

**ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES**

PhD THESIS

Hüseyin Turan ARAT

**EXPERIMENTAL INVESTIGATION OF HYDROXY GAS ENRICHED
NATURAL GAS AS AN ALTERNATIVE FUEL (HHO-CNG) IN PILOT
INJECTION DIESEL ENGINES**

DEPARTMENT OF MECHANICAL ENGINEERING

ADANA, 2016

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ABSTRACT

PhD THESIS

EXPERIMENTAL INVESTIGATION OF HYDROXY GAS ENRICHED NATURAL GAS AS AN ALTERNATIVE FUEL (HHO-CNG) IN PILOT INJECTION DIESEL ENGINES

Hüseyin Turan ARAT

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DEPARTMENT OF MECHANICAL ENGINEERING**

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Increasingly restrictive emissions norms and renewed focus on energy efficiency drive the current search for alternative fuels and combustion strategies for IC engines. Using natural gas and hydrogen blends that can absorb their own negative effect on combustion and emission parameters when mixed each other can be a very good alternative due to the attractive fuel properties regarding emission reduction and engine operation. Alternative gaseous fuels can be easily used on SI engines without any modification. However, in CI engine, two optional ways were answered the problem when gas fuels usage. First one is converted diesel engine to SI working structure and it needs modification which is expensive and does not allow diesel operation again. But, second method is, that used in this thesis, dual-fuel mode operation which can be handled with pilot diesel ignition phenomenon. The aim of the thesis is to investigate the effects of a non-modified pilot diesel ignition CI engine's performance and emissions under operated with HHO-CNG fuel mixtures experimentally. A brief introduction and critical literature review presented. Experimental set-up, mixtures ratios of HHO-CNG, substitution of diesel fuel process and devices explained and performed briefly. The effects of 20, 25, 30 % (vol/vol) HHO-CNG operation was explored. A comparison of HCNG and HHO-CNG fuel mixtures affects on engine performance and emission parameters also determined. Additionally a cost analysis was performed and explained. As a result, this study exhibits the availability of usage HHO-CNG fuel mixtures in a non-modified diesel engine via pilot diesel ignition resulted improving the engine performance and reducing the exhaust emissions.

Key Words: HHO, CNG, pilot diesel injection, performance, emission.

ÖZ

DOKTORA TEZİ

HIDROKSI GAZ İLE ZENGİNLEŞTİRİLMİŞ DOĞALGAZIN (HHO-CNG) PILOT PÜSKÜRTMELİ DİZEL MOTORLARDA ALTERNATİF YAKIT OLARAK KULLANILMASI

Hüseyin Turan ARAT

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Giderek kısıllanan emisyon normları ve enerji verimliliği üzerine yenilenen yakıtlar, içten yanmalı motorlar için alternatif yakıtlar ve yanma stratejileri geliştirilmesi husunda yeni çalışmaların yapılmasına sağlanmıştır. Hidrojen ve doğalgazlı motorlarda alternatif yakıt olarak kullanımı motor performans ve egzoz gaz emisyonlarının iyileştirilmesinde tercih edilebilen bir yakıt olarak ele alınmaktadır. Alternatif gaz yakıtları dizel motorlarda kullanıldığında, hem maliyetli olan hemde tekrar dizel prensibinde çalıştırma ile sonuçlanan modifikasyonlar yerine bu çalışmada da kullanılarak, pilot dizel püskürtme yöntemi ile çift-yakıt sistemine göre çalıştırılması tercih sebebidir. Bu tezin amacı yapısal değişiklik yapmamak ve pilot dizel püskürtmeli dizel motorda, hidroksigaz -sıkıştırılmış doğalgaz yakıt karışımlarının performans ve emisyonlara etkilerinin detaylı biçimde incelenmesidir. %20, 25, 30 hacimsel oranlara sahip HHO-CNG yakıt karışımlarının etkileri incelenmiş ve HCNG & HHOCNG farklılıkları karşılaştırılarak olarak grafiklendirilmiştir. Ayrıca mikro-maliyet analizi yapılmış ve açıklanmıştır. Sonuç olarak, bu çalışmada, modifiye edilmemiş bir dizel motorda, pilot dizel püskürtme metodu ile HHO-CNG yakıt karışımlarının kullanılabilirliği test edilmiş ve sonuçlar bu yakıt karışımlarının motor performansını artırıp, egzoz emisyonlarının azaltılmasında kullanılabileceğini ortaya koymuştur.

Anahtar Kelimeler: Hidroksi, Doğalgaz, Pilot püskürtme, Performans, Emisyon

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CONTENTS	PAGE
ABSTRACT	I
ÖZ	II
ACKNOWLEDGEMENTS	III
CONTENTS	V
LIST OF TABLES.....	VII
LIST OF FIGURES	IX
LIST OF ABBREVIATIONS AND NOMENCLATURE	XIII
1. INTRODUCTION	1
1.1. Overview	1
1.2. Diesel Engines	2
1.3. Dual Fuel Diesel Engines and Pilot Diesel Injeciton	7
1.4. Hydrogen, HHO (Hydroxy) and CNG	13
1.5. Objectives and Approaches	16
1.6. Future Foresight Perspective	17
2. PRELIMINARY WORK	23
2.1. Dual Fuel Engines	24
2.2. Pilot Diesel Injection	28
2.3. Natural gas, Hydrogen, HCNG and HHO fuels in diesel engines	31
2.3.1. Natural gas in diesel engines.....	31
2.3.2. Hydrogen in diesel engines	37
2.3.3. HCNG fuel in diesel engines	41
2.3.4. HHO (Hydroxy) gas in diesel engines	47
2.4. Minor Conclusion of Literature Survey Results	50
3. MATERIAL AND METHOD	53
3.1. Experimental Procedure	52
3.1.1. Test Engine and Dynamometer	52
3.1.2. Measurement Devices	54
3.1.2.1. Exhaust gas analyser and Datalogger.....	54
3.1.2.2. CNG, H2, HHO procurements.....	56

3.1.2.3. Gaseous fuel flow measurement and control.....	59
3.1.2.4. Gaseous mixture chamber before intake manifold	60
3.1.3. Fuel Properties	62
3.2. Substitution of Diesel Fuel	64
3.2.1. Determinig the substitution of diesel fuel.....	64
3.2.2. Sensitive measurement with stepping motor and devices.....	66
3.2.3. Determinig the mixture of gaseous fuels	69
4. RESULTS AND DISCUSSION.....	71
4.1. Analysis of the major findings with expected results.....	74
4.2. Effects of using 20-25-30HHOCNG under quarter pilot diesel operation	77
4.3. Effects of using 20-25-30HHOCNG under semi pilot diesel operation	80
4.4. Comparison of HCNG vs HHOCNG under quarter pilot diesel operation	83
4.5. Comparison of HCNG vs HHOCNG under semi pilot diesel operation	92
4.6. Brake Thermal Efficiency and Exhaust Gas Temperature	101
4.7. Micro Scale Cost Analysis.....	105
5. CONCLUSIONS	107
REFERENCES	113
CURRICULUM VITAE	125
APPENDIX	127

LIST OF TABLES	PAGE
Table 3.1. Test Engine Specifications.....	54
Table 3.2. Technical specifications of datalogger	56
Table 3.3. Flow Meters Specifications	60
Table 3.4. Overall comparison of properties of hydrogen, CNG, (vol 18%) HCNG and diesel	62
Table 3.5. A general look of HHO properties and fractions	62
Table 3.6. Hydrogen & HHO fuel potential benefits and challenges.....	63
Table 3.7. Specifications of stepping motor.....	67
Table 4.1. The description of operating cases.....	72
Table 4.2. Approximate investment cost of converting modified diesel engine and present work	105

LIST OF FIGURES	PAGE
Figure 1.1. One of the engine diagrams of Dr. Rudolf Diesel's studies	4
Figure 1.2. Schematic of a four cylinder diesel engine	5
Figure 1.3. Operating cycle of a four-stroke diesel engine	5
Figure 1.4. Valve-timing diagram for a four-stroke diesel engine	5
Figure 1.5. Variation of the pilot quantity in the (BSFC) with (BMEP) of a dual-fuel engine operating at constant speed on propane at atmospheric conditions	10
Figure 1.6. Typical DI engine Heat Release Rate Diagram	12
Figure 1.7. Combustion process in CI	12
Figure 1.8. Dual-fuel pilot injection CI	12
Figure 1.9. Schematic representations of the components of the heat release development at (a) light load and (b) heavy load	13
Figure 1.10. World energy consumption illustration by fuel for both history and future	18
Figure 1.11. Estimated percentage saving in GHG emissions if petroleum fuels were to be replaced by one of these alternative fuels	19
Figure 1.12. Ideal CNG engine operating conditions	21
Figure 1.13. Hydrogen production sources	21
Figure 2.1. Variation of combustion noise output with gas equivalence ratio at constant pilot and speed	30
Figure 2.2. Technical approaches to NG Heavy-Duty engines	33
Figure 2.3. Variation of heat release with crank angle at 30% hydrogen enrichment mixture at full load condition	39
Figure 2.4. Hydrogen vehicles overview	40
Figure 2.5. Properties of methane and hydrogen	43
Figure 2.6. Emission potential of HCNG engine	46
Figure 3.1. Base test engine	54
Figure 3.2. Equipped test engine	54
Figure 3.3. The principle schema of NDIR and details of CLD	55

Figure 3.4.	CNG bundles and Lovato CNG kit	57
Figure 3.5.	A photograph of hydrogen tank and analyses certificate	58
Figure 3.6.	The system of hydroxy generator.....	59
Figure 3.7.	Maxtor needle vanes and Alicat flow meters.....	60
Figure 3.8.	Mixture chamber	61
Figure 3.9.	Mass fraction of CNG and H ₂ at 90° injection angle	61
Figure 3.10.	Bosch fuel-injection pump test bench with electronic test system	65
Figure 3.11.	Experiments with acupled micrometer to fuel pump plunger.....	66
Figure 3.12.	Stepping motor and driver	67
Figure 3.13.	A sample image from software of stepping motor driver.....	68
Figure 4.1.	BT, BP and BSFC for Diesel vs. quarter pilot diesel CNG, HHOCNGs	78
Figure 4.2.	CO ₂ , NO _x and CO for Diesel vs. quarter pilot diesel CNG, HHOCNGs.....	79
Figure 4.3.	BT, BP and BSFC for Diesel vs. semi pilot diesel CNG and HHOCNGs	81
Figure 4.4.	CO ₂ , NO _x and CO for Diesel vs. semi pilot diesel CNG and HHOCNGs.....	82
Figure 4.5.	Comparative performance data for Diesel, CNG, 20HCNG, 20HHOCNG	84
Figure 4.6.	Comparative emission data for Diesel, CNG, 20HCNG and 20HHOCNG	85
Figure 4.7.	Comparative performance data for Diesel, CNG, 25HCNG, 25HHOCNG	87
Figure 4.8.	Comparative emission data for Diesel, CNG, 25HCNG and 25HHOCNG	88
Figure 4.9.	Comparative performance data for Diesel, CNG, 30HCNG, 30HHOCNG	90
Figure 4.10.	Comparative emission data for Diesel, CNG, 30HCNG, 30HHOCNG	91

Figure 4.11. Comparative performance data for Diesel, CNG, 20HCNG, 20HHOCNG	93
Figure 4.12. Comparative emission data for Diesel, CNG, 20HCNG, 20HHOCNG	94
Figure 4.13. Comparative performance data for Diesel,CNG, 25HCNG, 25HHOCNG	96
Figure 4.14. Comparative emission data for Diesel, CNG, 25HCNG, 25HHOCNG	97
Figure 4.15. Comparative performance data for Diesel,CNG, 30HCNG, 30HHOCNG	99
Figure 4.16. Comparative emission data for Diesel, CNG, 30HCNG, 30HHOCNG	100
Figure 4.17. Analysis of Brake Thermal efficiency and Exhaust Gas Temprature.....	104

LIST OF ABBREVIATIONS AND NOMENCLATURE

AFR	: Air Fuel Ratio
BSFC	: Brake Specific Fuel Consumption
CI	: Compression Ignition
CNG	: Compressed Natural Gas
CO	: Carbon Monoxide
CO ₂	: Carbon Dioxide
DI	: Direct Injection
EGR	: Exhaust Gas Recirculation
EIA	: Energy Information Administration
EPA	: Environmental Protection Agency (U.S.)
H ₂	: Hydrogen
HC	: Hydrocarbon
HCNG	: Hydrogenated Compressed Natural Gas
HD	: Heavy Duty
HHO	: Hydroxy, Brown Gas, Oxyhydrogen, Aquagen
HHOCNG	: Hydroxy- Compressed Natural Gas
ICE	: Internal Combustion Engine
LHV	: Lower Heating Value
LPM	: Liter per Minute
NGV	: Natural Gas Vehicle
NO _x	: Nitrogen Oxide
PCCI	: Premixed Charge Compression Ignition
TDC	: Top Dead Centre
η_{th}	: Brake Thermal Efficiency

1. INTRODUCTION

This chapter presented an introduction and overview to the concept of energy, alternative fuels, diesel engines, dual fuel engines & pilot injection phenomena and gas fuels usage on diesel engines. The role of hydrogen, HHO and CNG fuel mixtures for improvement of engine parameters is also touched. Objectives, approaches and a future foresight perspective are given detailed.

1.1. Overview

Energy has always been the foremost important resource upon which humans have relied for survival and productive activities. Industrialization and technological advancement of modern society have also been possible through the effective use of energy. There is a strong correlation between the index for quality of life and energy consumption. Utilization of the energy is relevant with some factors that affected the energy synergies. These factors can be listed as resource availability, convenience of energy utilization, efficiency of conversion, technological feasibility, portability and ease of transportation, sustainability, renewability, cost and affordability, regional strength, safety and health effects, environmental acceptance and impact (Lee, 2015).

Fossil fuels have an important place in energy. However, the fossil fuel resources upon which industry is heavily dependent are limited in available quantities and are expected to be close to depletion in the near future. With this assumption, alternative fuels are playing a colossal role in usage of future fuels. The term alternative fuels have come to indicate any fuel that may be used in engine applications other than those conventional liquid fuels, such as gasoline or diesel fuel. They may include the following fuel groups (Karim, 2015):

- Pipeline and wellhead gases, methane, liquefied natural gas (LNG), compressed natural gas (CNG), biogases, landfill gases, and coal bed methane
- Liquefied petroleum gases (LPGs), propane, and butane

- Industrially processed fuel-gas mixtures such as those of coal gas, coke oven gas, blast furnace gas, synthesis gas, and producer gas
- Hydrogen, as both a gas and a liquid
- A range of liquid fuels that includes alcohols and some forms of bio-derived fuels.

Alternative fuels are available worldwide, the demand for which strongly depends on application and use, geographical location and regional resources, cost and affordability, cleanliness and environmental impact factors, safety of generation and utilization, socioeconomic and techno-economic factors, global and regional politics, new energy technologies, and so forth. R&D efforts in alternative-fueled vehicles and utilization of renewable energy sources have intensified in the past few years. Alternative-fueled vehicles and emission-free cars are expected to gain more popularity due in part to enforcement of stricter emission standards, the unmistakable fate of depletion for conventional transportation fuels, and numerous tax incentives for such vehicles (Lee, 2015).

When looking the big picture perspective on energy and fuels world, the major expected issue from all R&D participators, is improving the energy performance of fuels and applicants while reducing the harmful products such as emissions.

1.2. Diesel Engines

The purpose of internal combustion engines is the production of mechanical power from the chemical energy contained in the fuel. In internal combustion engines, as distinct from external combustion engines, this energy is released by burning or oxidizing the fuel inside the engine. The fuel-air mixture before combustion and the burned products after combustion are the actual working fluids (Heywood, 1988).

In 1892, the German engineer Rudolf Diesel (1858–1913) outlined in his patent (*On 23 February 1893, he received patent document DRP 67207 entitled*

Operating Process and Type of Construction for Combustion Engines) a new form of internal combustion engine. Diesel's idea was to design an engine with significantly greater efficiency than the steam engine, which was popular at the time. An engine based on the isothermal cycle should, according to the theory of the French physicist Sadi Carnot, be able to be operated with a high level of efficiency of over 90%. Diesel worked with companies as Gasmotoren-Fabrik Deutz AG and Maschinenfabrik Augsburg- Nürnberg (MAN) to realizing the first diesel engine building. After many months of endeavor, Diesel's engine carried out the acceptance tests on 1897. The test results confirmed what was then for combustion engine a high level of efficiency of 26.2% (Reif, 2014). One of the engine diagrams of Diesel's studies can be seen in Figure 1.1. From him to now, in spite of the dominant position it now holds in many applications that it is today the subject of intensive development and capable of improvements.

The diesel engine is a compression-ignition engine in which the fuel and air are mixed inside the engine. The air required for combustion is highly compressed inside the combustion chamber. This generates high temperatures which are sufficient for the diesel fuel to spontaneously ignite when it is injected into the cylinder.

General detailed schematic of a four cylinder diesel engine illustrated in Figure 1.2. Driven by the combustion of the air/fuel mixture, the piston in each cylinder performs up-and-down movements. This method of operation is why it was named the "reciprocating-piston engine". The connecting rod, converts the linear reciprocating action of the piston into rotational movement on the part of the crankshaft. A flywheel connected to the end of the crankshaft helps to maintain continuous crankshaft rotation and reduce unevenness of rotation caused by the periodic nature of fuel combustion in the individual cylinders. The speed of rotation of the crankshaft is also referred to as engine speed (Reif, 2014). Operating system of diesel engine and valve timing of diesel engine illustrated Figure1.3 and Figure1.4, respectively. The combustion phase of diesel engine is given in the next subheading for comparisons with dual fuel diesel engine.

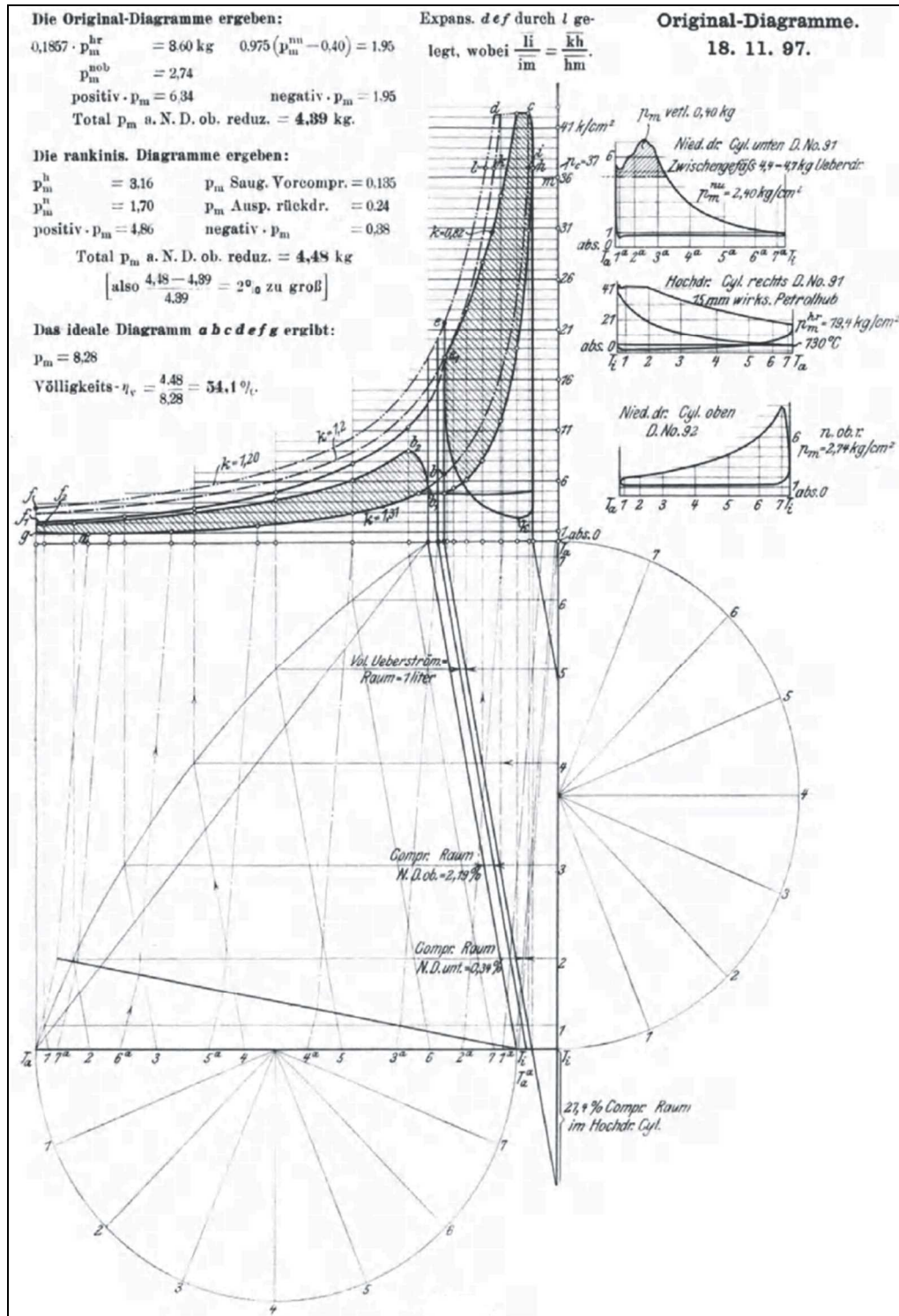


Figure 1.1. One of the engine diagrams of Dr. Rudolf Diesel's studies (Diesel, 1987)

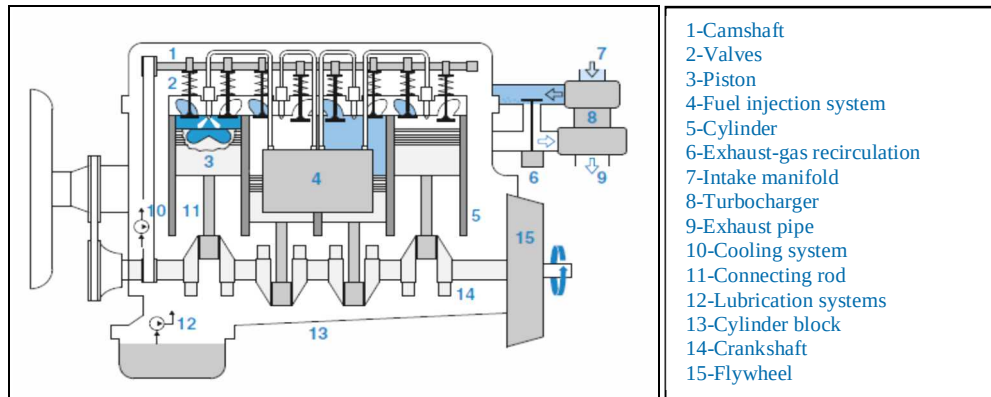


Figure 1.2. Schematic of a four cylinder diesel engine (Reif, 2014)

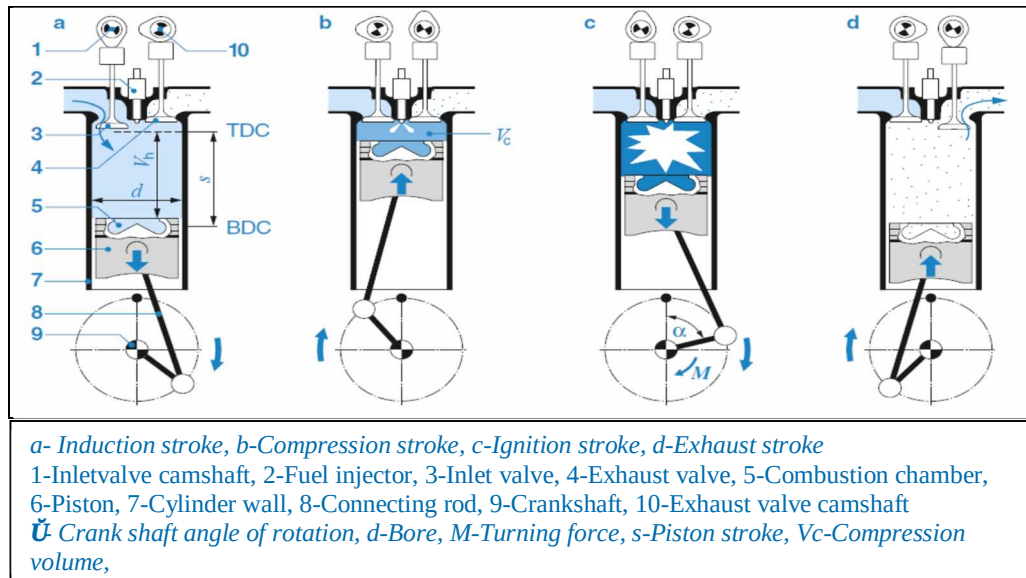


Figure 1.3. Operating cycle of a four-stroke diesel engine (Reif, 2014)

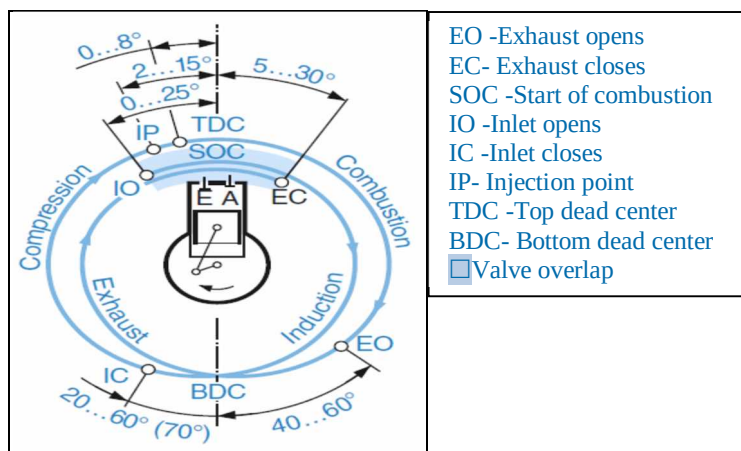


Figure 1.4. Valve-timing diagram for a four-stroke diesel engine (Reif, 2014)

Diesel engines specific features and differences from common spark ignition type can be listed below (Karim, 2015):

- Diesel engines need to have sufficiently high compression ratios to ensure reliable, prompt, and well-controlled auto ignition of the injected fuel. They involve non homogenous fuel/air mixtures leading mainly to heterogeneous diffusion type combustion. The rapid energy releases produced require robust engine construction to withstand the resulting high mechanical and thermal loading rates.
- The engine requires suitable liquid fuels that, in comparison to those of the spark ignition, are more prone to auto ignition and have high Cetane numbers, but at the same time very low octane numbers. Excess air operation is employed throughout with intense turbulence and swirling fluid action provided so as to aid in the rapid atomization, vaporization, and subsequent mixing of the fuel and air.
- The engine normally operates unthrottled at lower speeds than the spark ignition types and is relatively harder to start unaided under cold weather and intake air conditions. But, it tends to have superior work production efficiency and torque characteristics. The engine is well suited for high levels of turbocharging and can be made of extremely large size and power capacity.
- The exhaust emissions in diesel engines tend to show normally low levels of carbon monoxide and unburned hydrocarbons, but relatively high levels of NO_x and particulates. At present, to render their exhaust gas emissions environmentally acceptable, most engine types require special treatment.

