	0	0	0	0	0	0	0	0
PRE-CATALYST														
		0.6	0.7	0.71	0.725	0.74	0.8							
NOx		779.6326	758.4329	746.7365	738.7619	716.5095	593.3636							
THC		179.3615	187.6238	189.0966	191.7576	196.1129	207.3246							
CO		500.1066	713.7316	785.364	871.5799	1100.219	2272.652							
Nox error		0.790804	1.03813	1.202823	0.865548	1.252469	1.785716							
THC error		0.294373	0.279092	0.332975	0.205288	0.215678	0.166478							
CO error		6.689615	10.29532	13.51464	10.1218	14.58954	11.70406							
VOC		23.23923	23.19493	23.42754	23.27839	23.19537	24.35176							
NH3		0	0	0	0	0	0							
HCHO		3.713556	3.335677	3.231364	3.116169	2.928852	2.50286							
CATALYST-EFFICIENCY														
		0.6	0.7	0.725	0.74	0.8								
NOx		31.86524	90.93165	99.4554	99.42227	93.96383								
THC		20.07037	56.51761	39.74834	19.17811	3.738976								
CO		99.34307	99.43352	93.52085	86.9619	17.60387								
Nox error		1.355844	1.420024	0.172314	0.246808	0.414274								
THC error		0.412906	1.401152	1.606667	0.936282	0.134255								
CO error		1.885507	2.034514	1.705115	1.941624	1.024507								
VOC		68.98784	79.27816	72.12624	65.47756	36.00958								
HCHO		100	100	100	100	100								

GV1 H2 SWEEP DATA								
POST-CATALYST								
H2 %	Limits	0	1.062576	1.944441	5.084465	9.921897	14.89409	19.92161
NOx	11	4.023291	4.914077	4.854667	4.588878	4.909228	23.13229	13.68726
THC		115.5371	114.0984	111.7379	108.8782	91.83481	73.07544	62.77736
CO	250	56.471	61.56589	63.22272	58.20774	51.52386	15.50601	13.10178
Nox_err		0.360972	0.626931	0.537797	0.523506	0.477049	6.635067	2.532484
THC_err		3.072976	3.424607	3.299459	3.646382	3.182013	2.686269	2.509287
CO_err		5.367161	6.467583	6.173452	5.790635	6.061856	1.757364	1.207347
VOC	30	9.209361	8.91943	15.38714	7.842038	6.398984	5.147714	4.110373
NH3		7.993229	16.70618	13.91599	11.84841	11.34134	10.99652	6.708802
CH2O		0	0	0	0	0	0	0
PRE-CATALYST								
NOx		711.5945	726.2201	733.7949	755.6799	794.7014	840.1396	878.3776
THC		195.5901	194.3635	194.5674	191.4691	186.2721	179.5733	170.596
CO		856.6631	836.7175	892.6592	859.3131	844.447	766.778	714.0995
Nox_err		1.466572	1.015849	1.147433	1.556593	1.318014	1.180359	1.321406
THC_err		0.319008	0.230779	0.219855	0.309296	0.266384	0.227044	0.22155
CO_err		17.7518	14.68318	15.31642	18.65358	16.9996	13.40348	14.52817
VOC		30.74685	57.99083	30.06623	29.5883	29.03101	28.27095	26.8689
NH3		13.52793	6.535464	4.578283	3.080015	7.802396	4.331796	2.475264
CH2O		2.299414	2.652598	2.81658	3.333054	3.334816	3.082794	2.892616
CATALYST EFFICIENCY								
NOx		99.43461	99.32334	99.33842	99.39275	99.38226	97.24661	98.44176
THC		40.92894	41.29638	42.57109	43.13536	50.69857	59.30607	63.20116
CO		93.40803	92.64197	92.91749	93.22625	93.89851	97.97777	98.16527
Nox_err		0.295035	0.215226	0.232275	0.298573	0.241407	0.81371	0.357334
THC_err		1.580984	1.766636	1.700233	1.912531	1.715769	1.503123	1.478896
CO_err		2.903983	2.513962	2.44215	3.043302	2.85325	2.457924	2.855919
VOC		70.04779	84.61924	48.82251	73.49615	77.95811	81.79151	84.70212
CH2O		100	100	100	100	100	100	100

H2 %	Post Cat	Pre Cat
0.00	1181.353	1109.286
1.06	1180.987	1108.346
1.94	1179.25	1108.207
5.08	1177.362	1106.538
9.92	1175.676	1104.436
14.89	1175.629	1099.698
19.92	1169.731	1100.692