For a commercial diesel engine manufacture, diesel engine performance related with some design and operational variables such as;

- ✓ Fuel type, quality, and properties, both physical and chemical

- ✓ Various features of engine design and operation, including turbocharging, EGR, cogeneration, throttling, and variable valve timings employed
- ✓ Combustion chamber fluid flow and turbulence characteristics
- ✓ Fuel injection characteristics and timing
- ✓ Engine size, compression ratio, number of cylinders, and speed range
- ✓ Specific operating conditions, such as intake temperature and pressure, overall equivalence ratio, percentage of total load, and water jacket temperature.

1.3. Dual Fuel Diesel Engines and Pilot Diesel Injection

Fuel research and developments are always possessing importance as much as engine technologies at automotive industry. Common objective is to create more economical and environmental friendly future for both. In CI engines, dual-fuel mode operation gives promotional utilize when use gaseous fuels. In dual-fuel operations mostly two options have been preferred to induct gases into the combustion chamber. First one is directly mixed with air and straight the mixture (air and fuel) via intake manifold. The second one (Mtui, 1996) is mixed in two fuels in an injector that used gas and diesel. At the first option any kind of structural modification is not required on the engine expect set up to pilot injection system for combustion. Minimum diesel fuel injected towards of air and gas fuel mixtures in combustion chamber. On the other hand; original injectors of engine has to exchange with the new ones for second option. Additionally; in transportation sector, diesel engines recompose like a gases engine with some structural engine modifications. These modifications of diesel engines to gas engines, causes necessary changes of parts with higher costs. Beside, this transformation in CI engines, allowed the system only mono-fuel. Obviating these problems, diesel engines can combust with pilot diesel injection by using gaseous fuels without any structural modification.

The term, dual-fuel diesel operation, describes compression ignition engines that burn *simultaneously* two entirely different fuels in varying proportions. These

two fuels are usually made up of a gaseous fuel, which supplies much of the energy released through combustion, and a second fuel, which is a liquid employed mainly to provide the energy needed for ignition and the remaining fraction of the energy release by the engine. Another term sometimes used in gas-fueled engine applications is the *gas-diesel engine*. These have tended to relate to dual-fuel engines where the gaseous fuel is injected directly into the cylinder either during the early stages of compression or sometimes after the injection of the liquid fuel toward the end of compression. The gaseous fuel does not auto ignite on its own via compression ignition, but usually burns with the assistance of the injected liquid-fueled ignition processes. Accordingly, these engines are dual-fuel engines that employ different forms of introduction of the gaseous fuel that does not undergo auto ignition on its own (Karim, 2015).

The operation of dual-fuel engines depends in a large way on how the gaseous fuel is introduced. The common approach is to introduce the gaseous fuel into the incoming air well ahead of the intake valve, as commonly accomplished in gasoline-fueled spark ignition engines. The gas may also be introduced at the beginning of the compression process so that much of the gaseous fuel becomes thoroughly mixed with the air before pilot fuel injection. These engines can be described as premixed dual-fuel engines, and this mode of gas introduction as fumigation. The relatively small quantity of the liquid diesel fuel injected to provide controlled ignition in dual-fuel engines is commonly described as the *pilot* (Karim, 2015).

A pilot injection phenomenon is a critic issue in dual fuel diesel engines. Its characteristics (quality of fuel, CN number, and spray), size, mass, time and pressure is very important for the optimum steady state combustion occurs. Pilot diesel injection phenomenon clearly summarized by Papagiannakis R.G. et al (2003,2007) In dual fuel CI engines operating with gaseous fuels as primary fuel and a *pilot* amount of liquid diesel fuel as an *ignition source*, the gaseous fuel is inducted along with the intake air and is compressed like in a conventional diesel engine. The mixture of air and gaseous fuel does not auto ignite due to its high autoignition

temperature. A small amount of liquid diesel fuel is injected near the end of the compression stroke to ignite the gaseous mixture.

The minimum pilot quantities may be different for different combustion chamber structures and operating conditions. Conventional diesel fuel injection systems limit the minimum pilot fuel quantity to not less than 5% of the full load fuel quantity when operating on diesel alone. However, in practical dual fuel engines, the diesel flow is usually not reduced below 10 or 15 percent of the total energy required in part to maintain the fuel injection system for diesel engine operation and to ensure adequate injection nozzle cooling. In so much as, for older CI engines, Miyake M. et al (1983) suggested that, "natural gas and pilot liquid diesel fuel were mixed prior to injection and found that 40% pilot diesel fuel was needed for stable ignition".

It is stated in here which is much related with pilot injection that dual fuel diesel engines tended to combust in a lean combustion situation because of the introduction into the engine of gaseous fuels such as methane or hydrogen displaces a significant portion of the intake air. This lean combustion has some advantages and challenges which they referred next sections.

Mainly for economic and environmental reasons, the quantity of the diesel fuel pilot needs to be minimized relative to that of the cheaper fuel gases. The pilot quantity of a dual fuel engine represented the major role for balancing of the engine performance and exhaust emissions. This is to be done while maintaining optimum combustion and engine performance characteristics. As an example, with the employment of greater than 30% of normal diesel, as shown in Figure 1.5., for a dual-fueled engine operating on propane, engine performance with respect to power and specific energy consumption can become superior even to those corresponding values of normal high load diesel performance (Karim, 2015).

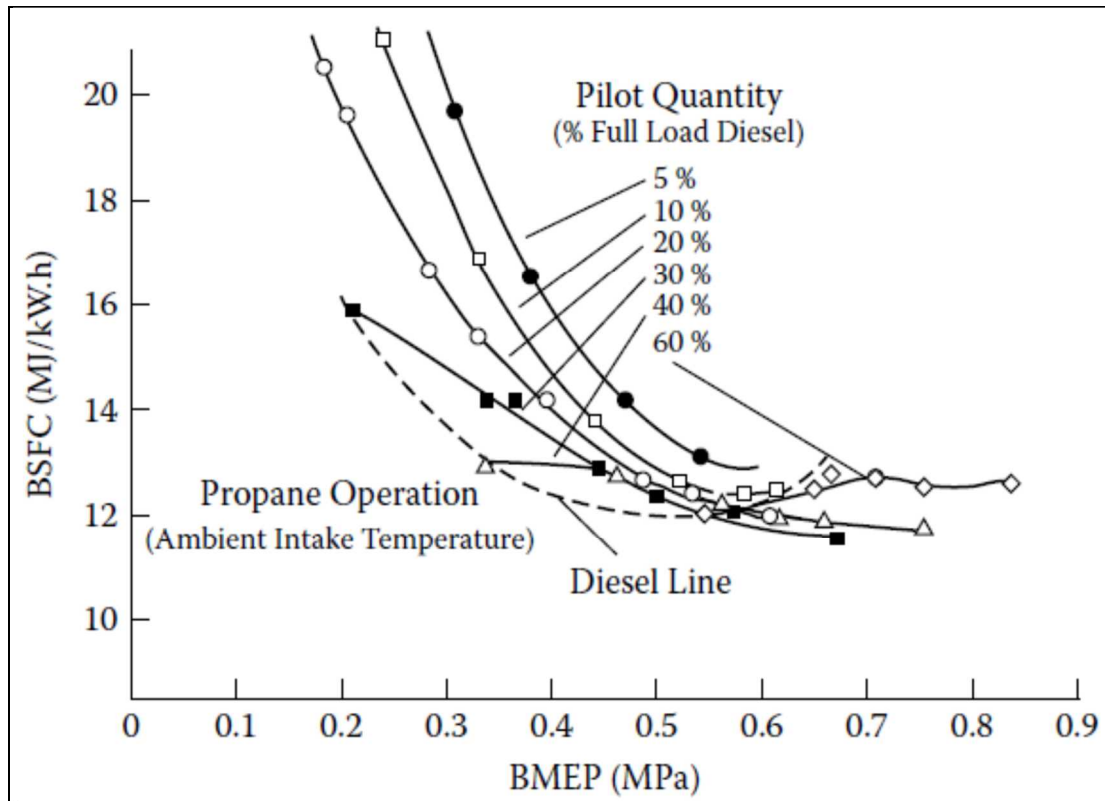


Figure 1.5. Variation of the pilot quantity in the (BSFC) with (BMEP) of a dual-fuel engine operating at constant speed on propane at atmospheric conditions (Karim, 2015).

As similarly, pilot diesel injection strategy exhibits the factors of *total economy* as lower specific fuel consumption and does not necessary to modify the engine; *environmental issues* as lower undesirable exhaust emissions can be obtained with dual-fuel operation with pilot diesel injection. There is a very substantial reduction in the emissions of carbon and particulates, with a significant reduction in the production of oxides of nitrogen. This is mainly since the bulk of the energy release is produced by the combustion of *very lean gaseous fuel-air mixtures* and the associated reduction in the size of the very hot combustion zone, which mainly involves the liquid diesel pilot fuel. *Additional benefits* as; relevant pilot quantity can lead to improvements in engine durability, reduced maintenance costs, and quieter running. There will also be less heat transfer, lubricant degradation, and surface deposition of the liquid fuel, leading to its surface ignition and combustion (Karim, 2015).

After the important points of usage pilot injection, one topic had to explain; comparison of the combustion stages between dual fuel diesel engines and normal diesel engines.

Combustion is an increasingly important topic of much economic and social importance. To bring about substantial improvements to the performance of internal combustion engines, there is a need to understand the nature of the combustion processes (Karim, 2015).

The combustion process during diesel-only operation consists of four stages which can be identified on a heat release rate diagram presented in Figure 1.6. (Heywood, 1988)

The first stage, ignition delay (a-b on Figure 1.6), is the duration between the start of diesel injection and the start of combustion. Fuel injected during this stage follows a sequence of physical and chemical steps: atomization (forms a spray of droplets due to jet velocity), vaporization (forms a vapor due to heat transfer from the aerodynamic drag of droplet), fuel vapor mixing with air, and pre-combustion reactions leading to autoignition (oxidation of HC's causing multiple areas of localized ignition).

The second stage, premixed combustion (b-c on Figure 1.6.), is the combustion of diesel mixed with air to its proper flammability limits during the ignition delay stage. This stage occurs rapidly with high pressure rise rates and heat release rates. The characteristic noise emitted from a diesel engine is a result of the pressure rise rates occurring during this stage.

The third stage, mixing-controlled combustion (c-d on Figure 1.6.), is the combustion of diesel that is injected after the premixed combustion phase. Fuel injected during this stage follows all of the physical and chemical steps outlined in the ignition delay stage but is controlled by the rate of diesel injection subsequently mixing with air.

The fourth stage, late combustion (d-e on Figure 1.6.), is the combustion of products left over from the stages before. These products include unburned fuel, soot, and fuel rich combustion products.

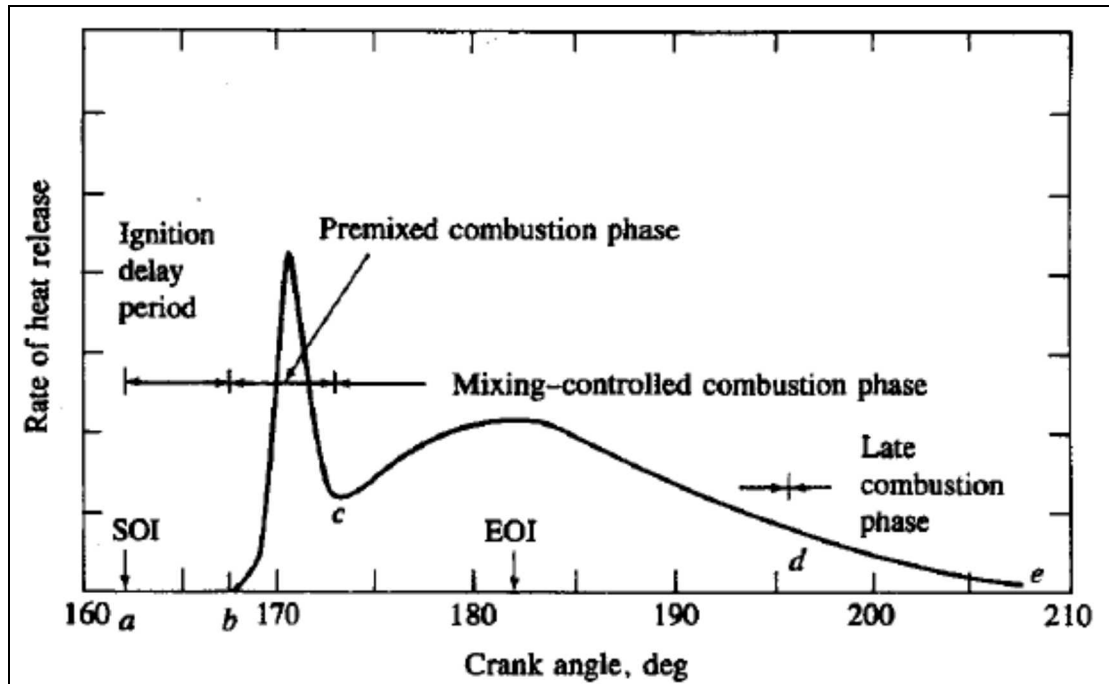


Figure 1.6. Typical DI engine Heat Release Rate Diagram (Heywood, 1988)

As it seen from figure 1.7. (Sahoo, 2009), combustion processes in CI engines running on pure diesel fuel can be divided into four stages. However, the combustion processes in gas-fumigated dual-fuel engines using pilot injection have been identified to take place in five stages as shown in figure 1.8. (Sahoo, 2009). They are the pilot ignition delay (AB), pilot premixed combustion (BC), primary fuel ignition delay (CD), rapid combustion of primary fuel (DE) and the diffusion combustion stage (EF) (Sahoo, 2009).

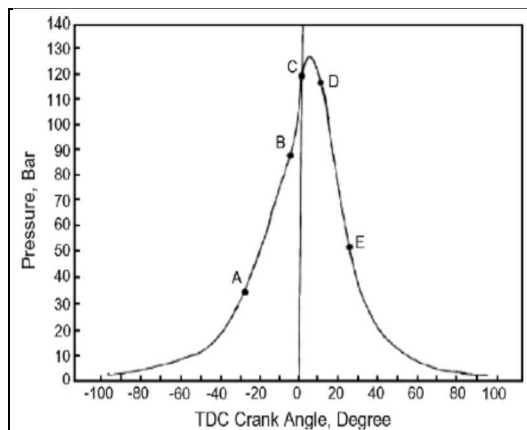


Figure 1.7. Combustion process in CI

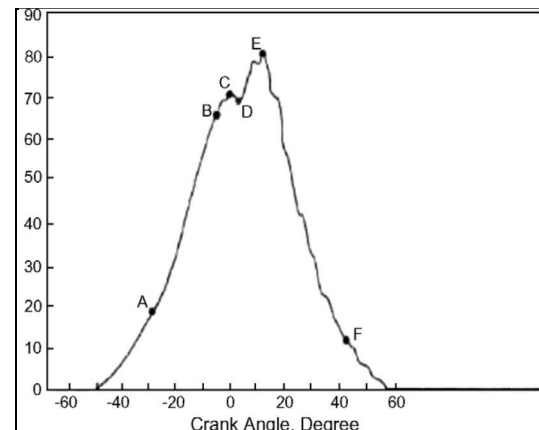


Figure 1.8. Dual-fuel pilot injection CI

The combustion process in a typical engine during premixed dual-fuel operation depends on both the spray and ignition characteristics of the diesel pilot and on the type of gaseous fuel used and its overall concentration in the cylinder charge. Disturbingly, the mechanism of light load and heavy load conditions are playing critical role on premixed dual fuel engines. Karim G.A. (2015), summarized this issue with graphics as shown in figure 1.9.

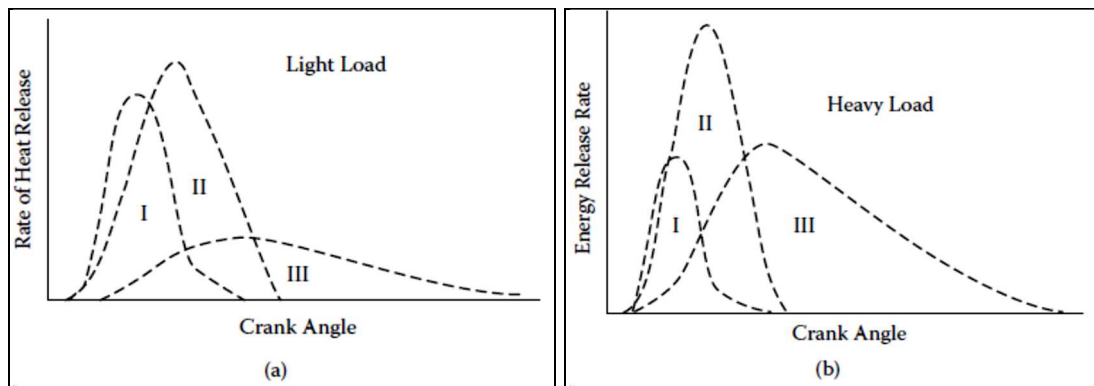


Figure 1.9. Schematic representation of the components of the heat release development at (a) light load and (b) heavy load (Karim, 2015).

According to the same author, the combustion energy release rate of a dual-fuel engine can be considered as three overlapping components, where;

- ❖ Component I is the energy release from the pilot diesel combustion
- ❖ Component II is the energy release from the CNG component that is in the immediate vicinity of the pilot diesel combustion
- ❖ Component III is the energy release from the pre-ignition reaction activity of the CNG and flame propagation from the combustion of the pilot diesel and CNG within its immediate vicinity to the CNG/air mixture outside of the immediate vicinity of the pilot diesel combustion.

1.4. Hydrogen, HHO (Hydroxy) and CNG

As it mentioned previously, alternative fuels preferability is increasing by growing a high proportion. These fuels have significant importance on engine

performance and exhaust emissions. Especially gas fuels (Hydrogen, HHO and CNG) which use in ICE assisted reducing emissions. Hydrogen and compounds are the major players in energy world. The heating value of hydrogen is much higher than that of conventional fuels if taken as per unit of weight and hydrogen combustion is completely clean, producing only water vapor in the exhaust gas

Nowadays, hydrogen can be applied for transport as a main fuel (or supplement fuel) for ICEs and for fuel cell; and most of the hydrogen stations on over the world are attending to fuel cell vehicles. Hydrogen internal combustion engines have the potential for high power because of more energy per unit mass and high flame speed, high efficiency because of high flame speed that causes high rate of pressure rise in the cylinder and hence near constant-volume combustion and they also have near-zero emissions, except NO_x at higher loads, because of the absence of carbon in the fuel molecular structure.

Natural gas is regarded as one of the most promising alternative fuels and probably one of the cleanest fuels in combustion. Natural gas is a mixture of different gases where methane is its major component. The combustion of natural gas produces less emission than that of gasoline and diesel fuels due to its simple chemical structure and absence of fuel evaporation. According to NGVA Europe, total ngv (natural gas vehicle) population (other than ships, trains and aircraft) on worldwide is 17.730.433, for 2013 and for 2014 Europe ngv population is 1.899.602 and additional notes come from Mintz (2014), that in transportation sector, use of natural gas is increasing in both established and new markets and CNG is the only fossil fuel that can compete with petroleum diesel for vehicle applications.

But natural gas has the penalty of slow burning velocity and poor lean burn ability and this may lead to the incomplete combustion. One effective way to solve the problem is to mix the natural gas with a fuel that possesses the high burning velocity. Hydrogen is an excellent additive into natural gas in improving the burning velocity of mixture due to the high burning velocity of hydrogen. Adding a small amount of hydrogen into natural gas can improve the combustion characteristics and reduce exhaust emissions.

The engineering properties of hydrogen based gaseous fuels and natural gas mixtures are unique parameters for engine design and reducing the exhaust emissions. Ma (2010) , reported the importance of these mixture with these considerations. Natural gas is often thought of as the most promising alternative fuels for vehicles. Natural gas is a much more abundant fuel than petroleum and is often described as the cleanest of the fossil fuels, producing significantly less carbon monoxide, carbon dioxide, and nonmethane hydrocarbon emissions than gasoline; and when compared to diesel it nearly eliminates the particulate matter. Other advantages of natural gas include a high H/C ratio and a high research octane number (RON) causing the exhaust to be clean and allowing for high anti-knocking properties. On the other hand; hydrogen is the most abundant element on earth, and is often thought of as the ideal alternative fuel. However, the current infrastructure does not support hydrogen as a wide-spread fuel. In order to expand the role of hydrogen in the near term, one option is to use hydrogen for transportation by mixing it with natural gas and use it for use in ICE engines. This new blended fuel is known as HCNG, or Hythane, for which the use will create a basic infrastructure for the use of hydrogen in the future (Ma,2010).

Although the most common of all elements, H_2 does not exist in nature, but is bound in water (H_2O), hydrocarbons (C_nH_m) and various other compounds. Electrolysis is the most common method used to split H_2 from water. Currently, 12-15% of hydrogen production globally source is presented by electrolyses. Early studies were initiated by Yull Brown in 1977 via equipment generally referred to as electrolyzers and the resulting gas is known as "brown" gas or HHO (Al-rousan, 2010). *(In literature, scientists can be named of this gas differently- Aquygen (registered trademark owned by HTA inc. (Santilli,2006)), HHO, hydroxy, oxyhydrogen, hydroxygen, knallgas,etc.)*. HHO is a trademark and comes from the separation of water molecules H-OH that contains (theoretically) 66% H_2 and 33% O_2 . It has high calorific value and 1 kg of HHO is three times as potent as gasoline and eight times as potent as diesel. Also achieving of HHO gas under water electrolyses, several item affected the end product. This affected the efficiency of the HHO generators.

1.5. Objectives and Approaches

The present work investigates of using 20%, 25%, 30% (by volumes) HCNG (Hydrogenated Compressed Natural Gas) and HHOCNG (hydroxy-compressed natural gas) fuel mixtures on a non-modified diesel engine operated with pilot injection experimentally. HCNG and HHOCNG mixtures were used as a replacement fuel in a non-modified diesel engine via intake manifold and reduction of diesel fuel by dint of pilot injection. Reduction of diesel fuel mass was prepared as two different substitutions like quarter and semi-pilot injection controlled by stepping motor devices. 20%, 25%, 30% (by volumes) HHOCNG and HCNG fuel mixture were tested in a 3.6 L, four cylinders, four stroke and water coolant diesel test engine between 1200-2600 rpms. Effects of these two different diesel substitution on engine performance and exhaust emissions parameters were compared and illustrated with graphics as brake power, brake torque, and brake specific fuel consumption; CO, CO₂ and NO_x. Previous studies were also refereed with separated related topics. Experimental procedure and devices were explained detailed. The minimum and optimum quantities of pilot injection at specific engine operational conditions are determined, and the effectiveness of different measures to improve engine performance for various operational conditions are examined. Results of this study are given a comparable situation between HHOCNG and HCNG. Also improvement scales of usage these fuel mixtures were described. Additionally, a micro cost analyses of pilot injection diesel engine which fumigated under these fuel mixtures were also examined. Conclusion of such an investigation benefits the development of effective attraction of HHOCNG and HCNG fuels were explained detail with additional future works.

Objectives and Approaches:

The main objectives and approaches of the present research are:

• Investigate the engine performance and exhaust emission characteristics of HHOCNG and HCNG gas fueled engines experimentally.

- ÅMinimize the amount of liquid fuel consumption relative to that of the gaseous fuel in dual fuel engines, and investigate the engine characteristics of different quantities of pilot fuel injection.
- ÅDevelop for optimization of the pilot injection amount with step motor and driver devices.
- ÅInvestigate the differences between HHO and H₂ addition to CNG fuel that operating with substituted diesel liquid fuel.
- ÅProvide guidelines for effective approaches to the implementation of the technology in the controlling of dual fuel engines with small pilot injection.
- ÅProvide the privileged emission characteristics on dual fuel mode with these gaseous fuel mixtures.
- ÅExhibit a cost analyses that includes the economically aspects of these fuels.
- ÅProduct a mixture chamber before the intake manifold for the optimum mixturing gaseous fuels with air.

1.6. Future Foresight Perspective

History shows that world energy consumption has been steadily increasing and also that a huge increase in the energy consumption has taken place in the last two centuries. The reasons for this steady increase include enhancements in quality of human life, population increase, industrialization, rapid economic growth of developing countries, increased transportation of people and goods, and so forth (Lee, 2015). From the point of view for the reasons of increase enhancement, it can be clearly say; energy consumption is growing widely. In figure 1.10., world energy consumption illustrated both history and future projections, for each of the principal fuel types from 1990 to 2040 (referred from EIA by Lee, 2015). Additionally, in Figure 1.11, illustrated life-cycle analyses of alternative fuel sources and their impact forward on to potential GHG emission savings.

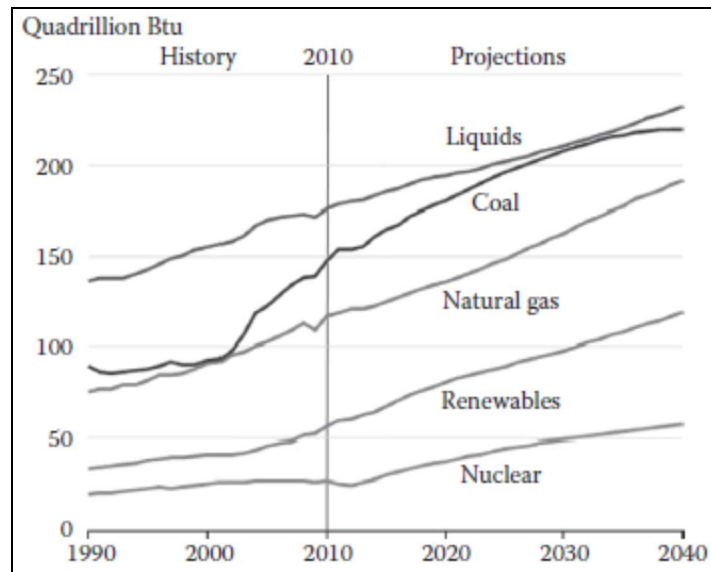


Figure 1.10. World energy consumption illustration by fuel for both history and future (Lee, 2015).

Accordingly to International Energy Outlook 2013 (IEO2013) projects, the world's total energy consumption will grow by 56% for the period from 2010 to 2040, from 524 quadrillion to 820 quadrillion Btu. One quadrillion Btu is 10^{15} Btu. This rate of growth is, approximately, at an annual rate of 1.5% growth. Lee (2015), referred and touched upon that; "IEO2013 also projects that the Organization for Economic Co-operation and Development (OECD) nations's consumption growth will be only 17%, while the non-OECD nations's consumption growth will be 90%". The following observations regarding the future projections can be made:

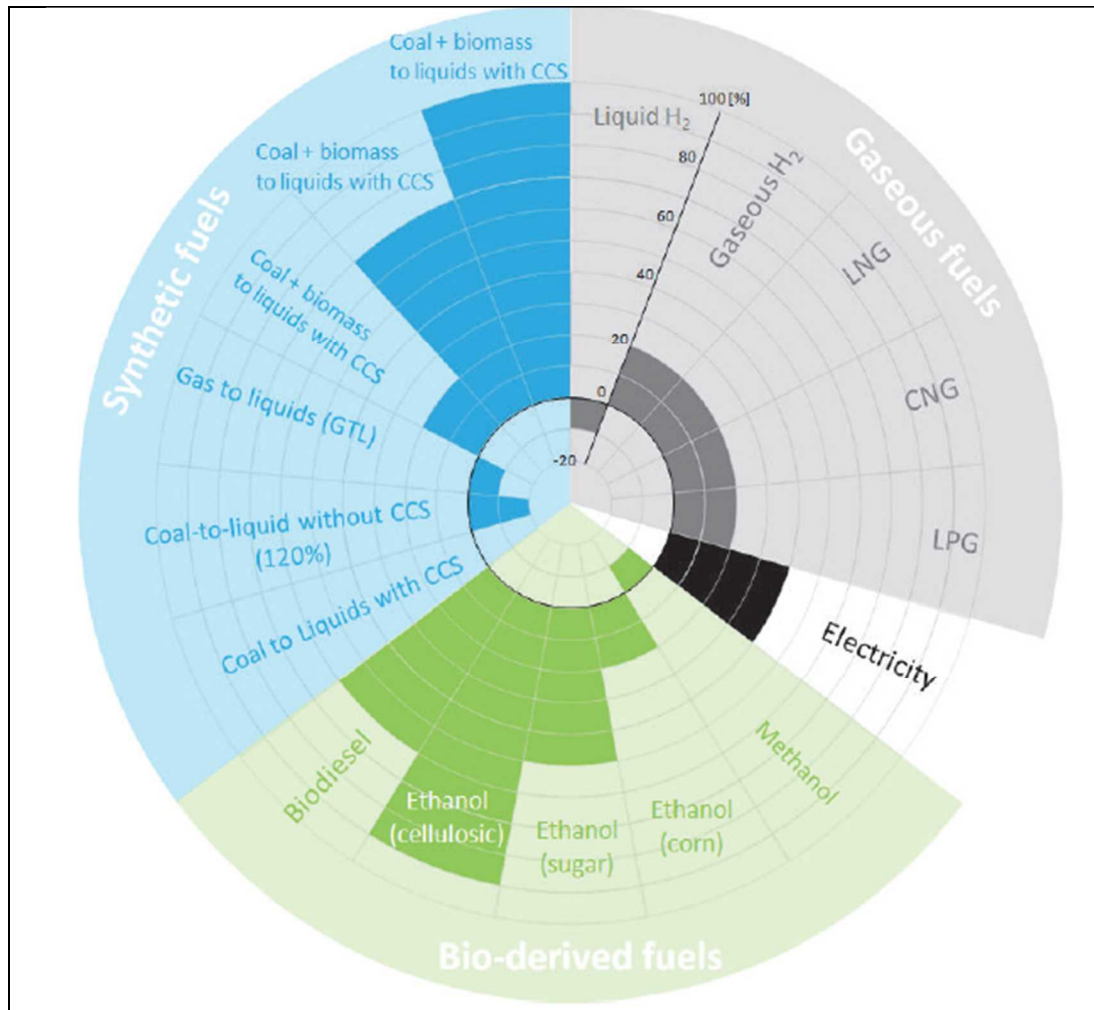


Figure 1.11. Estimated percentage saving in GHG emissions if petroleum fuels were to be replaced by one of these alternative fuels (EPA,2007)

1. Fossil fuels will continue to supply a great portion, approximately 80%, of the world energy through 2040.
2. Renewable energy will be the single fastest-growing energy source in the world, at an annual rate of approximately 2.5% per year. This optimism is based on the recent technological advances in the field as well as the global commitments in energy sustainability.
3. The average annual growth rate of 1.5% is lower than the generally expected economic growth of the world for the period. Considering that the energy consumption has somewhat outpaced that of the economic growth for the past 100 years, this may seem to be low at first glance.

However, this projection by the IEO2013 includes the global efforts and achievements in energy efficiency increase in all aspects of energy consumption.

4. Projected growth in natural gas consumption is faster than that for liquids, which may reflect optimism developed in recent years with shale gas development in the U.S. Since shale fuel is distributed abundantly throughout the world, its commercial development would increase the availability of affordable natural gas. Further, this is also attributable to stronger demands for natural gas in industrial and residential heating, increased installations of natural gas-based electric power plants, and new discoveries of large natural gas deposits, both conventional and unconventional.
5. A sharp increase in nuclear energy consumption is also projected for the period, which reflects the growing interest in and large orders for new power plants in non-OECD countries.

With these considerations; H₂, HHO and CNG (also theirs mixtures) have been playing a very important and critical role in the future as a fuel. Although natural gas concern with fossil fuel family, its reservoir life and availability is bigger than diesel and petrol with shale gas and applications developing. The extent of these two fuels (H₂ and CNG) illustrating for; CNG engines operations and hydrogen production sources figures, given in 1.12. and 1.13., respectively.

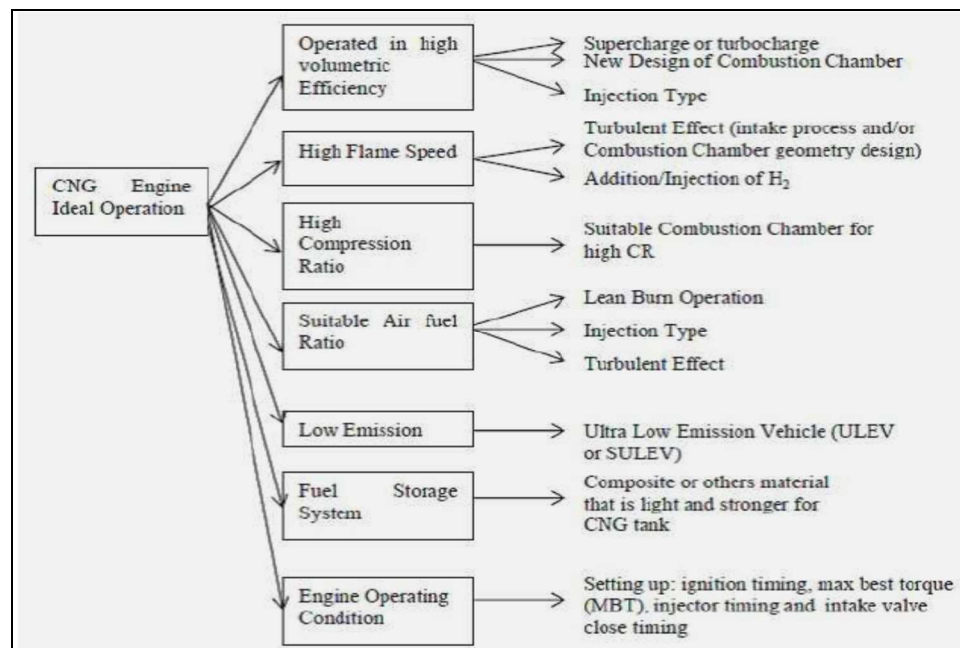


Figure 1.12. Ideal CNG engine operating conditions (Bakar, 2012)

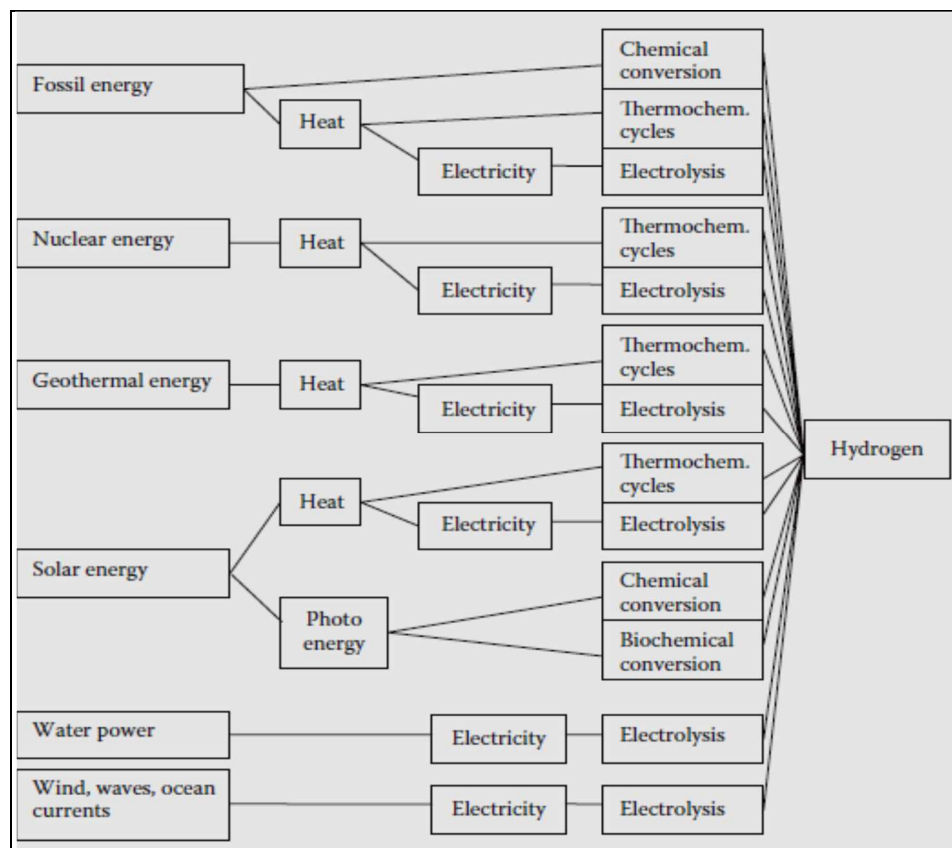


Figure 1.13. Hydrogen production sources. (Lee, 2015)

2. PRELIMINARY WORK

This chapter informed the literature survey on dual-fuel pilot injected diesel engines. Chapter has consisted with four subheadings as; dual-fuel engines; pilot diesel injection; natural gas, hydrogen, hydrogenated-cng and hydroxy fuels in diesel engines; HCNG and HHOCNG fuel mixtures on diesel engines operated under dual-fuel mode. A minor conclusion of the preliminary work added the end of this chapter.

The dual fuel topic includes several parameters that relevant to combustion and emission characteristics. These characteristics influence the design, manufacture and usage of internal combustion engines. Some related parameters can be sorted as; engine structural characteristics; availability for dual fuel; intake manifold design; temperature, pressure and flow characteristics of gaseous fuels; pilot injection timing, quantity, amount, size, spray, penetration and atomization characteristics; induction strategies to intake manifold; using of same injectors or dual fuel injectors; intake air properties; EGR, turbocharger and several devices usage; physical and chemical properties of gaseous fuels; gas fuel and air mixtures quantity; mass and/or volume percentages; valve timing; effects of exhaust emissions; safety issues; production of the gaseous fuels and their standardization; lean combustion, thermal and volumetric efficiency, rapid burning, COV, inlet and exhaust gas temperature; costs; future consumptive conjecture, etc.

With these considerations, researchers and practitioners studied this phenomenological issue for improving the targets. This chapter divided into four parts for better approach and understandability of the main outcomes about the aforementioned topics.

Before starting the previous work, it should be noted some of the research teams. Their studies and experiments are improved the topic of dual-fuel engines, hydrogen, CNG and other gaseous fuels in literature. The years of their studies can be seen in preferences part of this thesis that they listed as; Karim, Arat, Papagiannakis, Korakianitis, Çeper, Dinçer, Ma, Wang, Lee, Saravanan, Liew, Nwafor, Park, etc.

2.1. Dual Fuel Engines

Dual fuel internal combustion engines presented hugely cover on literature. Both SI and CI engines could use these systems for improving the performance and reducing fuel consumption and harmful exhaust emissions. General details and important parameters for using dual-fuel in ICEs are summarized from literature.

The discovery of the dual fuel engine is credited to Cave in 1929 and Helmore et al. in 1930 when hydrogen fuel was introduced as a supplementary fuel in diesel engines. However, at that time, dual fuel had limitations which made it less popular for commercialization. The challenges included mechanical complexity, expensive components, large inefficiencies, and significant knocking. Serious attention to dual fuel began during the Second World War when petroleum supplies were lacking, leading to new technology exploration including the dual fuel engine. In their early days, many dual fuel engines, especially heavy-duty engines, ran on waste gas from the oil industry or sewage gas from sewage treatment plants. After the war, the market returned to fuel oil because of environmental concerns associated with coal and the large supply of very inexpensive oil from Saud Arabia. This enabled the petroleum gas industry to expand and many gas transport companies started to increase production and expand pipeline systems during this time. In recent engines, the development of dual fuel technology is motivated by emissions regulations which require specific limits be met for pollutants released into the atmosphere. Development is also motivated by the potential savings on operations costs for dual fuel engines compared to diesel engines. For these reasons, many diesel engines are converted to run with gaseous fuels such as natural gas and retain positive features of diesel operation. Natural gas is preferred because it is cheap and widely available. It is also shown to reduce emission problems in diesel engines (Mansor, 2014).

The modern high-compression-ratio diesel engine is imminently suited to dual-fuel operation, particularly when using a fuel such as methane, the main component of a wide range of natural and biogases. Largely by virtue of the provision of a high compression ratio with excess air and an adequate sized,

consistently timed pilot liquid fuel injection, almost any gaseous fuel or vapor can be utilized to a varying degree of success. A wide range of pure gaseous fuels, such as methane, ethane, propane, butane, hydrogen, and ethylene, have been employed in dual-fuel engine applications.

Karim G.A.(2015) suggested that; some of the contributory factors to these trends could have included the following:

ÅThe combustion process in the gas-fueled diesel engine of the dual-fuel type is quite complex. It displays some of the features and associated problems of the compression ignition diesel engine, as well as those of the premixed spark ignition type.

ÅThe exhaust emissions of dual-fuel operation, until relatively recently, were not easy to deal with satisfactorily when in combination with the widely varying quality of the fuel systems possible, over the whole ranges of load and speed. However, many recent advances have been made, making it easier to deal with these difficulties.

ÅTo obtain the potential benefits associated with gas-fueled operation, many influencing operational and design factors require careful optimization and control. Suitable computer controls of the many engine variables were not widely available in the past, while relying mainly on mechanical type control devices. This tended to make transport applications harder to implement satisfactorily and lacked the versatility and reliability required for the frequent transients in performance. The need to provide two complex sets of controls and adequate portable storage for two sets of fuel systems of widely different properties has also contributed to the challenges.

ÅThere has been a continuing need to retain the capacity of gas-fueled engines to revert to the diesel operational mode promptly and smoothly when needed. This facility is required to be retained without undermining the performance of the engine as a diesel. This sometimes represented a challenge since diesel engines are required to satisfy increasingly stricter and more challenging requirements of performance and controls.

Until recently, relatively small diesel engines were less operationally flexible and tended to be more costly in comparison to their spark ignition counterparts. Accordingly, the exclusive conversion to fuel gas spark ignition operation was easier to accomplish and more satisfactorily performed, especially while retaining the bi-fuel operational capacity.

Large output stationary engines, such as those employed exclusively for the generation of electric power, consume very large quantities of fuel. The need to lower fuel costs and maintain high efficiencies is an important consideration. These tended to favor employing the efficient and reliable liquid-fueled diesel engines, which in recent years have reached a very advanced stage of sophistication and reliability. They are readily turbocharged, and their performance is well optimized. However, only when relatively cheap and abundant fuel gas supplies were available were dual-fuel engines employed.

A consequence of operating diesel engines in the premixed dual-fuel mode is that some of the intake air is displaced by the gaseous fuel induced. The amount of air displaced increases with the decrease in average molecular weight of the fuel. For example, for stoichiometric mixtures, the decrease by volume is 3.13% for butane, 4.03% for propane, 5.66% for ethane, 9.51% for methane, and 29.6% for hydrogen. This air displacement can have a significant influence on the volumetric efficiency, emissions, and associated power output of the engine, requiring remedial measures to recoup the potential shortfall in engine power output and performance. Otherwise, relatively bigger engines are needed with increased capital and operational costs.

The low efficiency and sensitivity to changes in the fuel gas composition of the low-compression-ratio spark ignition gas engine made it fall increasingly out of favor in comparison to the gas-fueled diesel engine. However, diesel engines, with their continued improvements in the control of their emissions, efficiency, and reliability, tended to relegate the dual-fuel engine to a secondary role, confining it increasingly to special applications where

economic advantages can be assured through the exploitation of much cheaper gaseous fuels. The increased attention in recent years to reduce the emission of greenhouse gases is aiding in the widespread application of dual-fuel engines in transport applications.

Although dual fuel systems have been operating satisfactorily and economically, there is still room for reducing costs and enhancing their performance further, whether in terms of efficiency, power production, maximizing diesel fuel replacement, displaying a wider tolerance to changes in gaseous fuel composition, or ensuring additional improvements in exhaust gas emissions.

The satisfactory operation of dual-fuel engines depends on numerous operating and design variables that tend to be greater in number than those controlling the performance of conventional spark ignition or diesel engines and refereed by Karim (2015).

- The type of fuel used, its composition and heating value, the physical and chemical properties of the fuel, and their variations with temperature and pressure; values of the effective flammability limits and burning rates.
- Intake and exhaust temperatures and pressures, the equivalence ratio values used, the presence of any diluents in the fuel or air supplied, the autoignition characteristics, ignition energy and limits, and their corresponding variations with equivalence ratio and temperature, and operational knock limits.
- The associated operational volumetric efficiency with throttling when employed, the type of pilot fuel employed and its relative size, injection characteristics, and timing.
- Values of the engine compression ratio, bore, and stroke, combustion chamber shape, engine speed range, and any surface activity.

2.2. Pilot Diesel Injection

It was mentioned in previously chapter, pilot diesel injection is an important topic for dual fuel engines and this type of injection related with several parameters. These parameters could be explain and required detailed studies for an effective combustion.

Papagiannakis et.al (2010) studied on a single cylinder, naturally aspirated, air-cooled, high speed, direct injection diesel test engine, located at the authors's laboratory, properly modified to operate under dual fuel (i.e. diesel and natural gas) mode. The results reported here concern brake thermal efficiency, exhaust gas temperature, and NO, CO, HC and Soot emissions for various engine operating conditions, i.e. loads and speeds. Additionally, the maximum percentage of the liquid diesel fuel substituted by natural gas is up to 86%, while the least total relative air-fuel ratio goes down to 1.28 depending on engine operating conditions, i.e. load and speed.