CFR LEAN BURN TESTING DATA															15% O2				
Datapt	H2 %	phi	Power (kW)	Speed	Methane	CH4 [%]	H2 [lpm]	H2 [%]	C2H6 Flow	C2H6 [%]	Air Flow [	AFR flwr	AFR mea	Efficiency	O2	THC	NOx	CO2	CO
9_1	0	0.568438	2.297653	944.3391	12.94867	0.90263	0	0	1.396814	0.09737	280.9486	32.47747	27.24661	26.79043	9.277742	418.58	339.69	2.950736	168.26
9_2	0	0.568594	2.301705	944.144	12.93159	0.902823	0	0	1.391913	0.097177	280.4326	32.47271	27.24089	26.88268	9.275136	415.32	341.60	2.95221	167.91
10_1	0	0.603018	2.280835	944.0705	12.91261	0.903866	0	0	1.37337	0.096134	263.8062	30.65394	25.78396	26.7294	8.523061	347.93	609.86	2.949195	157.18
10_2	0	0.600316	2.294079	944.2794	12.90732	0.903836	0	0	1.373285	0.096164	264.7666	30.77635	25.86124	26.89412	8.58544	351.88	549.77	2.950461	156.88
11_1	0	0.646914	2.331964	944.6661	13.17057	0.89981	0	0	1.466482	0.10019	252.1797	28.50512	24.14831	26.59374	7.546133	260.45	1084.20	2.943938	135.80
11_2	0	0.645608	2.329833	944.5871	13.15583	0.900264	0	0	1.457475	0.099736	252.2919	28.57476	24.18729	26.62148	7.571283	253.62	1054.86	2.944181	132.04
8_4	0	0.693078	2.273523	943.7765	13.18725	0.902331	0	0	1.427402	0.097669	235.5247	26.71847	22.61854	26.01512	6.511983	213.93	1591.81	2.934138	111.84
8_5	0	0.687811	2.289355	943.9044	13.16569	0.902433	0	0	1.423421	0.097567	237.1281	26.94973	22.76675	26.24411	6.626922	215.55	1541.45	2.934932	113.01
13_2	10	0.558343	2.314039	944.6604	12.70613	0.815423	1.503442	0.096484	1.372693	0.088093	285.516	33.22982	28.46147	26.71379	9.617859	449.16	219.87	2.920553	174.72
13_3	10	0.55625	2.29553	944.5808	12.68022	0.816473	1.480038	0.095299	1.370218	0.088228	286.2017	33.38171	28.58902	26.56345	9.675803	491.19	191.06	2.919299	189.34
14_2	10	0.61872	2.356858	944.4895	13.0134	0.810689	1.6239	0.101163	1.414969	0.088148	264.0631	29.95559	25.75296	26.49784	8.284781	278.15	734.63	2.91322	149.30
14_3	10	0.613232	2.335691	944.3896	12.86523	0.810254	1.604709	0.101065	1.408081	0.088681	263.9214	30.25088	25.9719	26.53497	8.408873	292.36	638.02	2.915321	151.50
12_4	10	0.678367	2.336368	944.2826	12.92383	0.81308	1.544483	0.097168	1.426594	0.089752	242.1222	27.60075	23.62063	26.41918	6.976911	230.14	1337.96	2.91872	120.51
12_5	10	0.67695	2.326481	944.1179	12.85744	0.813201	1.510522	0.095537	1.442931	0.091262	242.1275	27.67069	23.67175	26.38534	7.006709	226.34	1293.06	2.921055	121.12
5_2	20	0.540888	2.321068	944.1686	12.26544	0.720373	3.422278	0.200997	1.338789	0.07863	293.2479	34.73848	30.03977	26.6908	10.10014	481.85	137.38	2.861461	176.85
5_3	20	0.539605	2.314427	944.1094	12.26607	0.720514	3.421474	0.200979	1.336516	0.078507	293.9081	34.8253	30.07282	26.62067	10.14479	538.42	120.43	2.858779	182.98
6_1	20	0.587584	2.357385	944.7477	12.77992	0.726382	3.608741	0.205113	1.20527	0.068505	272.6153	31.70152	27.5943	26.54939	9.057327	307.99	421.66	2.846447	145.79
6_2	20	0.591859	2.375633	944.7572	12.6487	0.719678	3.538538	0.201334	1.388255	0.078988	272.8187	31.30806	27.43429	26.46362	8.965515	300.21	484.82	2.85465	144.07
7_1	20	0.64457	2.374679	944.2547	12.77897	0.725984	3.472054	0.19725	1.351245	0.076765	252.4892	28.8792	25.33753	26.38045	7.821925	245.07	888.78	2.855853	134.21
7_2	20	0.644932	2.385031	944.3833	12.77821	0.726625	3.47002	0.197321	1.337466	0.076054	252.6578	28.94825	25.38388	26.53809	7.857069	243.91	839.26	2.880565	131.63
4_3	20	0.698103	2.389163	944.9462	12.70861	0.721141	3.52468	0.200006	1.389623	0.078853	234.5096	26.80801	23.41827	26.51876	6.612668	191.35	1498.75	2.844794	104.40
4_4	20	0.698146	2.38676	944.7277	12.71201	0.721385	3.524881	0.200031	1.384784	0.078584	234.1874	26.7809	23.41369	26.50059	6.612526	193.58	1504.86	2.84418	108.45