Nwafor (2000) examined the effect of choose of pilot fuel. It mentioned that, test series were designed to find means of replacing a diesel fuel pilot injection with an alternative environmentally friendly pilot fuel for combustion of natural gas in a diesel engine. Natural gas has a high self ignition temperature (704°C) and cannot be used in c.i. engines without a means of initiating combustion since the temperature attained at the end of the compression stroke is relatively lower than the autoignition temperature of the gas. In this case, ignition is brought about by the injection of a small pilot liquid fuel. Baseline test results on the diesel fuel pilot were first established. The gas flow rate for various pilot fuel operations was the same for a given speed and load, and the variable pilot fuel was controlled by the engine governor. Important result could be drawn that, The overall test results indicate that engine performance with the plant oil injection was satisfactory and comparable with the diesel fuel pilot operation.

Sahoo et.al (2009) presented a critical review for effect of engine parameters and type of gaseous fuel on the performance of dual-fuel gas diesel engines. Study has a lot of useful parameters for understanding the dual fuel diesel engines. Paper is

explained the effect of pilot fuel injection timing clearly. According to this explanation, the injection timing of the pilot fuel is an important factor that influences the performance of dual-fuel engines. For a fixed total equivalence ratio, advancing the injection timing increase the peak cylinder pressure because more fuel is burned before TDC and the peak pressure moves closer to TDC. Retarding the injection timing decreases the peak cylinder pressure because more of the fuel burns after TDC. This is because, the pilot fuel combustion is delayed and thus, the temperature of the mixture is not enough to propagate the flame in the whole gaseous fuel_i air mixture; and consequently, incomplete combustion of the gaseous fuel mixture takes place. The charge temperature increases with advancing the injection timing of the pilot fuel and the associated higher energy release rates of the mixture. Similarly, the rates of pressure rise during the combustion of the gaseous fuel increases with advancing the injection timing of the pilot fuel. As s general results concluded by Sahoo et al (2009) consisting the effects of; engine load & speed, pilot fuel injection timing, mass of pilot fuel inducted, engine compression ratio, engine intake manifold conditions and type of gaseous fuels. And mentioned, it seems that dual-fuel combustion using gaseous fuels is a promising technique for controlling both NO and soot emissions even on existing diesel engines with slight modification to the engine structure. The penalty in ϕ_{sfc} experienced is partially compensated by the lower price of gaseous fuels. The observed disadvantages, at low engine load condition, concerning ϕ_{sfc} HC and CO can be reduced by applying modifications in engine tuning, i.e. injection timing of the pilot fuel. Again, in diesel dual-fuel engines the ignition characteristics of the gaseous fuels are still to be understood and needs more research on it. Thus, in overall, the engine operating and design parameters, and selection of type of gaseous fuel has to be chosen accordingly for an existing diesel engine to run on dual-fuel concept. This can minimize the engine performance, combustion and emission characteristics divergences between the existing diesel engine and a dual-fuel diesel engine.

Mbarawa et.al (2001) studied the experiments and modeling of natural gas combustion ignited by a pilot diesel fuel spray. The main of goal of the study expressed as; improve the understanding of how a pilot injection of diesel fuel affects

the combustion of a natural gas/air mixture in an environment approximating that of a diesel cycle. Study included the combustion rate of mixture burning rates of natural gas and diesel and a three-dimensional (3D) numerical model incorporating complex interaction between the fuels during combustion was used. As the results of experiment conclusion, simulation results compare well with the experiments. It was shown that NG combustion in diesel environments can be improved by using an injector with a great number of small holes and by increasing the injection pressure of the pilot diesel fuel, in this case to about 60 Mpa.

Torregrosa et.al (2013) examined the sensitivity of combustion noise and NO_x and soot emissions to pilot injection in PCCI diesel engines. Results showed that, PCCI combustion with two injections reduces NO_x and soot but affects engine torque, PCCI combustion noise level and quality depend on the pilot injection, combustion noise must be improved before PCCI becomes a suitable alternative.

By the way, when stated in combustion noise of dual fuel, Liu (2006) reported that, the power output at constant pilot and speed varies essentially linearly with the extent of fuel gas admission. Also, the noise at very light load tends to be mostly associated with the rapid combustion of the diesel pilot, but decreases rapidly with the increased admission of methane. The noise later becomes much less dependent on the amount of gas burned which can be seen in figure 2.1.

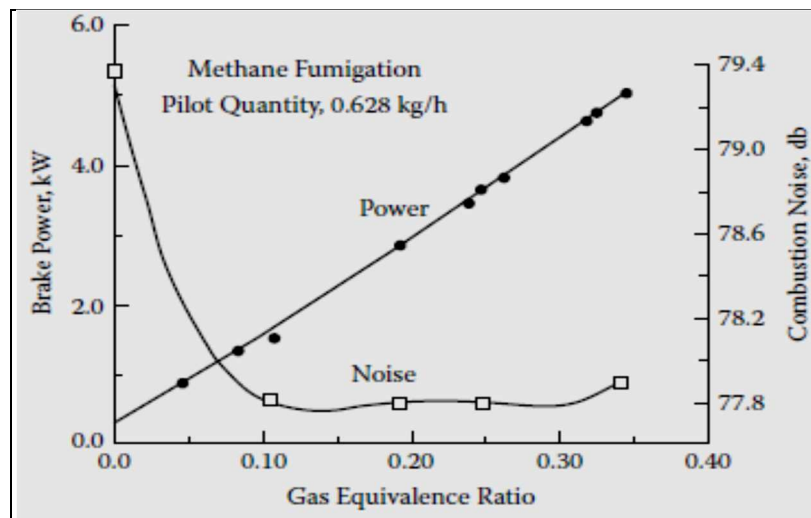


Figure 2.1. Variation of combustion noise output with gas equivalence ratio at constant pilot and speed (Adapted from Liu,2006).

Yang et.al (2015) executed the parametric investigation of natural gas port injection and diesel pilot injection on the combustion and emissions of a turbocharged common rail dual-fuel engine at low load study. They used a common rail diesel research engine was converted to operate in dual-fuel mode and extensive experiments were conducted to investigate the effects of natural gas injection timing on the combustion and emissions performance under different pilot injection pressure and timing at low load conditions in experiment. Consequently they mentioned that, employing appropriate natural gas injection timing accompanied with reasonable pilot injection parameters is critical to further improve combustion performance and exhaust emissions of a dual-fuel engine at low loads. Additionally they related the advanced pilot injection timing and higher pilot injection pressure obtains better BTE and emissions except for NO_x , with the results.

Liu et.al (2013) introduced the results of effects of pilot fuel quantity on the emissions characteristics of a CNG/diesel dual fuel engine with optimized pilot injection timing experiments. They touched upon the emission characteristics of the CNG/diesel dual fuel engine and mentioned, reducing NO_x emissions averagely by 30%, unburned HC emissions are obviously higher, HC emissions occurs by unburned methane around 90% and PM was increased with the increase of pilot diesel quantity.

2.3. Natural gas, Hydrogen, HCNG and HHO (hydroxy) fuels in diesel engines

2.3.1. Natural gas in diesel engines

The attractiveness of natural gas as a vehicle fuel is premised in large part on its low price (on an energy-equivalent basis) compared to gasoline and diesel fuel. While natural gas has other benefits such as producing lower emissions than gasoline and diesel and protecting users of transportation fuels from the volatility of the international oil market it is largely the cost advantage, if any, that will determine the future attractiveness of natural gas vehicles (Ackerman, 2015)

Additionally, in the Advancing Technology for America's Transportation report (chp.2) (2012), heavy-duty engines with perspective of 2015-2050; CNG vehicles are the strongest economic competitor to liquid ICE vehicles. As natural gas supplies have increased and prices have dropped, automakers and truck manufacturers have begun taking steps to introduce new vehicle lines fueled by natural gas, principally compressed natural gas (CNG) and liquefied natural gas (LNG). Several factors have referred from Ackerman (2015) and contributed to this interest:

- ☑ *Price differential.* On an energy-equivalent basis, oil has been more expensive than natural gas in recent years. Moreover, while oil prices are set in a global market, U.S. natural gas prices are largely determined domestically, and the discovery of large domestic reserves suggests that prices may remain relatively low.¹
- ☑ *Environmental preference.* Natural gas, while also a fossil fuel, generally produces lower emissions per vehicle km than diesel and heavier oil.
- ☑ *Energy diversity and security.* Increased use of domestic natural gas for transportation may mean that less oil will be imported. The United States might be more insulated from global petroleum price volatility if more forms of transportation were based on natural gas.
- ☑ *Growth potential.* Only 2.9% of U.S. natural gas production is currently used in transportation, mainly to move gas through the pipelines, and expanded use of natural gas vehicles would likely lead to increased demand for natural gas.

Due to its high auto ignition temperature, natural gas needs an ignition source when used in engines, and two paths are in use today: spark ignition and compression ignition, using diesel fuel as the ignition source.

Both approaches are typically built off existing diesel engine blocks to retain the structural robustness and durability required in this market. The choice of ignition approach drives many of the subsequent technical requirements. Some of the key technical characteristics of the two approaches are summarized in Figure 2.2. (Advancing Technology for America's Transportation report (chp.14) (2012).

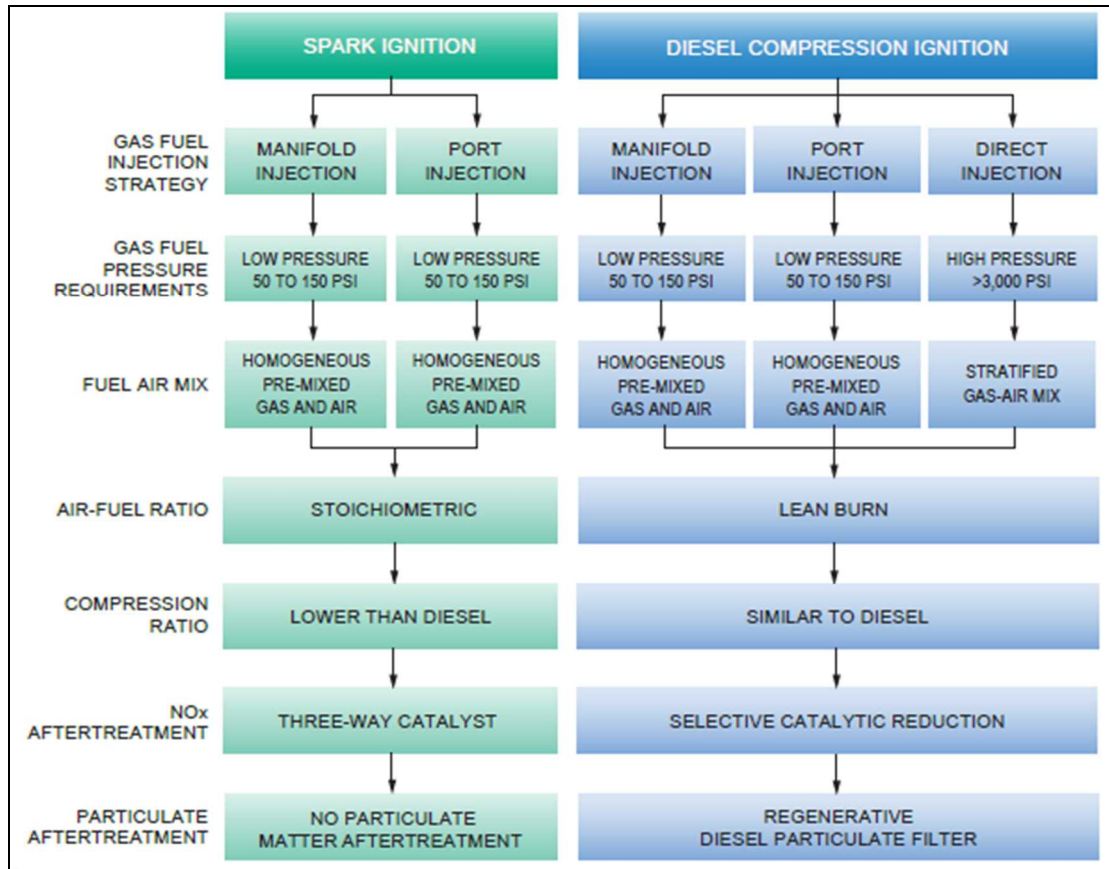


Figure 2.2. Technical approaches to NG Heavy-Duty engines. (ATAT report, 2012)

The preferable properties on economical and environmental benefits of natural gas, impelled the scientists to this hardly motivated research area for few decades.

Papagiannakis and team (2003, 2004, 2007, 2010 and 2012), studied on the dual fuel compression ignition engine operated with pilot diesel fuel and natural gas, both experimentally and theoretically. Generally approach on their studies under a single cylinder, naturally aspirated, four-stroke, air-cooled, direct injection, high speed, having a bowl-in-piston combustion chamber Lister LV1 diesel engine, that; dual fuel combustion using natural gas as a supplement for liquid diesel fuel is a promising technique for controlling both NO and soot emissions. And they mentioned the observed disadvantages concerning brake efficiency, HC and CO can be possibly mitigated by applying modifications on the engine tuning, e.g. injection timing of liquid diesel fuel mainly at part loads.

Karabektak et al. (2013), examined the effects of using diethyl ether as additive on the performance and emissions of a diesel engine fuelled with CNG. They used a single-cylinder, water cooled, direct injection, naturally-aspirated, Super Star diesel engine as a test bench. They concluded that, the use natural gas as a dual fuel has a significant negative effect on the engine performance at low and medium loads. However, the engine performance improves at high engine loads. The use of natural gas as a dual fuel causes lower NO emissions at low and medium loads, while yielding higher NO emissions at high loads compared with the use of dual fuel. CO and HC emissions increase considerably with the use of natural gas at low and medium loads, while showing a decreasing trend at high loads. The addition of DEE to pilot fuel in a diesel engine using dual fuel causes lower specific energy consumption and higher brake thermal efficiency.

Carlucci et.al (2011) studied the combustion and emissions control in diesel/methane dual fuel engines: The effects of methane supply method combined with variable in-cylinder charge bulk motion. In the tests, diesel common rail research monocylinde engine used with 17.1:1 compression ratio. In the results, they demonstrated that; the port injection, as a methane supply method for dual fuel engines, is a very effective strategy to reduce unburned hydrocarbons and nitric oxides concentrations, especially when implemented with variable intake geometry systems to produce the suitable in-cylinder bulk motion and turbulence intensity for different engine operating parameters.

Bakar et.al (2012), presented the study of application of natural gas for internal combustion engines, which they compared the diesel engine and conversion to natural gas engine from the same engine. They introduced that, the original diesel engine cylinder pressure is higher than the modified diesel engine and CNG engine. It caused the compression ratio of NG engine is lower than the original diesel engine and the combustion energy output of diesel fuel has to produce the highest power than natural-gas fuel. Decreasing engine speed of NG engine has increase maximum temperature in engine. Engine torque, power, mean effective pressure and efficiency performance of original direct injection diesel engine cylinder pressure is higher than the modified diesel engine and sequential port injection dedicated NG engine.

It meant that the thermodynamics energies were resulted from the diesel fuel combustion is higher than the NG fuel. It caused by the hydrocarbon chain, density and energy of diesel fuel of the diesel engine is higher than the gas fuel of NG engine were ignited using to spark assistant. The fuel consumption of NG engine is higher than the diesel engine. Fuel consumption is increased because the unburned fuel is increased in the medium to the highest speed of NG engine. The effect of the increasing unburned fuel is can decrease the engine brake torque and brake power. The effect of lower brake torque and brake power increases the brake specific fuel consumption. (*Important Note: To avoid such as these problems; in this thesis, the diesel engine has not required any modifications by dint of the help of pilot injection.*)

Mbarawa and Milton (2005) added theirs study in to the literature with the aspects of an examination of the maximum possible natural gas substitution for diesel fuel in a direct injected diesel engine. The engine used in their study was a Cummins Model 519, a six cylinder, naturally aspirated, four stroke DI diesel engine. As results drawn with; stable engine operation could be maintained with as much as 86 % NG energy substitution for diesel fuel. At low speeds of 1200 rpm to 1300 rpm, the maximum substitution of NG to 86% could provide torque levels equivalent to those for full load diesel fuel only operation; the overall equivalence ratios for DF exceeded those for straight diesel fuel operational mode at all loads and emissions of CO were higher for dual fuel than those for diesel fuel only operation.

Korakianitis et.al (2011) earned a useful review task to literature that, Natural-gas fueled spark-ignition (SI) and compression-ignition (CI) engine performance and emissions. They compared the open literature for SI and CI engines. In conclusion part, they expressed that, there is no significant loss in power in dual-fuel operation compared to conventional CI-engine operation provided a sufficient amount of natural gas-air mixture can be admitted in the chamber. In some of the literature the induction method employed prevents a premixed natural gas-air mixture to form in the inlet manifold (by keeping the natural gas supply separate from the incoming air until very close to the intake valve).

This minimizes the volumetric efficiency penalty of natural gas induction or injection in the intake manifold, but it also results in a loss of power at higher speeds because comparatively lower amounts of natural gas are inducted per cycle. Failure of the pilot fuel to ignite the entire natural gas-air charge at the low and intermediate loads (as a result of low charge temperatures) causes lower thermal efficiencies. Low engine operating temperatures at these loads also result in lower NO_x emissions compared to normal CI-engine operation. Conversely, HC and CO emissions are significantly increased, while at high loads NO_x, HC and CO emissions are comparable to normal CI-engine levels. A variety of alternative high-cetane fuels can be used as pilot fuels, while water-in-fuel pilot fuel emulsions and water injection can be used to reduce emissions at select equivalence ratios. And they had attracted attention in the suggested future work that, the effects of various additions such as EGR or water (to reduce NO_x) or *hydrogen (to accelerate combustion progress)* are *even less well known*. A few computational studies are available in the open literature, but quality experimental data to provide basic insight or to validate the numerical work are currently not available. *(Note: To decrease this less well know situation; this thesis introduced the effects of engine performance and exhaust emissions of hydrogen and HHO addition to CNG mixtures experimentally.)*

Kavtaradze et.al (2005) from Munich Technical University, calculated the ignition delay parameters in a diesel engine utilizing different fuels. They have suggested a theoretical-and-experimental method of determining the time of ignition delay, based on the chain theory of combustion of Semenov. And they focused that, Formulas have been derived for the first time for the calculation of the time of ignition delay for advanced gas fuels (natural gas, various options of synthesis gas), as well as for conventional diesel fuel in view of recirculation of exhaust gases. Additionally, the suggested method may be employed to determine the ignition delay for almost any fuel used in diesel engines.

2.3.2. Hydrogen in diesel engines

Hydrogen is a long-term renewable and less-polluting fuel. In addition hydrogen is clean burning characteristics and better performance drives more interest in hydrogen fuel. All over the world, the countries has been preparing their hydrogen program. Karim (2015) listed the advantages and challenges of hydrogen as a fuel;

Following favorable characteristics can be assigned to hydrogen:

It is a renewable fuel that can be manufactured from widely available sources, such as water, through the expenditure of energy.

It is a clean fuel that produces much less exhaust emissions on combustion than other fuels. Its exhaust gas produces water and, on condensation, energy through cogeneration. However, its combustion in air produces oxides of nitrogen.

Hydrogen is catalytically sensitive and has some very attractive combustion characteristics, such as clean combustion, fast burning rates, and a wide flammable mixture range. It requires low ignition energy, but with relatively high autoignition temperatures. It has a very high heating value on mass bases with high flame temperatures. It is highly buoyant, diffusive, and remains a gas down to extremely low cryogenic temperatures.

However, at present there are some limitations to its wide application as a fuel, especially in engines:

It requires much useful energy for its manufacture and lacks at present the infrastructure for its wide distribution, resulting in its high cost on an energy basis in comparison to other fuel resources.

It has potential problems relating to safety, material compatibility, portability, storage, handling, and transport. It is extremely difficult to liquefy and keep as a liquid, requiring much useful work.

It has a very low heating value on volume and liquid bases, with its flames having very low luminosity.

From the point of view, Ciniviz and Köse (2012)'s review study listed the topics on combustive properties of hydrogen as; wide range of flammability; small quenching distance; flame velocity and adiabatic flame; minimum ignition source energy; high diffusivity; low density; high auto-ignition temperature; stoichiometric air-fuel ratio and mixture energy content. Drawbacks were also listed as; pre-ignition, backfire, autoignition and knock.

Again, Ciniviz and Köse (2012)'s review study touched upon the hydrogen usage on diesel engines and reported that, hydrogen increases the H/C ratio of the entire fuel. Secondly, injecting small amounts of hydrogen to a diesel engine could decrease heterogeneity of a diesel fuel spray due to the high diffusivity of hydrogen which makes the combustible mixture better premixed with air and more uniform. However hydrogen cannot be used as a sole fuel in a compression ignition (CI) engine, since the compression temperature is not enough to initiate the combustion due to its higher self-ignition temperature.

Additional literature comes from Lilik et.al (2010) and explained this situation with "Hydrogen has an autoignition temperature of 858 K requiring an ignition source to burn in an IC engine. Diesel fuel, which has an autoignition temperature of 525 K, can be used as a pilot fuel to ignite hydrogen. The literature contains many reports in which hydrogen was used in conjunction with diesel fuel to power CI engines. This "dual-fuel" combustion is often called "*diesel pilot-ignited hydrogen combustion*." Diesel pilot-ignited hydrogen combustion at low quantities of hydrogen is beneficial since the diesel fuel is being replaced by hydrogen, which may stretch the supply of hydrocarbon fuels, but a range of emissions impacts have been reported for this process.

Referring to continue with Ciniviz and Köse (2005), the pilot fuel quantity may be in the range of 10-30% while the rest of the energy is supplied by the main fuel. Hydrogen operated dual fuel engine has the characteristics to operate at leaner equivalence ratios at part loads, which results in NO_x reduction, and increase in thermal efficiency thereby reducing the fuel consumption. Oxides of nitrogen (NO_x)

are the major problem in hydrogen operated dual fuel engine. (*This NO_x problem can be solved with the mixture of hydrogen and cng which used in this thesis, HCNG; and explained next subheading.*)

Saravanan and Nagarajan (2008) conducted a study that introduced the experimental investigation of hydrogen-enriched air induction in a diesel engine system. They used a four-stroke, water-cooled, single cylinder stationary diesel engine developing power of 3.78kW at the rated speed of 1500 rpm. Beside they mentioned the system of study with the process of mixing air and fuel is called enrichment. By varying the percentage of diesel (10%, 30%, 50%, 70%, 80% and 90%) by volume (l/min), they studied the performance and emission characteristics of the hydrogen-enriched engine. The pilot quantity of diesel was set and the pump rack locked and hydrogen flow varied simultaneously to maintain a constant speed. They arranged the conclusions with; brake thermal efficiency outputs increased to 29.1% with 90% hydrogen enrichment, but results in knocking. Best results are obtained with 30% hydrogen: an efficiency of 27.9% is achieved without knocking over the entire load range. Specific energy consumption decreases with increase in hydrogen percentage over the entire range of operation. PM decreased significantly from 4 to 1 g/kWh with 90% hydrogen enrichment. Figure 2.3., illustrated for shown the effect on performance in terms of hydrogen as variation of heat release with crank angle at 30% hydrogen enrichment mixture at full load condition (Saravanan, 2008).

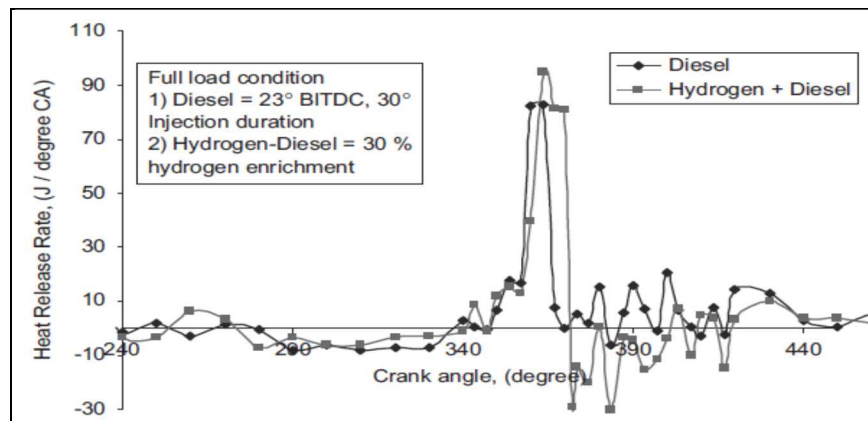


Figure 2.3. Variation of heat release with crank angle at 30% hydrogen enrichment mixture at full load condition (Adapted from Saravanan, 2008).

Maki and Prabhakaran (2011), investigated the performance and emissions of a multi cylinder diesel engine fueled with hydrogen-diesel blends experimentally. They used a test bench which consisted with a four cylinder, four stroke, water cooled, indirect injection, naturally aspirated, and compression ignition engine and running at varied speed equipped with a hydrogen induction system and an eddy current dynamometer with variable loading arrangement. Their result showed that; a continuous hydrogen induction into the inlet manifold is a unique way of addressing simultaneously issues related to thermal performance and pollutant emission from diesel engine operated with diesel as a fuel. There was a monotonous effect of continuous hydrogen induction rate on thermal performance parameters such as brake thermal efficiency, diesel fuel consumption rate and volumetric efficiency. And they mentioned that, it was seen that hydrogen induction rate about 7.5 lpm gives an optimum performance keeping the emissions level at a reasonable low levels. At 7.5 lpm, the levels of CO, CO₂ and HC are not increase significantly while the NO_x is reduced and same rate approximately reduced the diesel fuel consumption by 20% and increased the brake thermal efficiency by about 8~9%.

Verhelst and Wallner (2009) have written an important review and given the all details about hydrogen with the 281 references. Hydrogen-fueled internal combustion engines from Verhelst and Wallner (2009) enclosed the introduction, fundamentals, modeling regular combustion, abnormal combustion, measures for engine design or conversion, mixture formation and load control strategies, hydrogen safety, hydrogen internal combustion engine vehicles, hydrogen in combination with other fuels and conclusions. Hydrogen vehicles overview is illustrated in figure 2.4.

Name	Year	Engine	Tank	Capacity	Range	Units made
Rivaz	1807	1-cyl	Compressed			Prototype
Lenoir	1860	1-cyl	Water electrolysis			Prototype
Norsk Hydro	1933		Ammonia reforming			Prototype
Musashi 1	1974		Compressed	7 Nm ³		Prototype
Musashi 2	1975		Cryo	230 L		Prototype
Musashi 3	1977	2-stroke	Cryo	65 L		Prototype
BMW	1979	3.5 L	Cryo		300 km	
Ford P2000	2001	2.0 L I4	Compressed	1.5 kg	100 km	
BMW Hydrogen 7	2003	6.0 L V12	Cryo	8 kg	200 + 480 km	~100
Mazda RX-8 Hydrogen RE	2003	2 × 654 cc	Compressed	2.4 kg	100 + 550 km	>30
Ford Shuttle Bus	2004	6.8 L V10	Compressed	29.6 kg	240–320 km	
ETEC Silverado	2004	6.0 L V8	Compressed	10.5 kg	up to 335 km	~20
Quantum Prius	2005	1.5 L I4	Compressed	1.6 kg (reg.)/2.4 kg (ext.)	100–130 km	>30

Figure 2.4. Hydrogen vehicles overview, Verhelst and Wallner (2009).

Tang et.al (2014) mentioned a review which titled with Progress in combustion investigations of hydrogen enriched hydrocarbons. More dominantly goal of hydrogen expressed as; hydrogen is a versatile energy carrier that can be made from a variety of primary energy sources such as natural gas, coal, and biomass, and non-carbon energy sources such as solar, nuclear, hydroelectric, and wind. Hydrogen can burn with high efficiency and produce essentially zero emissions. However, attractive as it is, a hydrogen economy is challenged by technical, economical and infrastructural barriers. For instance, there are significant difficulties associated with hydrogen storage due to its high flammability limits, low ignition energy (which causes safety problems), and its low volumetric energy content, which requires extra energy for high pressure storage. Additionally, there exists some unresolved issues for pure H₂ combustion, such as knock, detonation, pre-ignition, and flash-back. For these reasons, fossil fuels still dominate the current primary energy supply. To bridge this situation, a more rational approach is to use hydrogen/hydrocarbon fuel blends, which synergistically resolve storage and combustion problems associated with burning pure hydrogen or pure hydrocarbons.

2.3.3. HCNG fuel in diesel engines

This part of thesis was formed from the Arat et.al (2013)'s paper which titled "A review of hydrogen-enriched compressed natural gas (HCNG)-fuel in diesel engines".

Introduction: The difficulty of controlling prices and the uncertain reserves are strong incentives for pursuing energy security. Global warming and local pollution hot spots associated with fossil fuel usage are further significant environmental and societal problems. Natural gas and hydrogen blends can be a viable alternative to pure fossil fuels because of the expected reduction of the total pollutant emissions. These blends offer a valid opportunity for dealing with a sustainable development in transportation sector, in view of the future more stringent emission limits for road vehicles in European Countries. HCNG (hydrogen-enriched natural gas) as a new engine fuel not only owns the advantages of hydrogen and

CNG but also overcomes their disadvantages. Using HCNG fuel can improve the fuel economy, decrease CO (Carbon Monoxide), HC (Hydrocarbon) and CO₂ (Carbon Dioxide) emissions and realize lean burn. The gaseous fuels are getting more positive response from researchers and end-users compared to past because of current unfolding developments. Therefore, it is more economical and of environmental advantage to use gaseous fuel in diesel engines that use the dual-fuel concept. Most researches have focused on the use of natural gas as an alternative fuel, mainly due to its wide availability, clean burning and low cost compared to other gaseous fuels. In spite of the advantages of natural gas, it has some disadvantages such as low burning velocity and poor lean burn capability. These problems lead to engines having high cyclic variation, longer combustion duration and lower power output. Hydrogen is the best additive candidate to natural gas due to its unique characteristics. Moreover, hydrogen has a wide flammability range which allows higher efficiency with leaner operation for reduced toxic emissions, low ignition delay, and higher flame stability. The effect of adding hydrogen to natural gas can lead to shorter burning time, extended flammability and leaner limits of the mixture. Moreover, hydrogen addition could broaden the range of EGR while maintaining low cyclic variations and low level of NO_x emissions. Hythane is a patented mixture of hydrogen and CNG, created by Hydrogen Components, Inc. in Littleton, Colorado. According to US Patent #5,139,002 (Lynch & Marmaro, 1992), Hythane® was invented by Frank Lynch and Roger Marmaro and was granted a US patent in 1992. In this patent, Hythane is defined as a blend of hydrogen and natural gas provided for burning in an engine without the need for modifications to engine parameters, and is defined as roughly a 15% blend of Hydrogen in CNG fuel and several demonstrations have been carried out in North America, often with limited commercial operation, (Denver, 1992, Montreal, 1995-1996, Thousand Palms, 1999 and on, Las Vegas, Phoenix, etc.) and more lately in Europe (Sweden, Italy) and Asia (India and China). When used in an internal combustion engine, even the addition of small amount of hydrogen to natural gas (5-30% by volume) leads to many advantages, because of some particular physical and chemical properties. According to Dalton's partial pressure law, hydrogen fraction was decided by the partial

pressure of these two fuels in HCNG tank. The influence of gas composition on engine behavior can be adequately characterized by Wobbe index. If the Wobbe index remains constant, change in the gas composition will not lead to a noticeable change in the air-fuel ratio and combustion rate.

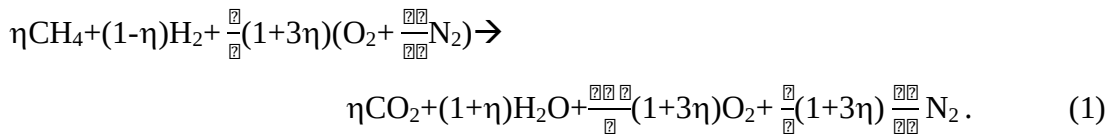
Engineering properties of HCNG: As we mentioned HCNG is a newly dual-fuel which contains of natural gas and hydrogen components using in the ICEs. Figure 2.5 illustrated the properties of methane and hydrogen. The mole fractions of OH (Hydroxyl) and O increase with hydrogen fraction, while the increase of OH and O improves the rate of combustion and reduces the emissions of HC and CO. This explains that hydrogen addition is good for CNG combustion in molecular scale [3].

property	Unit	Methane	Hydrogen
Molar mass	kg/kmol	16.043	2.016
Density (at 1 bar, 25 °C)	kg/m ³	0.648	0.081
Stoichiometric air requirement	kg _{air} /kg _{fuel}	17.2	34.3
	Vol%	9.5	29.5
Lower gravimetric energy density (calorific value)	MJ/kg	50	120
Lower volumetric energy density (350 bar, 25 °C)	MJ/dm ³	11.6	2.8
Mixture calorific value (in air at 1 bar, 25 °C, $\lambda = 1$) external mixture formation	MJ/m ³	3.40	3.19
Mixture calorific value (in air at 1 bar, 25 °C, $\lambda = 1$) internal mixture formation	MJ/m ³	3.76	4.52
Ignition limit (in air at 1 bar, 25 °C)	Vol%	4.4 ÷ 15	4 ÷ 76
	λ -Bereich	2 ÷ 0.6	10 ÷ 0.13
Auto-ignition temperature (in air at 1 bar)	°C	595	585
Laminar flame speed (in air at 1 bar, 25 °C, $\lambda = 1$)	cm/s	≈ 42	≈ 230

Figure 2.5. Properties of methane and hydrogen (adapted from Klell et.al (2012) by Arat et.al (2013))

The laminar burning speed of hydrogen is nearly eight times higher than that of natural gas, so the addition of hydrogen can increase the burning velocity of the mixture, and it brings some advantages such as shorter combustion duration, greater degree of constant volume combustion and improved indicated thermal efficiency and it is also noted that the quench distance of hydrogen is much smaller than that of natural gas, the heat loss to chamber wall will be increased by addition of hydrogen into the natural gas. With other words, enriching natural gas with hydrogen for use in an internal combustion engine is an effective method to improve the burn velocity, with a laminar burning velocity of 2.9 m/s for hydrogen verses a laminar burning velocity of 0.38 m/s for methane. Dual-fuel engines or ‘gas diesel engines’ usually have the gaseous fuel mixed with the air in the engine cylinders, either through direct mixing in the intake manifold with air or through injection directly into the cylinder.

The resulting mixture after compression is then ignited through the injection of a small amount of diesel fuel (the pilot) in the usual way. This pilot liquid fuel auto-ignites to provide ignition sources for subsequent flame propagation within the surrounding gaseous fuel mixture. With increasing hydrogen content, the irreversibility produced during combustion decreases as a percentage of total injected fuel availability, and the second-law efficiency increases. A general chemical HCNG Equilibrium (Eq.1), the combustion of 1 mol of fuel composed of η moles of CH_4 and $(1-\eta)$ moles of H_2 . Assuming complete combustion of the fuel in air with a given air-to-fuel ratio (ϕ):



Effects of HCNG on diesel engine performance: The natural gas/hydrogen blends maintained high thermal efficiency at high engine load and the effective thermal efficiency is almost constant or slightly increases with the increase of hydrogen fraction at the small and medium engine loads; Two factors due to hydrogen addition influence the variation of thermal efficiency; on one hand, the increase of combustion velocity by hydrogen addition shortens the combustion duration and increases the thermal efficiency, and on the other hand, the heat loss to the chamber wall will be increased by hydrogen addition due to the decreased quench distance and increased combustion temperature, and this will decrease the thermal efficiency. Brake effective thermal efficiency increased with the increase of hydrogen fraction at low and medium engine loads and high thermal efficiency is maintained at high engine load, which makes it an ideal fuel for high load applications and heavy-duty vehicles. One an important detailed about CNG vs HCNG is the brake thermal efficiency for HCNG is greater than CNG for the same excess air ratio (ϕ) and the difference in brake thermal efficiency between HCNG and CNG increases with increasing excess air ratio. Also experimental results indicated that under certain conditions, the maximum cylinder gas pressure, maximum heat

release rate increased with the increase of hydrogen fraction. The beginning of heat release advanced with the increase of hydrogen fraction. Another advantage to lean burn is that as the excess air ratio is increased, the brake specific fuel consumption decreases. This is because as the air-fuel ratio is increased, it usually leaves less unburned fuel. That is true until the excess air ratio reaches a certain limit when the cycle-by-cycle variations begin to increase because of the lack of fuel. Lean operation also reduces the likelihood of knocking, which allows the use of a higher compression ratio. The addition of hydrogen can greatly improve the performance and emissions of the fuel. There have been many studies completed in efforts to obtain the ideal hydrogen ratio, and the general consensus is that hydrogen/natural gas blends around 20%, results in the best overall combination of emissions and engine performance.

Fundamentally, the addition of hydrogen provides a large pool of H and OH radicals whose increase makes the combustion reaction much easier and faster, thus leading to shorter burn duration. With these important engine performance criterions, the pilot injection phenomena and combustion chamber issue should not be forgotten. The optimized design of the combustion chamber is an important way of improving the mechanism of HCNG combustion. The engine operating and design parameters include load, speed, compression ratio, pilot fuel injection timing, pilot fuel mass inducted, intake manifold conditions, and type of gaseous fuel. The amount of pilot fuel needed for this ignition is between 10% and 20% of the operation on diesel alone at normal working loads and the amount differs with the point of engine operation and its design parameters. For a dual-fuel engine or gas diesel engines, diesel combustion phases occurs five parts; the pilot ignition delay , pilot premixed combustion , primary fuel ignition delay, rapid combustion of primary fuel, and the diffusion combustion stage. Summarily, increasing the load at constant speed results in an increase in the mass of gaseous fuel admitted to the engine, since the pilot mass injected remains constant at all loads. This increase in the mass of methane then causes an increase in the ignition delay period of pilot diesel which then auto-ignites and starts burning the gaseous fuel at a higher rate of pressure rise.

Effects of HCNG on diesel engine emissions: When it comes to alternative fuels, arguably the most important factor in determining the feasibility of the fuel is the exhaust emissions. Because of the strictly controlled emissions regulations, it is not only necessary to find a fuel that has optimum performance, but it is also very important to find a fuel that can meet the respective emissions standards. Considering emissions, when HCNG fuel is compared with gasoline and diesel it appears to be a very appealing alternative fuel. When compared with diesel, it nearly eliminates the particulate matter which is often of great concern. Methane has a relatively stable chemical structure, therefore making it difficult to reduce emissions by after treatment. For this reason, the engine fueled with HCNG has a large advantage regarding the hydrocarbon emissions than that of CNG fueling. Probably the largest advantage to running the engine on lean burn is that it has the ability to greatly reduce the NOx emissions. The reduction in NOx emissions are due to the increased airflow which causes the engine to run at a lower temperature, therefore reducing the NOx emissions. Emissions can also be improved with the addition of hydrogen. Compared to pure natural gas, HCNG reduces the HC emissions, which is in part due to the increased combustion stability that comes with the addition of hydrogen. However, due to the increased temperature and combustion duration that accompanies the hydrogen addition, an increase in NOx emissions is observed. Figure 2.6., represented the emission potential of HCNG engines.

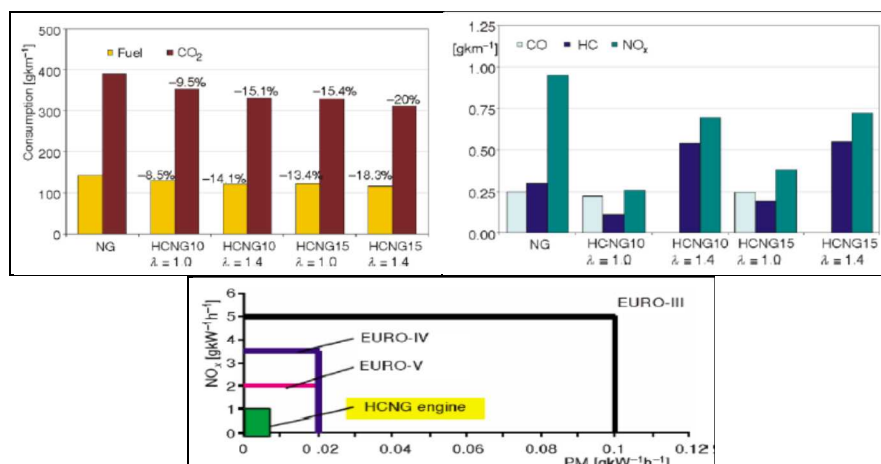


Figure 2.6. Emission potential of HCNG engine (referred from Nanthagopal et al. (2011) by Arat et.al (2013))

Challenges of HCNG: One of the biggest challenges using HCNG as a fuel for engines is determining the most suitable hydrogen/natural gas ratio. There is a minor reduction in power output and higher BSFC for the engines at high engine loads and it is important to take prevention on HCNG storage and supply infrastructure.

Conclusions: Researchers in various countries have carried out many experimental and numerical studies using gaseous fuels as diesel engine fuel substitute in a dual-fuel mode of operation. An attempt has been made here to review the previous studies on dual-fuel concept minimizing with hydrogen-enriched natural gas, known as HCNG or Hythane. The overall observation from these experimental results is that the engine operating and design parameters and type of gaseous fuel play an important role in the performance of HCNG engines. Addition of hydrogen and natural gas blends effects of engine performance and emissions were mentioned with detailed. Engineering fundamentals and properties of HCNG were examined and discuss in the review. Lastly look through the challenges of HCNG fuel which use in diesel engines. Especially research on hydrogen and natural gas blends (in more particular HCNG) combustion in the IC engine has intensified, the number of published papers in the field of hydrogen and natural gas diesel combustion is not as rich as for the hydrogen and/or natural gas used in spark ignited engines. According to this situation, authors survey the limited previous works and curve out the review of HCNG in CI engines.

2.3.4. HHO (Hydroxy) gas in diesel engines

Water can be decomposed into hydrogen and oxygen molecules due to an electric current with using suitable conditions with electrolyses like a fuel cell. Before starting the previous studies, it can be noted that, the number of published papers in the field of HHO-diesel combustion is not as rich as for the HHO-SI engines.

HHO-diesel fuel's first previous study began with our colleague, Yılmaz et.al (2010). They used the same test engine and dynamometer which be used in this

thesis. They prepared a hydrogen generator (Plexiglas reactor) and used various ion conducting ions as; KOH, NaOH, NaCl. Besides, they produced a hydroxy electronic control unit (HECU) and manufactured to decrease HHO flow rate by decreasing voltage and current automatically by programming the data logger. They concluded the results with HHO system addition to the engine without any modification, an increasing engine torque output by an average of 19.1%, reducing CO emissions by an average of 13.5%, HC emissions by an average of 5% and SFC by an average of 14%. It is stated and noted here that, the major differences with current thesis; in their studies there was not used pilot injection or replacement of diesel liquid fuel so they used the enrichment of HHO to diesel engine. Additionally HHOCNG is using for the first time in literature with this thesis. Whereat these parameters, the results of the thesis and their studies tended to differ and detailed discussion of this case given in chapter 4.

Birtas and Chiriac (2011) studied on a study of injection timing for a diesel engine operating with gasoil and HRG gas with simulation method. They used a 3.8 L, naturally aspirated, direct injection and 17.5:1 compression ratio diesel engine to predict the simulation. They mentioned the results of the study as; the simulations performed with the AVL Boost program have showed that for reduced HRG flow rates and optimized diesel fuel injection timing. Slight increase in the engine brake thermal efficiency and moderate increase of the maximum cylinder pressure was obtained. Significant smoke and CO emission were reduced, but important NO_x emission increase was performed. These aspects seem to be particularly interesting from the perspective of modifying the injection characteristic of the injection pump, in direction of advancing the static injection timing.

Bari and Esmaeil (2010) investigated the impacts of using a small amount of H₂/O₂ mixture as an additive on the performance of a four-cylinder diesel engine. The required amount of the mixture was generated using electrolysis of water considering on-board production of H₂/ O₂ mixture. Hydrogen which has about nine times higher flame speed than diesel has the ability to enhance overall combustion generating higher peak pressure closer to TDC resulting in more work. The results of their study showed that with the introduction of 6.1% total diesel equivalent H₂/O₂ mixture into

diesel, the brake thermal efficiency increased by 2.6% at 19 kW, 2.9% at 22 kW, and 1.6% at 28 kW. The brake specific fuel consumption of the engine reduced by 7.3%, 8.1%, and 4.8% at 19 kW, 22 kW, and 28 kW, respectively.

Zamit et.al (2012) investigated experimentally the effects of hydrogen enhanced combustion with comparisons between SI and CI engines on performance and emissions. They used two different HHO generator (additional HHO volume: 0.3 lpm and 1.67 lpm) and three different engines (Ford 1L and 1.4L petrol and peugeot1.8 L diesel). They suggested that, a comparison of operation at peak efficiency and peak power output with and without HHO addition showed that in most cases the increase in output power was still not enough to produce the hydrogen, even if a 75% efficient hydrogen generator was to be used. They referred that, test results showed, in agreement with the findings of other researchers, that hydrogen addition produced the best effects at lean mixture operation and HHO addition also extended the lean limit of the engine under many of the testing points.

Samuel and McCournic (2010) studied the hydrogen enriched diesel combustion. In experiments, they used a single cylinder research diesel engine under conducted 1500 rpm and 5.3 bar load with 2.8 lpm HHO addition. As a result, they introduced that, demonstrated that a device that can electrolyze the water using a conventional battery system can be used to enrich the air with HHO without modifying the engine at all. Their system provided up to 5.4% fuel economy and a similar reduction in CO₂ values. Increased amount of oxy-hydrogen to the intake system reduced the duration of combustion and increased the rate of pressure rise with out altering the location of combustion.

2.4. Minor Conclusion of Literature Survey Results

Related studies with this current thesis were preferred and discussed in this chapter. Approximately, 526 studies were reviewed, that included with books, research papers, PhD and MSc thesis, actual reports, etc. and 140 of them performed in references part of this thesis.

The major expectations from an alternative fuel titled with three important issues; (*This 3E will give direction to future development status of any fuels.*)

- ✓ Economy
- ✓ Efficiency
- ✓ Environmentally

If the CNG, HCNG and HHOCNG fuels are evaluated according to 3E system; the minor conclusions of this chapter approach draw following suggestions:

- ✚ Dual fuel usage on a non-modified diesel engine with operated pilot diesel injection under lean combustion plays preferable condition for 3E.
- ✚ When it comes to economical circumstance, alternative gaseous fuels have very attractive position for now and the future.
- ✚ When compared the diesel fuel; CNG, HCNG and HHOCNG fuels and mixtures are superior conditions on environmentally aspects with lower exhaust gas emissions.
- ✚ Especially hydrogen and/or HHO addition to the CNG with the percentages between 10-30%, affected positively the 3E argument with BSFC and exhaust emissions reductions at that time increases engine performance.
- ✚ Researchers and scientists touched upon the importance of gaseous fuels safety and on board infrastructures (re-fuelling, storage, on-board conditions and compartment safety, etc.).

- ✚ Combustion parameters (some of them were listed at the entrance of this chapter) are very important for dual fuel gaseous diesel engines and tended to need increase advancement.
- ✚ HHO needs more attention from the point of engineering properties and quantity of usage as a fuel.
- ✚ At the end, it may point out that, if today the use of mineral liquid fuels produces enormous pollution problems, tomorrow hydrogen will solve all environmental problems due to road transports.

3. MATERIAL AND METHOD

This chapter details the experimental procedure and overview of the substitution of diesel fuel as pilot injection. Test engine and dynamometer, measurement devices, gas fuels supplements and properties, determining the substituted diesel and gaseous fuel mixture ratios, usage of stepping motor and driver and accuracies of measurement devices were described in this chapter.

3.1. Experimental Procedure

3.1.1. Test Engine and Dynamometer

All tests are carried out on a 3.6 L, non-modified, commercial, four cylinders, four-stroke, naturally aspirated, water-cooled direct injection compression ignition engine which located in Automotive Engineering Laboratories, Faculty of Engineering in Çukurova University. Table 3.1 presented the engine specifications and Figure 3.1 and 3.2 illustrated the engine photographs with the differences with the base and equipped one. A Netfren mark hydraulic dynamometer was used for loading the test engine with the properties of torque range: 0-1700 Nm and speed range: 0-7500 rpm. S type load cell is used to measure the torque of dynamometer (Stainless steel which has a sensitivity of 1/3000) Dynamometer control unit was used for receiving and collecting all the data that was used by the system. The speed sensor used to detect prime mover speed is the magnetic pickup (MPU). When a magnetic material (usually a gear tooth driven by the prime mover) passes through the magnetic field at the end of the magnetic pickup, a voltage is developed. The frequency of this voltage is translated by the speed into a signal which accurately depicts the speed of the prime mover. Exhaust gas temperature is measured by a K type thermocouple. The thermocouple is located in the exhaust pipe closed to the cylinder block of the engine. Fuel quantity is measured by a load cell unit. Then, fuel consumption (g/s) is calculated with the aid of a control unit.