CFR STOICHIOMETRIC TESTING DATA													
H2 %	Avg. Peak	Peak COV	Max Peak	Min Peak	Avg. LPP	Peak Loc. CO	AVG IMEP	IMEP COV	AVG NMEP	NMEP COV	MFB 10%	MFB 50%	MFB 90%
0.00	6746.40	2.61	7190.91	6089.91	11.47	11.72	1034.45	1.58	1011.89	1.64	-4.84	5.34	15.07
0.00	6733.73	2.56	7148.72	6027.11	11.56	11.45	1034.71	1.52	1012.22	1.57	-4.82	5.43	15.08
10.07	6678.15	2.29	7082.07	5822.95	11.36	11.35	1044.85	1.08	997.82	1.19	-4.94	5.02	15.20
10.08	6680.64	2.30	7098.81	5842.60	11.27	11.39	1043.00	1.15	995.48	1.22	-4.98	4.96	14.87
15.09	6746.37	2.30	7197.67	6181.68	11.24	11.59	1045.85	1.08	1003.82	1.18	-5.00	4.76	11.97
15.12	6751.07	2.28	7169.01	6137.25	11.26	11.54	1048.08	1.05	1005.73	1.16	-5.03	4.76	11.95

CFR ENGINE KNOCK DATA						
H2 %	min ki	avg ki	max ki	no. of > 20 cycles	avg no. of cycles betn >100 cycles	% cycles > 20
0.00	0.36	16.72	319.47	380	116.58	26.95
0.00	0.35	15.92	129.14	360	127.27	25.53
10.07	0.43	16.61	301.93	361	92.4	25.60
10.08	0.39	17.77	175.26	401	86.56	28.44
15.09	0.4	17.23	298.54	366	62.68	25.96
15.12	0.46	17.14	212.64	373	72.74	26.45

Table 1: Measured CO₂ emissions^[13]

	CO ₂ g/km	ΔCO ₂ %	kgCO ₂ /kg _{fuel}
CH ₄	833.32	0	2.71
Hy 5%	782.06	-6.2	2.67
Hy 5% 1 deg	769.68	-7.6	2.69
Hy 10%	734.44	-11.9	2.65
Hy 15%	691.75	-17.0	2.65
Hy 20%	671.00	-19.5	2.62
Hy 25%	640.86	-23.1	2.60

Table 2: Theoretical CO₂ emissions^[13]

H ₂ %	CO ₂ g/Wh _{fuel}	ΔCO ₂ %
0	0.198	0
5	0.195	-1.55
10	0.192	-3.22
15	0.188	-5.03
20	0.184	-6.98
25	0.180	-9.09

Table 3: Operating Parameters^[13]

H ₂ %	
0%	No change in setup for NG
5%	As the NG mapping
5%	1 of delay for all load
10%	1 of delay for all load
15%	Partial load: no change with load < 50% and advance > 29 degrees
	75% > load > 50%: 2 degrees of delay Full load: 3 degrees of delay
20%	As 15% blend
25%	4 of delay for all the loads

LIST OF ABBREVIATIONS

AFR	–	Air/Fuel Ratio
AQMD	–	Air Quality Management District
ATDC	–	After Top Dead Center
BSE	–	Brake Specific Emissions
BSFC	–	Brake Specific Fuel Consumption
BTDC	–	Before Top Dead Center
CCC	–	Continental Controls Corporation
CFR	–	Cooperative Fuel Research
CH ₂ O	–	Formaldehyde
CH ₄	–	Methane
CLD	–	Chemi-Luminescence Detector
CNG	–	Compressed Natural Gas
CO	–	Carbon Monoxide
CO ₂	–	Carbon Dioxide
EGC2	–	Electronic Gas Carburetor 2
EECL	–	Engines and Energy Conversion Laboratory
ECM	–	Engine Controls and Monitoring
ECU	–	Electronic Control Unit
FID	–	Flame Ionization Detection
FTIR	–	Fourier Transform InfraRed
GC	–	Gas Chromatograph
GUI	–	Graphical User Interface
H ₂ -NG	–	Hydrogen/Natural Gas Blend
Hy	–	Hydromethane
ICE	–	Internal Combustion Engine
IR	–	Infrared Radiation
IT	–	Ignition Timing

LHV	–	Lower Heating Value
LPP	–	Location of Peak Pressure
MBT	–	Maximum Brake Torque
NH ₃	–	Ammonia
NO _x	–	Oxides of Nitrogen
NSCR	–	Non-Selective Catalytic Reduction
NTP	–	Normal Temperature and Pressure
O ₂	–	Oxygen
PM	–	Particulate Matter
PPMD	–	Parts per Million, dry
SI	–	Spark Ignition
SoCal Gas	–	Southern California Gas Company
THC	–	Total Hydrocarbons
VOCs	–	Volatile Organic Compounds