Table 3.1. Test Engine Specifications

Brand	Mitsubishi Canter
Model	4D32 - In line 4
Type	D.I. diesel with glow plug
Displacement and (BxS)	3567cc and 104mm*105mm
Power	78kW @ 2750rpm
Torque	235Nm @ 1400rpm
Compression Ratio	17.5:1
Start of injection (BTDC)	23
Oil cooler	Water cooled
Air cleaner	Paper element type
Weight	325kg



Figure 3.1. Base test engine



Figure 3.2. Equipped test engine

3.1.2. Measurement Devices

3.1.2.1. Exhaust gas analyzer and Data logger

In tests, MRU Delta 1600 V brand gas analyzer was used to measure exhaust gas emissions and ELIMKO PR-100 data logger used for collected the data with main computer.

In this thesis, all tests of emission analysis measured with CO, CO₂ and NO_x. MRU Delta 1600 V measured the values of CO and CO₂ concentrations with the system of Non-Dispersive InfraRed (NDIR) analyzers. The principle schema of NDIR is shown in Figure 3.3/a. Chemi- Luminescence Detectors (CLD) used for the measurement of NO_x concentrations (aggregate of NO and NO₂) and the details of CLD is presented in Figure 3.3/b. Also measuring ranges of standardization for CO, CO₂ and NO_x are included in OIML-class 1.

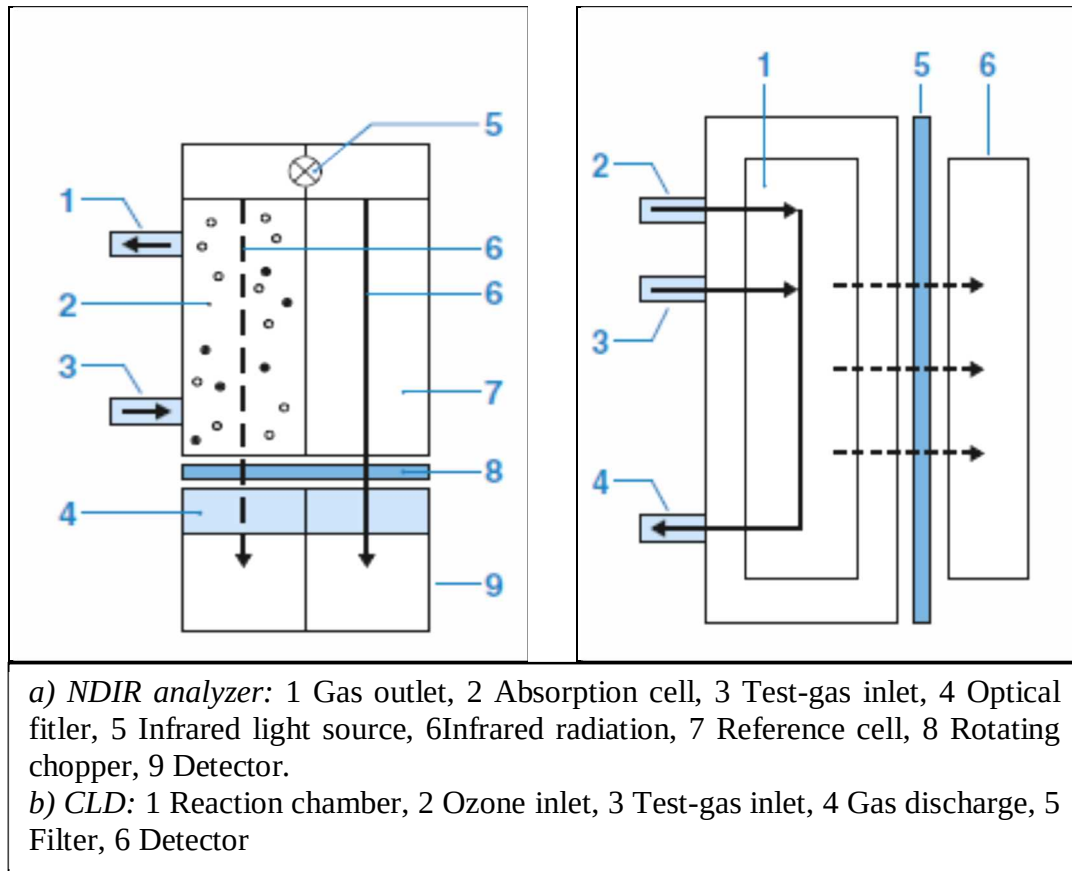


Figure 3.3. The principle schema of NDIR and details of CLD

Elimko-PR-100 series paperless recorders are designed using new generation micro controllers. Unit dimensions are 144 x144 mm. E-PR-100 series recorders are the touch screen paperless recorders with the configurable 12 channel universal inputs, 12 relay outputs, plug&play I/O cards and the most user friendly. E-PR-100 series paperless recorders are used at different fields of industry to record and data storage application of temperature, pressure, level, flow, current, voltage etc.

In this thesis; the flow of air, gaseous fuels (CNG, H₂ and HHO) and exhaust temperature data were recorded with Elimko datalogger. Table 3.2., showed the technical specifications of datalogger.

Table 3.2. Technical specifications of datalogger

Accuracy Class	0.5
Screen Type	5.7" TFT Color LCD, 640× 480 resolution, 18 bit color, touch panel screen
Relay Output	SPST-NO; 250 V AC, 5 A
Relay Outputs	Max. 24 Relay output (Depend on configuration)
A/D conversion	16 bit (isolated)
Analog Inputs	Max. 12 Analog Input (Depend on configuration)
Input Signal	RT (Pt-50, Pt-100, Pt-500, Pt-1000, Ni-100, Ni-200, Ni-500, Ni-1000), 0-20 mA, 0-10 V
Digital Inputs	Max. 64 Digital Inputs (Depend on configuration)
Digital Outputs	Max. 64 Digital Outputs (Depend on configuration)
Power Consumption	20 W max.
Sampling Rate	100 ms (For all channels)
Security	Security code for 5 user
Protection Class	IP 20
Operating Temperature	-10 ÷50°C
Data Storage	4 GB Compact Flash Internal
Operating Voltage	85-265 V AC, 85-375 V DC,
Communication	10 -100 Mbit Ethernet, RS-485, 2× USB Host
Weight	1,8 kg

3.1.2.2. CNG, H₂, HHO procurements

In the tests, CNG, H₂ and HHO gases used as additional gaseous fuels. Compressed natural gas (CNG) and Hydrogen (pure H₂) supplied with pressured tanks. CNG used in this study contains 97.372% Methane, 2.327% Nitrogen, 0.230% Ethane and 0.068% Propane.

CNG (Compressed Natural Gas) fuel supplied from a bundle tank which has capacity of 12.5 m³ and fixed on 200 bar pressure. A check valve used behind the checkout for hinders the reverse flow through the tank. After check valve, ex-proof pipelines fitting to the 2- stage regulator that brand of ñLOVATO easy fast smart CNG kit reducerò. This regulator has high pressure shut-off valve (powered by battery with 12 Volts) and level gauge. System of regulator has 2- stage regulation which throttled in first stage 200 to 12-14 bars and the second stage decreased the 12-14 to 1-0 bar. Additionally regulator consist with high pressure CNG inlet and filter, manifold absolute pressure connection (which added to entrance of intake manifold after air filter), coolant water pipes (rebuilt from engine radiator water), low pressure relief valve and CNG low pressure outlet. Exit from regulators, CNG pass through the needle valve and flow meter. Figure 3.4., illustrated the CNG bundles and Lovato CNG kit.



Figure 3.4. CNG bundles and Lovato CNG kit.

Hydrogen (purity 99.999 %.) tank which has gas capacity of 12.5 m³ and fixed on 170 bar. A back fire eliminator and CNG check valve used behind the checkout for hinders the reverse flow through the tanks. A photograph of hydrogen tank and analyses certificate is shown in Figure 3.5.



Figure 3.5. A photograph of hydrogen tank and analyses certificate

Basically, HHO system is electrolysis of distilled water with electrolyte to any substance containing free ions that make it electrically conductive. In this thesis, 30% weight KOH (potassium hydroxide) is chosen as an ion conducting support. System contains double parallel connected dry cells with 14 plate total, water reservoir, bubbler, solenoid relay switch, constant current Pulse Width Monitor

(PWM) with liquid crystal display, fittings and electrical wires. HHO generator runs with engine battery (24V), varying amps and 500 hertz frequency. HHO can be raised with increased the amps. Installed HHO generator gives 0 to 10 LPM oxy-hydrogen when the maximum amps values are used. The system of hydroxy generator is presented in Figure 3.6.



Figure 3.6. The system of hydroxy generator

3.1.2.3. Gaseous fuel flow measurement and control

Measurement of flow quantity and control of flow is the important issues for this thesis in order to evaluate the analyses. Thanks for the flow meters and needle vanes for measurement and control the flow quantities.

In this thesis; ALICAT M series flow meters were used for each gaseous fuels flow measurement. Measured data recorded by datalogger connection. Before entrance the flow meters, flow quantity can be controlled with the helped of Maxtor brand needle vanes which their pressure availability is between 0.8-15 Mpa. Figure

3.7, illustrated the needle vanes and flow meters. Table 3.3, expressed the flow meters specifications.



Figure 3.7. Maxtor needle vanes and Alicat flow meters.

Table 3.3. Flow Meters Specifications

PERFORMANCE	ALICAT M SERIES FLOW METER
Accuracy at calibration conditions after tare	$\pm (0.8\% \text{ of Reading} + 0.2\% \text{ of Full Scale})$
High Accuracy at calibration conditions after tare	$\pm (0.4\% \text{ of Reading} + 0.2\% \text{ of Full Scale})$
Repeatability	$\pm 0.2\% \text{ Full Scale}$
Typical Response Time	10 ms
Mass Reference Conditions (STP)	25°C & 14.696 Pisa
Operating Temperature	$\bar{1} 10 \text{ to } +50 \text{ }^{\circ}\text{Celsius}$

3.1.2.4. Gaseous mixture chamber before intake manifold

According to Chintala and Subramanian (2013), $\eta_{\text{combustion}}$ efficiency increases with increase in homogeneous mixing of fuel with air in the engine.

Mixture formation of gaseous fuel with air is more critical than liquid fuel due to its lower density and lesser fuel penetration.

In this thesis, this important issue handled with the acoupled of a mixture chamber which seen in figure 3.8.

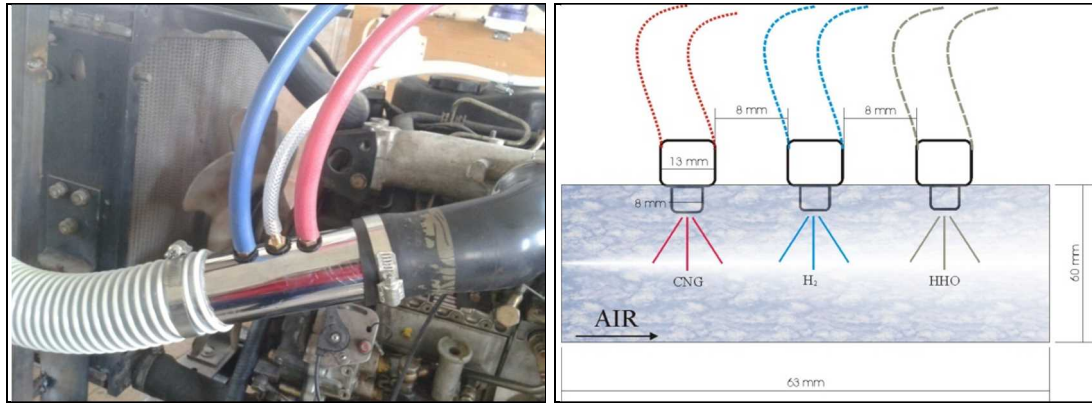


Figure 3.8. Mixture chamber

In figure 3.8., red pipe, grey pipe and blue pipe are used for CNG, HHO and H_2 gaseous fuels, respectively. If this entrances considered as an injector; assuming this approach, Chintala and Subramanian (2013) referred that, gas injector angle at position of 0° and 225° with reference to axial axis of intake manifold are the optimum angles based on better mixture formation characteristics. These optimum angles are applicable for both H_2 and CNG fuels. In our study this angle is 90° . For better seen, figure 3.9. adapted there from Chintala and Subramanian (2013) study.

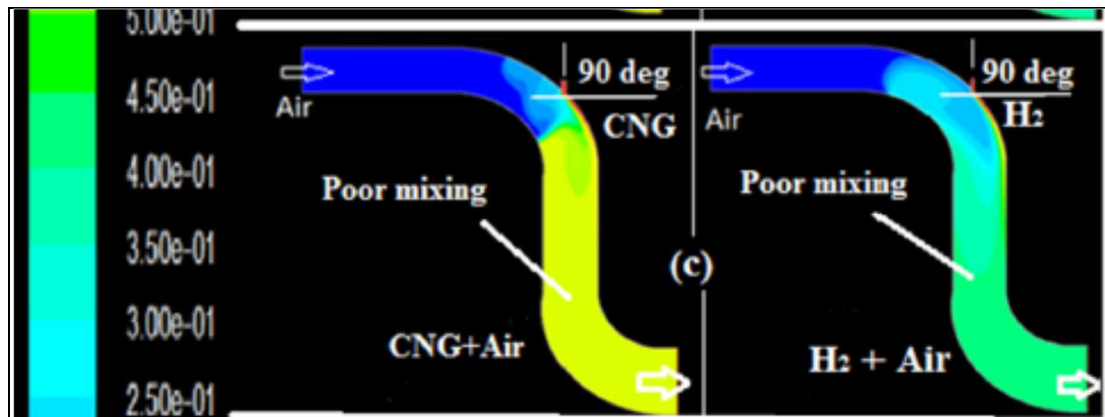


Figure 3.9. Mass fraction of CNG and H_2 at 90° injection angle (Chintala, 2013)

3.1.3. Fuel Properties

Technical properties and preferability of thesis gaseous fuels were noted previous chapters. In this subsection details of gaseous fuel properties were expressed.

An overall comparison of properties of hydrogen, CNG, HCNG (vol 18%) and diesel is shown in Table 3.4. A general look for HHO and hydrogen&HHO fuel potentials are given in Table 3.5 and Table 3.6., respectively.

Table 3.4. Overall comparison of properties of hydrogen, CNG, (vol 18%) HCNG and diesel

Properties	H ₂	CNG	HCNG	Diesel
Stoichiometric AFR	34	17.2	17.8	14.6
Limits of flammability in air, (vol %)	4-75	5-15	5-35	0.6-5.5
Auto ignition temp. K	858	813	825	490-525
Flame temp in air K	2318	2148	2210	2600
Max. energy for ignition in air, mJ	0.02	0.29	0.21	0.3
Burning velocity in NTP air, cm s ⁻¹	325	45	110	30
Quenching gap in NTP air, cm	0.064	0.203	0.152	-
Diffusivity in air, cm ² s ⁻¹	0.63	0.2	0.31	-
Equivalence ratio	0.1-7	0.7-4	0.5-5.4	-
Cetane number	-	-	-	44-55
Lower Heating Value (Mj/kg)	119.9	46.28	48.26	43.4

Table 3.5. A general look of HHO properties and fractions

Name	HHO, Hydroxy, Brown's Gas
Chemical form.	HHO; 66.6% Hydrogen and 33.3% Oxygen
Discoverer	Dr. Yule Brown
Purpose	- On-demand H ₂ fuel; to be consumed immediately after production. - Future replacement fuel for petroleum fuels - Supplemental role in efficient burning of gasoline fuel in vehicles
Production	Common ducted electrolyzer; parallel plate and series connected cells
Advantages	- Flame doesn't burst, is sootless due to the absence of carbon - Suitable for indoor work; cleanest energy
Applications	- Thermal processing industry: gas welding, jewelry process, etc. - HHO generators installed with IC Engines for improve the power

Table 3.6. H_2 & H_2O fuel potential benefits and challenges (Jordan, 2012)

Property	Benefits	Challenges
<i>Wide Flammability Range</i>	Enables lean or more dilute combustion	Lean combustion reduces power.
<i>Low Ignition Energy</i>	Allows lean yet rapid ignition	Can prematurely ignite on hot spots.
<i>Small Quenching Distance</i>	Flame can travel closer to walls	Can lead to flashback
<i>High Auto-Ignition Temp</i>	Enables higher compression ratio	Hard to ignite in CI engine.
<i>High Diffusivity</i>	Facilitates more uniform mixture	Can leak to undesirable areas.
<i>High Flame Speed</i>	More closely approaches ideal Otto engine cycle	N/A
<i>High Octane Rating</i>	Enables higher compression ratio, Reduces knock & MEP variation	Hard to ignite in CI engine.
<i>Low Density</i>	N/A	Lower energy density per volume.

3.2. Substitution of Diesel Fuel

3.2.1. Determining the substitution of diesel fuel

This part of thesis was adapted from the Arat et.al (2016)'s paper which titled "Optimizing the quantity of diesel fuel injection by using 25HHOCNG gas fuel mixture". This article was aimed to determine and optimize the quantity of substituted liquid diesel fuel for operating the diesel engine under pilot injection with alternative fueled 25HHOCNG gaseous fuel mixtures. The results of engine performance and exhaust emission of this article did not mentioned now in this subheading, it placed in chapter 4. The systematic substitution of diesel fuel like pilot injection express in there.

In this experimental study, three different quantities of pilot injection at specific engine operational conditions are determined, and the effectiveness of different measures to improve engine performance and exhaust emissions for various operational conditions are examined. Gaseous fuel mixture affected some effective results for non-modified diesel engine at dual fuel combustion with pilot injection into diesel combustion both of engine performance and exhaust emissions. 25HHOCNG gas fuel mixture operated in a non-modified diesel engine by substitution of diesel fuel with helped of stepping motor and pilot diesel injection quantities effects are examined. All results and experimental setup is illustrated and explained briefly.

Optimizing the substituted diesel fuel quantities is the major goal of this study. For this reason substitution of diesel fuel was obtained with the help of stepping motor (detailed explanation is given next subheading) and devices which mounted on mechanical diesel fuel pump plunger. A bipolar, 1.8 deg/step, 6.2 Nm holding torque stepping motor adjusted to plunger and controlled with Toshiba TA 8435 stepping motor driver. It operated with software in main computer and obtained more sensitive measurement results. Optimizing the quantities of diesel fuel, three clockwise rotations were selected.

Precisely at this point that should be mentioned the fuel pump calibration is playing an important role to optimize the substitution of diesel fuel. For this purpose, engine fuel pump calibrated in the Bosch diesel service in Adana city. Calibration tests and optimum point of normal diesel injection point of fuel pump plunger is identified and measured with fuel injection pumps test bench devices which can be seen in Figure 3.10.

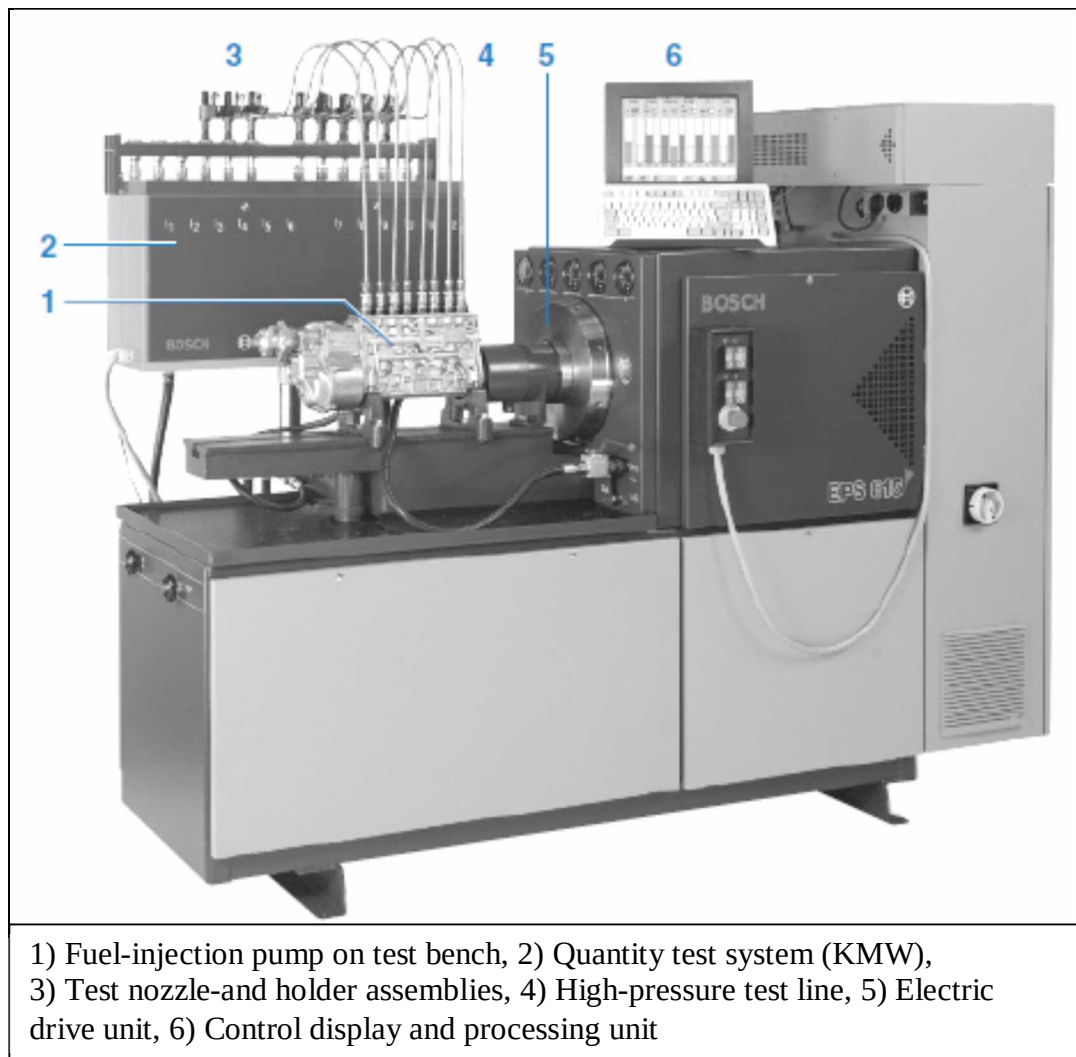


Figure 3.10. Bosch fuel-injection pump test bench with electronic test system (KMA)
(Adapted from Reif,2014)

Pilot diesel injections occurred with twisting the plunger pin one tour (360°), two tours (720°) and three tours (1080°) of fuel pump plunger pin. Additionally middle degrees of rotations were examined with 540°, 900° and 1440° but half rotation of plunger, 180°, did not show a noticeable decrease in this mechanical fuel pump for using pilot diesel injection quantity.

As we mentioned previously, minimum pilot quantities changeable in diesel engines for different combustion chamber structures and operating conditions. With these calibrating and optimizing approaches and with their results, two pilot diesel injection strategies are used in this thesis. One tour (360°) and two tours (720°) of fuel pump plunger gave the best results in engine performance and exhaust emissions. For this reason, in this thesis experimental investigations and their results were prepared under 360° and 720° pin rotations which discussed in chapter 4.

3.2.2. Sensitive measurement with stepping motor and devices

After the calibration of the fuel pump, some several experiments was conducted with the equipped the micrometer usage which photographed in Figure 3.11. The assemblage and the vibration problem of micrometer encountered some difficulties on the measurement. In particular, high loads and high engine speeds, the micrometer position affected negatively.

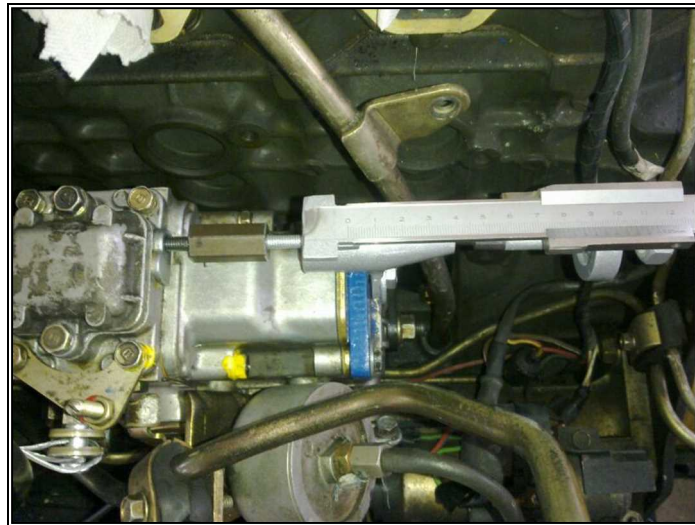


Figure 3.11. Experiments with acupled micrometer to fuel pump plunger

For more sensitive measurements, the system has to regenerate with more automatically and easy controlled structure. To achieve this situation, a stepping motor and driver used on the fuel pump plunger and helped the substitution of diesel fuel quantity more sensitively.

In figure 3.12., the stepping motor and driver is illustrated. A bipolar, 1.8 deg/step, 6.2 Nm holding torque stepping motor adjusted to plunger and controlled with Toshiba TA 8435 stepping motor driver. The specifications of stepping motor and driver is given in Table 3.7.

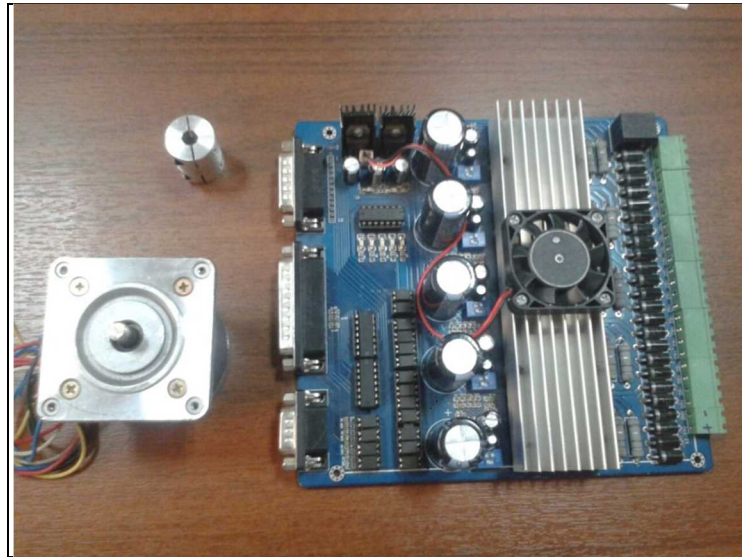


Figure 3.12. Stepping motor and driver

Table 3.7. Specifications of stepping motor (brand Nema)

Item	Specifications	Dielectric Strength	500VAC
Step Angle	1.8°	Shaft Radial Play	0.02Max.
Step Angle Accuracy	±5% (full step, no load)	Shaft Axial Play	0.08Max.
Resistance Accuracy	±10%(20Ω)	Max. radial force	150N
Inductance Accuracy	±20%(1KHz)	Max. axial force	40N
Temperature Rise	80° C Max.	Holding Torque	6.2 Nm
Ambient Temperature : -20°C ~ +50°C			

Step motor driver (Toshiba TA 8435) was generally used in amateur CNC applications with programmable software. In this thesis, this stepping motor and driver served one purpose that rotated the fuel pump plunger sensitively and more precision. A sample image of software (Mach3Mill) illustrated in figure 3.13.

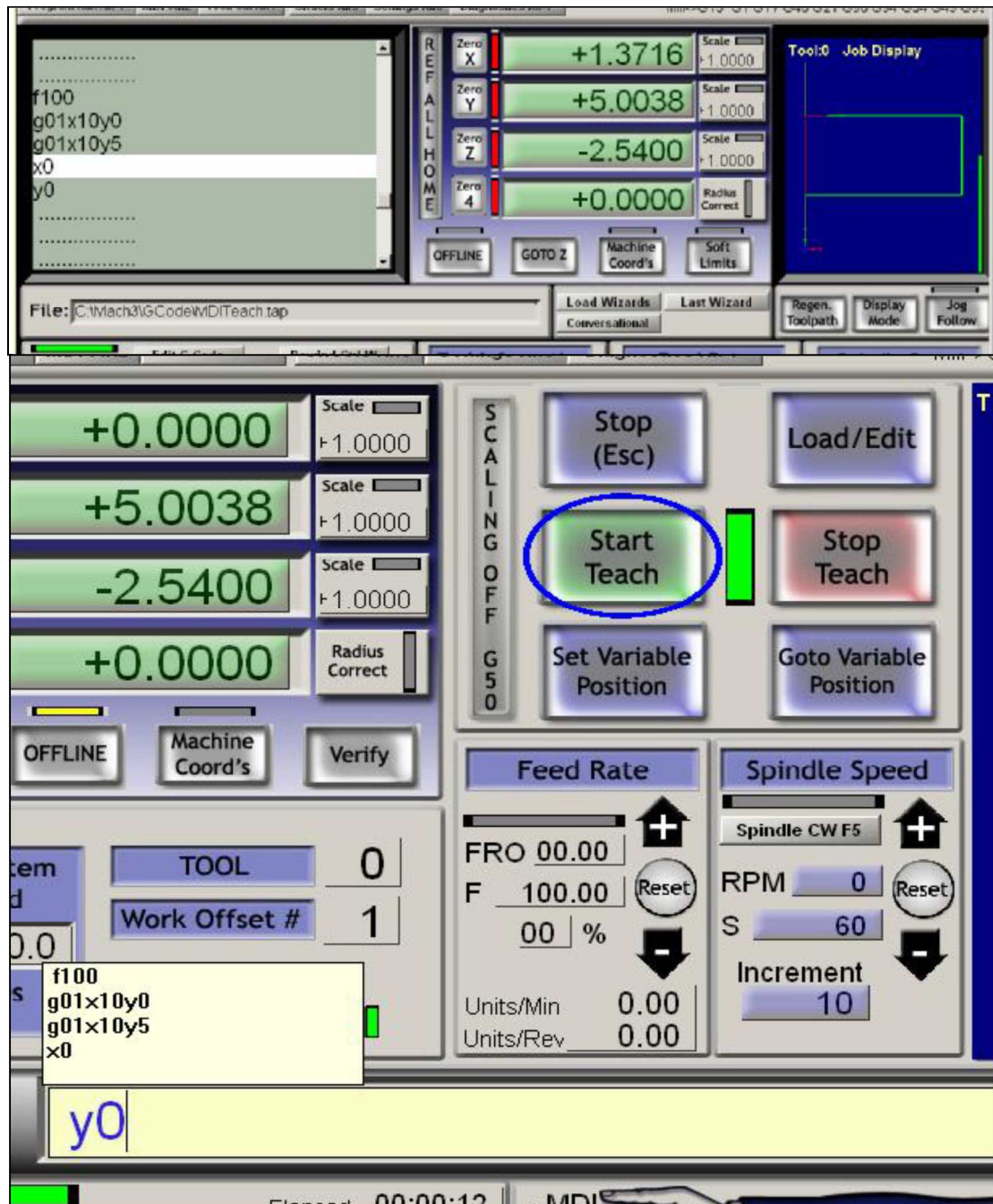


Figure 3.13. A sample image from software of stepping motor driver.

3.2.3. Determining the mixture of gaseous fuels

One of the important topics of this thesis is determining the mixture amount of gaseous percentages. Various researchers examined the several percentages (both mass and volume) for mixed the CNG and hydrogen. Previous studies in literature showed that, the percentage of hydrogen blends in CNG fuel mixture varying between 5-30% (that means ~1.5-10% by energy). Hythane is a 18% blend of hydrogen in CNG by energy content, which was patented by Frank Lynch of Hydrogen Components Inc, USA. A typical 20% blend of hydrogen by volume in CNG is 3% by mass or 7% by energy.

In this thesis, the volumetric ratios of HHO and hydrogen percentages in CNG fuel mixture were defined 20, 25, 30% by (vol/vol). This approach adhered to general literature and similar perspectives of previous studies.

The amount of Hydrogen, HHO and CNG gases supplied to the engine is measured by the flow meters and the amount is controlled by needle vanes. Certain amounts of gases are mixed in a mixing chamber. The volume of gas mixtures are calculated by Equations (2 a-d). All experiments were repeated three times and the mixture's percentages were collected by the average of these three tests. For all test of this thesis, the total average of hydrogen, HHO and CNG fuel mixtures percentages can be found below. Additionally this value has a similarity to literature for optimum usage (20-30% HCNG) of these gas fuels.(Nanthagopal et.al (2011)).

$$V_{HHO}(\%) = \frac{V_{HHO}}{V_{HHO} + V_{CNG}} * 100 \quad V_{CNG}(\%) = \frac{V_{CNG}}{V_{HHO} + V_{CNG}} * 100 \quad (2-a,b)$$

$$V_{H_2}(\%) = \frac{V_{H_2}}{V_{H_2} + V_{CNG}} * 100 \quad V_{CNG}(\%) = \frac{V_{CNG}}{V_{H_2} + V_{CNG}} * 100 \quad (2-c,d)$$

Total amount of gases: (sum of all gases; HCNG and HHOCNG) = 26 LPM

20HCNG = 5.3 lpm H₂+ 20.7 CNG

20HHOCNG= 5.3 lpm HHO+20.7 CNG

25HCNG = 6.5 lpm H₂+ 19.5 CNG

25HHOCNG = 6.5 lpm HHO+19.5 CNG

30HCNG = 7.8 lpm H₂+ 18.2 CNG

30HHOCNG = 7.8 lpm HHO+18.2 CNG

4. RESULTS AND DISCUSSION

This chapter presents the results of this study. The effect of the (20,25,30% (vol/vol))HHOCNG fuel mixture usage on engine performance and exhaust emissions is examined under quarter and semi pilot injection, followed by the comparison of HCNG and HHOCNG fuel mixtures with the same volumetric ratios, and finally a minor cost analyses of these system are investigated. For better interpretation and avoid the repetition, this chapter divided into several subheadings as; analysis of the major findings with expected results, engine performances, exhaust emissions and cost analyses parts.

Dual fuel operation and small amount of liquid fuel pilot injection is a very substantial fact that provides developments to future strategies about optimizing the engine and fuel parameters. One of the most widely used method for determining the engine characteristic parameters are performance and exhaust emission of an engine.

As it mentioned previously, the main goal of this study is to run a conventional diesel engine enriched with HHO-CNG mixture at the point of use without making any modification to the engine with improving the performance and reducing the harmful exhaust emissions.

In this point of view, some critical opinions come from Karim (2015), and reported that; some of the general measures that have been employed *to improve engine efficiency while reducing the associated emissions* are the following:

ÅResorting to operation on sufficiently fuel lean mixtures and employing direct gas injection per cylinder and fumigation, to ensure better control of the fuel introduction and its distribution among the different cylinders, with less fuel passing unreacted directly to the exhaust stage

ÅUsing optimized exhaust gas recirculation maintained warm at light load and cooled at high loads, for emissions and knock controls

ÅEmployment of properly stratified mixture combustion where relatively rich mixtures are arranged near the ignition source, while the remaining mixture is fuel lean, such that the overall mixture remains fuel lean

ÅEmployment of optimized variable valve timings and controlled exhaust gas turbocharging, including through variable geometry and exhaust gas bypass under selective conditions

ÅRetaining the high compression ratio of the engine subject throughout to the avoidance of the undesirable onset of knock or excessive NO_x emissions

ÅUsing sufficiently high quality processed fuels for both the gas and the liquid pilot and improving engine controls, especially under transient conditions

Before starting to evaluate the results of this thesis, some critical issues should be introduced. Firstly; in order to avoid confusion, Table 4.1, was prepared and showed the fuels and their mixtures which used in this thesis and properties were mentioned in previous chapter. In all results of experiments, the naming convention is given with common usage.

Table 4.1. The description of operating cases

Name	Descriptions and additional notes
Diesel	Neat and non-substituted normal operation diesel fuel
Spd/qpd	S emi- p ilot d iesel injection and q uarter p ilot d iesel injection
CNG + s/qpd	Totally 26 lpm, not mixtured, only CNG addition
HHO + s/qpd	Totally 6.5 lpm, not mixtured, only hydroxy gas addition
20HHOCNG+ s/qpd	Total 26 lpm (5.3 hho+20.7cng), 20% vol. mixture, HHOCNG addition
25HHOCNG+ s/qpd	Total 26 lpm (6.5 hho+19.5cng), 25% vol. mixture, HHOCNG addition
30HHOCNG+ s/qpd	Total 26 lpm (7.8 hho+18.2cng), 30% vol. mixture, HHOCNG addition
20HCNG + s/qpd	Total 26 lpm (5.3 hydrogen+20.7cng), 20% vol. mixture, HCNG addition
25HCNG + s/qpd	Total 26 lpm (6.5 hydrogen+19.5cng), 25% vol. mixture, HCNG addition
20HCNG + s/qpd	Total 26 lpm (7.8 hydrogen+18.2cng), 30% vol. mixture, HCNG addition

Secondly, the experimental conditions should be introduced. Before the tests, the engine was operated for enough time (10 minutes) with diesel fuel to reach the operation temperature. All tests were implemented with the engine speed between 1200 to 2600 rpm with an interval of 100 rpm at WOT and full load condition. Separately three sets of experiments were performed and average test data were used for the results for optimization of the test results with less experimental errors. Engine performance and exhaust emission parameters were measured and compared each other for all cases. Additionally, the temperature of the laboratory keeps constant at 24°C. All gaseous fuels induction pressures are atmospheric pressure conditions.

Third needful explanation is about brake specific fuel consumptions. Effects of the substitution of diesel fuel forms more lucrative fuel consumption. Substitution of diesel fuel likes pilot diesel injection is the main factor for the reduction of BSFC. It should be noticed here; in all experiments and cases; these decreased BSFC performed from *liquid diesel engine substitution and does not include the gaseous fuel*.

As last additional note; approximately 260 tests were examined with 100 sec. period (for one test) for all experiments of this thesis. The average data and optimization of test results selected from these tests. Beside, the error analyses of this thesis and test results were 3.26% when calculated the whole experiments outputs. In the impressions of test results; brake torque, brake power and brake specific fuel consumption data used for engine performance; CO₂, NO_x and CO outputs were used as exhaust emissions. In addition to this, a sample analyses of the brake thermal efficiency and exhaust gas temperature results were given for the superior gas fuel mixture which handled with 25% volumetric ratio mix. Prepared graphics were plotted with different schemas; and performance & emissions graphs illustrated together on a single page, for more understandable and easy comparisons of results.

4.1. Analysis of the major findings with expected results

Summarily expected results and major finding of this thesis is expressed in this subsection. This section's aim is giving the general major findings of results and expressed the more useful and understandable beginnings while gaining the readers for provide opportunity start.

All remarkable finding and expectations can be listed below:

Foreseen expectations:

- ☑ Before the tests, first contemplated issue is non-modification of the engine. For this purpose, dual-fuel operation with substitution of diesel fuel like pilot diesel injection has been envisioned for selection the strategy. This strategy prevented the unnecessary modification costs and did not required the changing the original parts of engine. This idea has reached its destination successfully.
- ☑ Although diesel substitution was occurring an energy loss; using gaseous fuels would affect positively for engine performance and exhaust emissions. This idea has reached its destination successfully, also.
- ☑ Selected gaseous fuels that; hydrogen, hydroxy and CNG would not allow the direct injection because of theirs auto-ignition scales. Solving this problem was needed to a different injection structure. Selecting the use of pilot injection method was intended to solve this problem. This idea has reached its destination successfully, too.
- ☑ The characteristics of hydrogenated gases and natural gases tented to endeavor their disadvantages and balanced the preferable advantages for using them as an alternative fuels. The inherent engineering properties of hydrogen occurred the improving the performance scale while natural gas indented to decreased the harmful exhaust emissions when compared both between diesel fuel. The determination of

gaseous mixture the limitations of these gaseous fuels should be forced and would be finding the necessity ratios. This idea has reached its destination successfully.

- ☑ It was already known that hydrogen has worthwhile effectiveness on combustion. To enlarge the improvements about performance, it was intended to use oxy-hydrogen. It was an important item and would be seen that how extra oxygen effect the performance. The hydroxy gas effected performance parameters slightly but positively.

Major findings:

- First of all, the originality of this thesis is to investigated the effects of HHOCNG fuel mixtures on a non-modified diesel engine's performance and exhaust emissions with usage of quarter and semi pilot diesel injection. From the point of view; HHOCNG fuel mixture analyses in a conventional diesel engine had been added to literature with this thesis and related articles which can be seen in appendix part.
- The goal of this thesis was reached the success result which expected that; *improving engine efficiency while reducing the exhaust emissions with non-modification.*
- Using the pilot diesel injection with the dint of stepping motor and devices on dual fuel mode, preventing the unnecessary structural modification on test engine.
- For all cases; semi-pilot diesel injection was more preferable than quarter-pilot diesel injection.
- Both quarter and semi pilot diesel injections improved the fuel economy perspective and reduced the specific fuel consumptions.
- As it predicted, gas fuel additives observed noticeable reductions on emission results relative to diesel fuel.

- HHOCNG and HCNG increased the performance parameters compared with single CNG usage on diesel engines. Insomuch that, HHOCNG and HCNG providing the positive performance affect slightly (which decreased the amount of liquid fuel with the substitution of diesel fuel); when compared the standard diesel operation.
- HHO showed the similar characteristic properties with hydrogen on performance base.
- The all test results were adapted with 3E (economical, environmental and efficiency) strategy, except CO exhaust emissions. (More detailed reason of this situation expressed in next subheadings)
- CO₂ and NO_x results have superior outputs when compared with normal diesel operation. Hydrogenated gaseous fuel mixtures emission results were placed between single CNG + pilot diesel operations and standard diesel operations.
- As a sample approach on thermal efficiency, slightly reductions were found on HHOCNG and HCNG fuel mixtures relative to normal diesel operation results. The dominant factor of this reduction depended on the quantity of diesel fuel.
- At higher speeds, hydrogenated gaseous fuel mixtures tented to increase the exhaust gas temperature.
- A minor cost analysis for a heavy duty engine performed and results were very promising when it comes to economy scale.
- Finally, under the conditions of this thesis, 25HHOCNG fuel mixture with semi-pilot injection operation was obtained the best mix when used as an alternative and additional fuel for run under this test engine.

With these considerations, below subheadings were more capable of being suggestions and clearly understandable. Improvements, increments, reductions and the average effects of results outputs were given detailed.

4.2. Effects of using 20-25-30HHOCNG under quarter pilot diesel operation

The performance and emission results of using 20-25-30HHOCNG under quarter pilot diesel operation, illustrated in Figure 4.1 and Figure 4.2, respectively.

Brake Torque, Brake Power and Brake Specific Fuel Consumption vs engine speed of standard diesel fuel; CNG+qpd; 20HHOCNG+qpd; 25HHOCNG+qpd and 30HHOCNG +qpd fuel mixtures are illustrated in Figure 4.1.

It can be clearly seen from the torque results; HHOCNG additives improved the torque values compared the CNG + qpd and neat diesel operation. HHO gas contains hydrogen and oxygen that allows more powerful and efficient combustion in the cylinders and the average of 0.78 %, 4.78% and 1.02% brake torque improvement was obtained for 20, 25 and 30 HHOCNG, respectively.

Similar improvements for brake power and torque are obtained with mixtures at same conditions. Average brake power improvements were 0,88%, 4.395% and 1.3% for 20, 25 and 30 HHOCNG, respectively.

It is evidently CNG and HHOCNG mixtures were decreased the BSFC with 19.2%, 18.3%, 16.3%, 15.1% for CNG, 20, 25 and 30 HHOCNG, respectively.

Figure 4.2., illustrated the variation of CO₂, NO_x and CO emission as a function of engine speed for standard diesel fuel; CNG+qpd; 20HHOCNG+qpd; 25HHOCNG+qpd and 30HHOCNG +qpd fuel mixtures.

It is clearly seen that, gaseous fuel mixtures were decreased the CO₂ emission values with 41%, 25.9%, 20.5%, 32.3% for CNG; 20; 25;30 HHOCNG, respectively.

NO_x effect could be listed as; 47%, 18.1%, 18.3%, 15.1% for CNG, 20, 25, 30 HHOCNG, respectively. The best improvement of NO_x value came from CNG mixtures because of the hydrogen's worse effect of NO_x parameters. Even, CNG mixture was minimized this effect and decreased the values under standard diesel operation.

CO emission values were increased for CNG, 20, 25, 30 HHOCNG with 31 %, 8.8%, 5.2%, 1.8% when compared with normal diesel fuel operation. This increment was strongly depended on CNG fact.

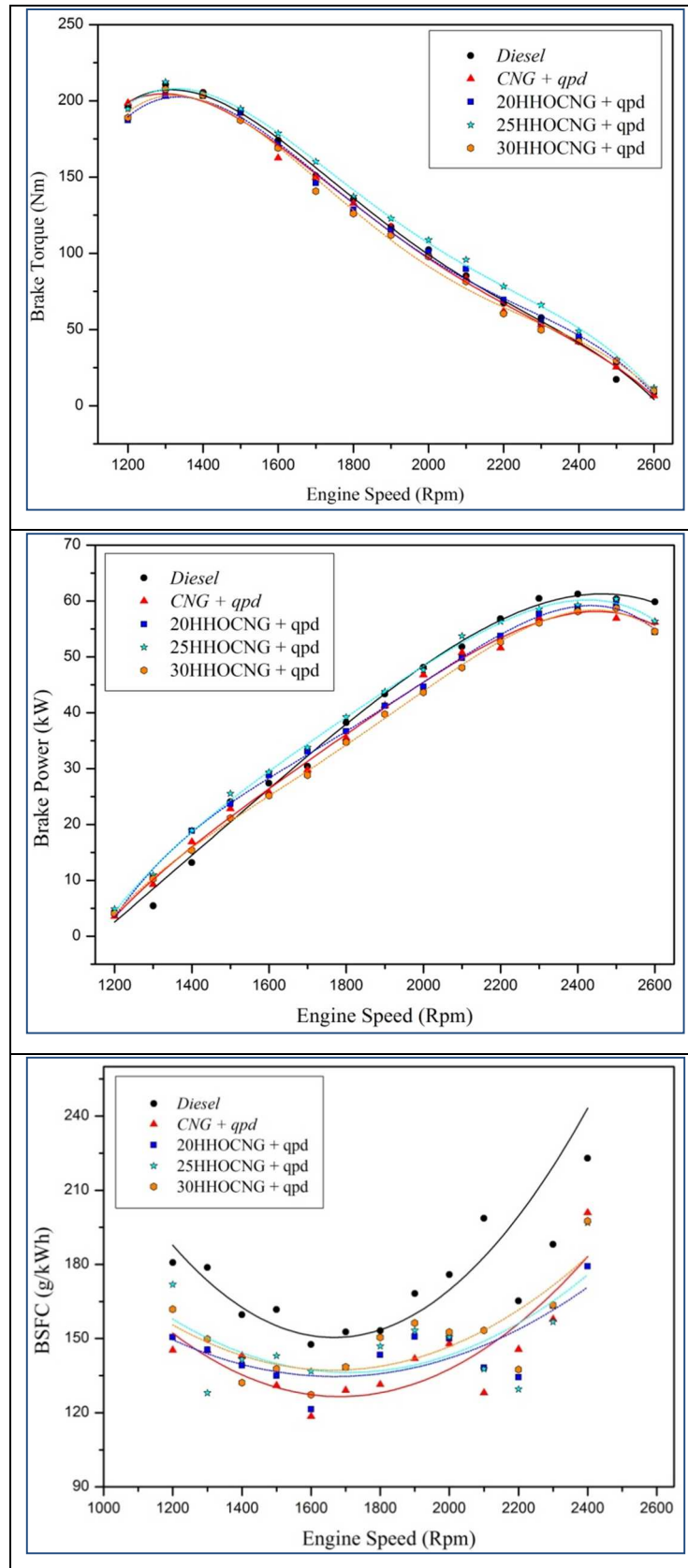
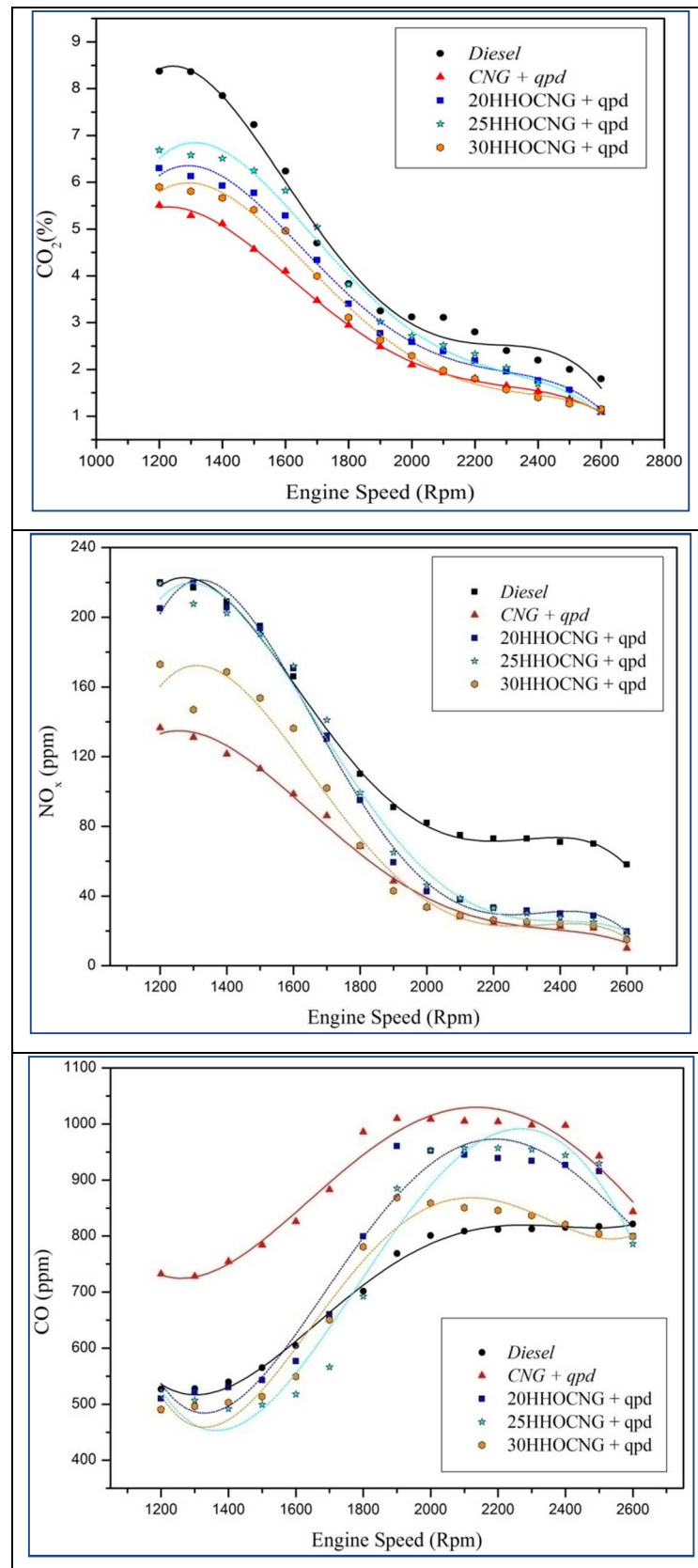


Figure 4.1. BT, BP and BSFC for Diesel vs. quarter pilot diesel CNG, HHOCNGs

Figure 4.2. CO₂, NO_x and CO for Diesel vs. quarter pilot diesel CNG, HHOCNGs

4.3. Effects of using 20-25-30HHOCNG under semi pilot diesel operation

The performance and emission results of using 20-25-30HHOCNG under semi pilot diesel operation, illustrated in Figure 4.3 and Figure 4.4, respectively.

Brake Torque, Brake Power and Brake Specific Fuel Consumption vs engine speed of standard diesel fuel; CNG+qpd; 20HHOCNG+qpd; 25HHOCNG+qpd and 30HHOCNG +qpd fuel mixtures are illustrated in Figure 4.3.

It can be clearly seen from the torque results; HHOCNG additives improved the torque values compared the CNG + qpd and neat diesel operation. HHO gas contains hydrogen and oxygen that allows more powerful and efficient combustion in the cylinders and the average of 0.8 %, 4.4% and 1.2% brake torque improvement was obtained for 20, 25 and 30 HHOCNG, respectively.

Similar improvements on brake power and torque were obtained with mixtures at same conditions. Average brake power improvements were 1.18%, 3.15% and 1.09% for 20, 25 and 30 HHOCNG, respectively.

It is evidently CNG and HHOCNG mixtures were decreased the BSFC with 26.2%, 22.3%, 20.3%, 19.1% for CNG, 20, 25 and 30 HHOCNG, respectively.

Figure 4.4, illustrated the variation of CO₂, NO_x and CO emission as a function of engine speed for standard diesel fuel; CNG+qpd; 20HHOCNG+qpd; 25HHOCNG+qpd and 30HHOCNG +qpd fuel mixtures.

It is clearly seen that, gaseous fuel mixtures were decreased the CO₂ emission values via 40.5%, 21.1%, 30.6%, 28.9% for CNG, 20, 25, 30HHOCNG, respectively.

NO_x effect could be listed as; 31.1%, 5.7%, 16.1%, 12.7% for CNG, 20, 25 and 30 HHOCNG, respectively. The best improvement of NO_x value came from CNG mixtures because of the hydrogen's worse effect of NO_x parameters. Even, CNG mixture was minimized this effect and decreased the values under standard diesel operation.

CO emission values were increased for CNG, 20, 25 and 30 HHOCNG with 15.6%, 14.2%, 10.9%, and 13.7% when compared with normal diesel fuel operation. This increment was strongly depended on CNG fact.

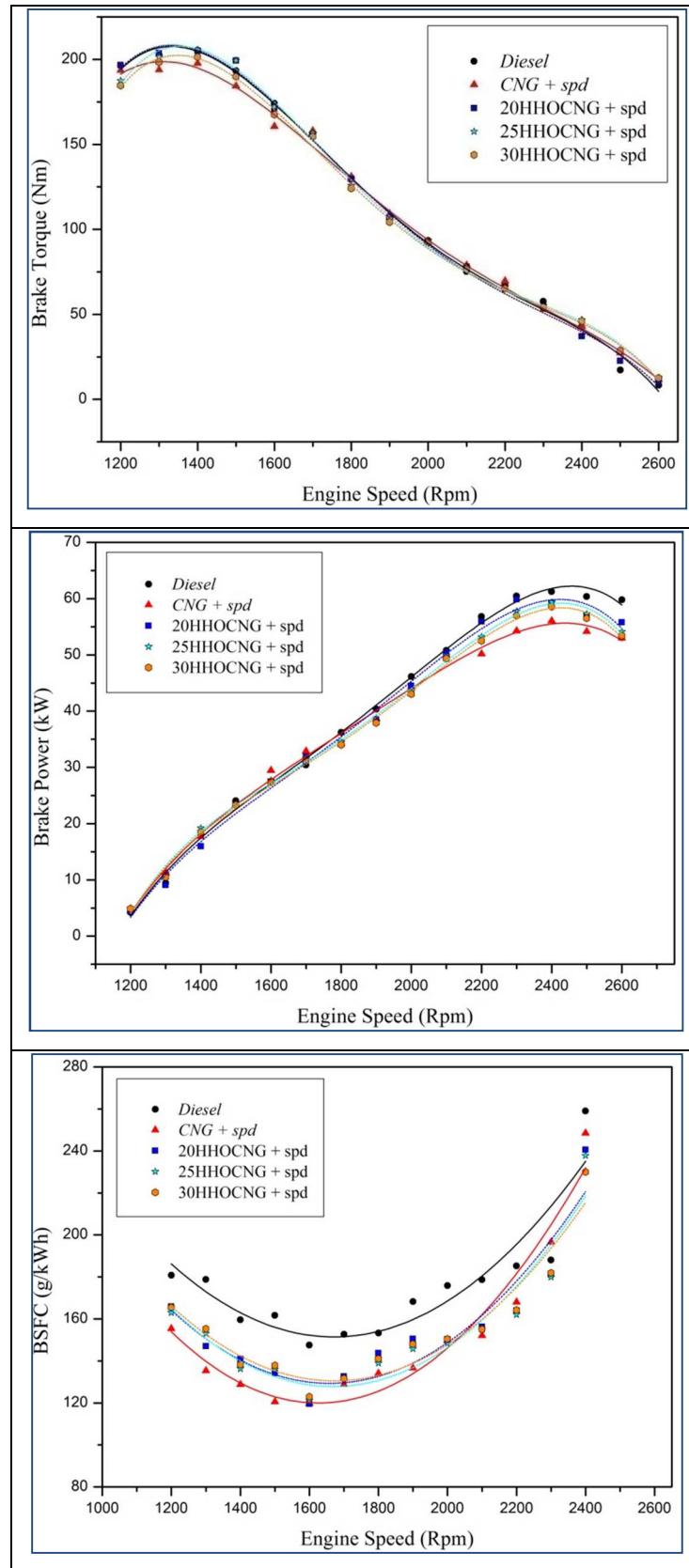
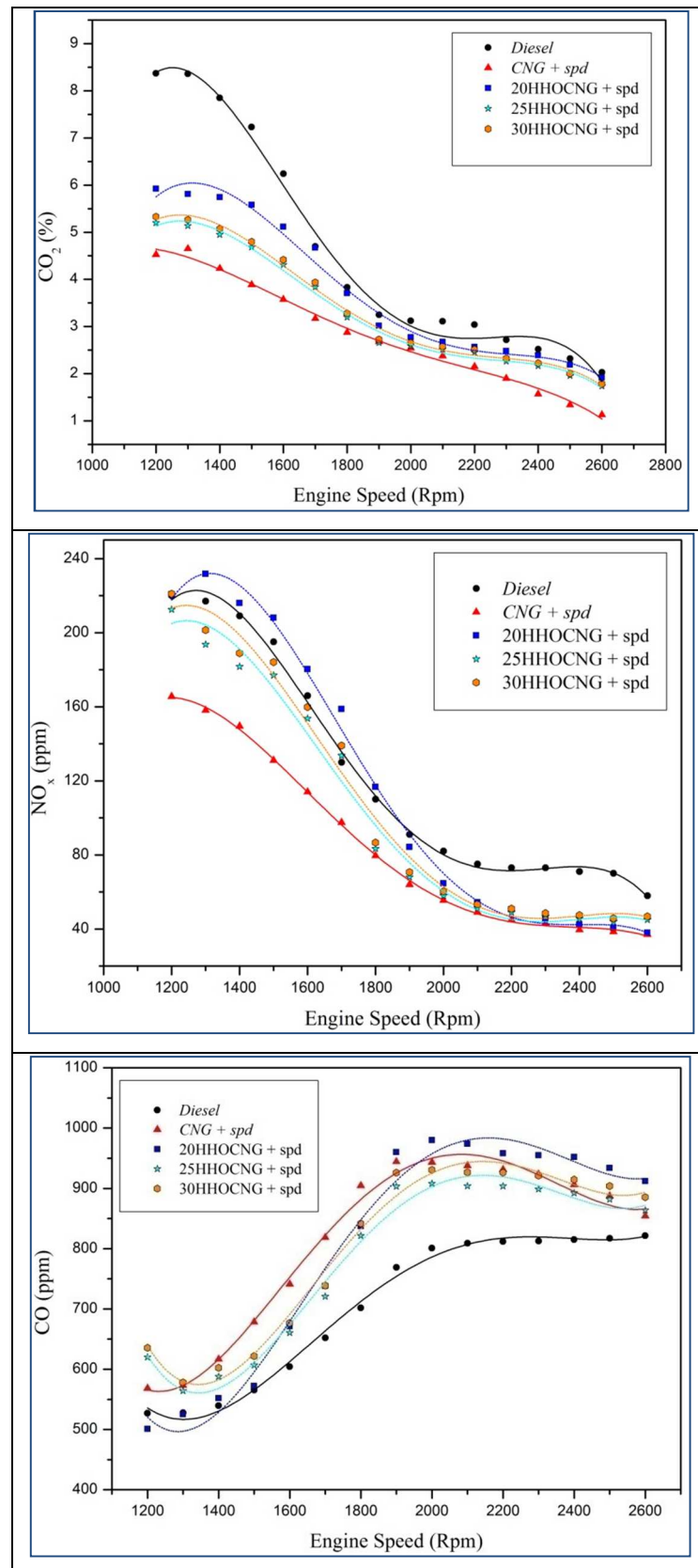


Figure 4.3. BT, BP and BSFC for Diesel vs. semi pilot diesel CNG and HHOCNGs

Figure 4.4. CO₂, NO_x and CO for Diesel vs. semi pilot diesel CNG and HHOCNGs

4.4. Comparison of HCNG vs HHOCNG under quarter pilot diesel operation

Comparison of using 20HCNG vs 20HHOCNG

The performance and emission results of comparison of using 20HCNG vs 20HHOCNG under quarter pilot diesel operation, illustrated in Figure 4.5 and Figure 4.6, respectively. Brake Torque, Brake Power and Brake Specific Fuel Consumption vs engine speed of standard diesel fuel; CNG+qpd; 20HCNG+qpd and 20HHOCNG+qpd fuel mixtures are illustrated in Figure 4.5.

It can be clearly seen from the torque results; HCNG and HHOCNG additives improved the torque values compared the CNG + qpd and neat diesel operation. Hydrogen and extra oxygen that allows more powerful and efficient combustion and the average of 0.39 % and 1.18 % brake torque improvement was obtained for 20HCNG+qpd and 20HHOCNG+qpd, respectively.

Similar improvements for brake power and torque were obtained with mixtures at same conditions. Average brake power improvements were 0.002% and 1% for 20HCNG+qpd and 20HHOCNG+qpd, respectively.

It is evidently CNG, HCNG and HHOCNG mixtures were decreased the BSFC with 19.2%, 22.8% and 18.2%, for CNG, 20HCNG and 20 HHOCNG, respectively.

Figure 4.6, illustrated the variation of CO₂, NO_x and CO emission as a function of engine speed for standard diesel fuel; CNG+qpd; 20HCNG+qpd and 20HHOCNG+qpd fuel mixtures.

It is clearly seen that, gaseous fuel mixtures were decreased the CO₂ emission values with 41.2%, 39.4%, 25.8% for CNG, 20HCNG, 20HHOCNG, respectively.

NO_x effect could be listed as; 47.4%, 37.8% and 18.2%, for CNG, 20HCNG and 20 HHOCNG, respectively. The best improvement of NO_x value came from CNG mixtures because of the hydrogen's worse effect of NO_x parameters. Even, CNG mixture was minimized this effect and decreased the values under standard diesel operation.

CO emission values were increased for CNG, 20HCNG and 20 HHOCNG with 19.2%, 22.8% and 18.2%, when compared with normal diesel fuel operation. This increment was strongly depended on CNG fact.

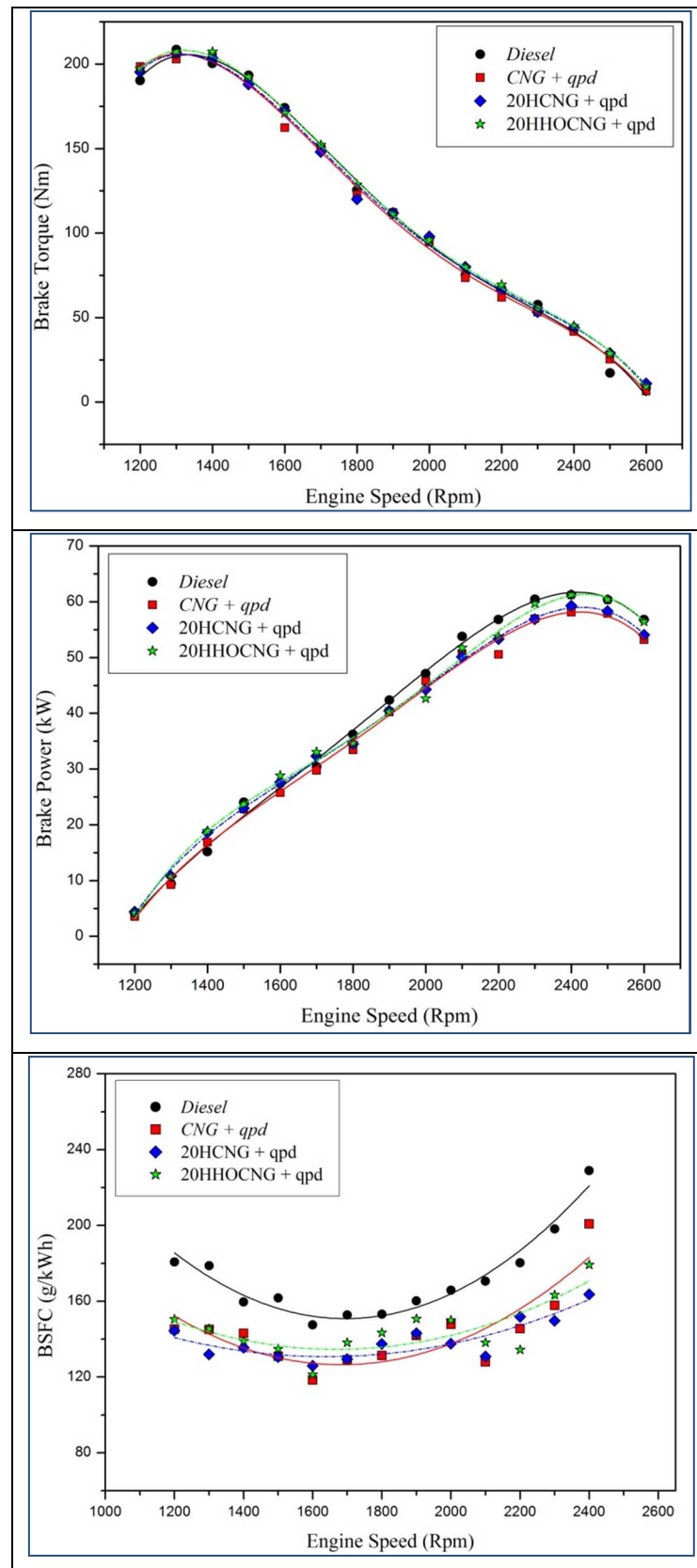


Figure 4.5. Comparative performance data for Diesel, CNG, 20HCNG, 20HHOCNG

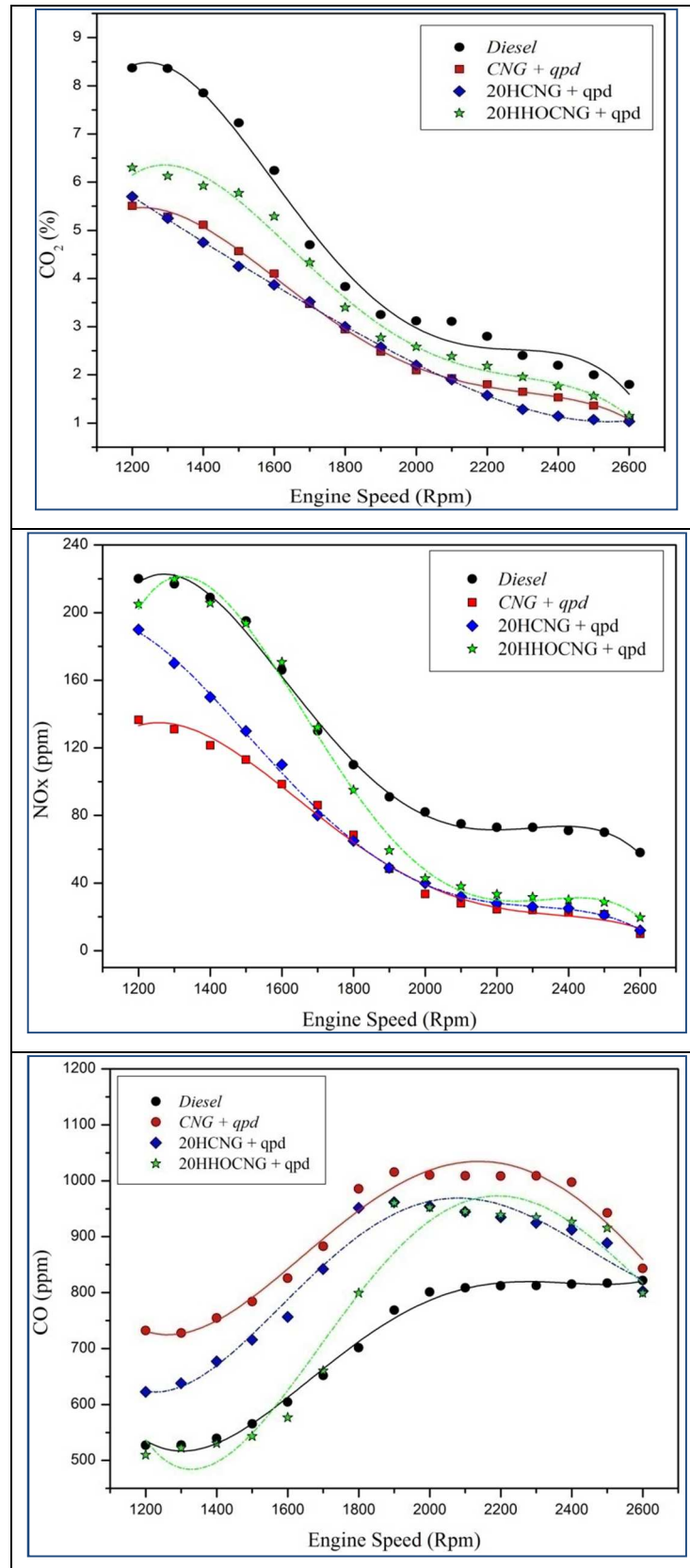


Figure 4.6. Comparative emission data for Diesel, CNG, 20HCNG and 20HHOCNG

Comparison of using 25HCNG vs 25HHOCNG

The performance and emission results of comparison of using 25HCNG vs 25HHOCNG under quarter pilot diesel operation, illustrated in Figure 4.7 and Figure 4.8, respectively. Brake Torque, Brake Power and Brake Specific Fuel Consumption vs engine speed of standard diesel fuel; CNG+qpd; 25HCNG+qpd and 25HHOCNG+qpd fuel mixtures are illustrated in Figure 4.7.

It can be clearly seen from the torque results; HCNG and HHOCNG additives improved the torque values compared the CNG + pad and neat diesel operation. Hydrogen and extra oxygen that allows more powerful and efficient combustion and the average of 1.4 % and 4.78% brake torque improvement was obtained for 25HCNG+qpd and 25HHOCNG+qpd, respectively.

Similar improvements for brake power and torque are obtained with mixtures at same conditions. Average brake power improvements were 0.03% and 2.39% for 25HCNG+qpd and 25HHOCNG+qpd, respectively.

It is ocularly CNG, HCNG and HHOCNG mixtures were decreased the BSFC with 19.2%, 21.3% and 16.3%, for CNG, 25HCNG and 25 HHOCNG, respectively.

Figure 4.8, illustrated the variation of CO₂, NO_x and CO emission as a function of engine speed for standard diesel fuel; CNG+qpd; 25HCNG+qpd and 25HHOCNG+qpd fuel mixtures.

It is clearly seen that, gaseous fuel mixtures were decreased the CO₂ emission values with 41 %, 31.6%, 20.6%, for CNG, 25HCNG, 25HHOCNG, respectively.

NO_x effect could be listed as; 47.4%, 25.8% and 17.6% for CNG, 25HCNG and 25 HHOCNG, respectively. The best improvement of NO_x value came from CNG mixtures because of the hydrogen's worse effect of NO_x parameters. Even, CNG mixture was minimized this effect and decreased the values under standard diesel operation.

CO emission values were increased for CNG, 25HCNG and 25HHOCNG with 31.02%, 2.68% and 5.21% when compared with normal diesel fuel operation. This increment was strongly depended on CNG fact.

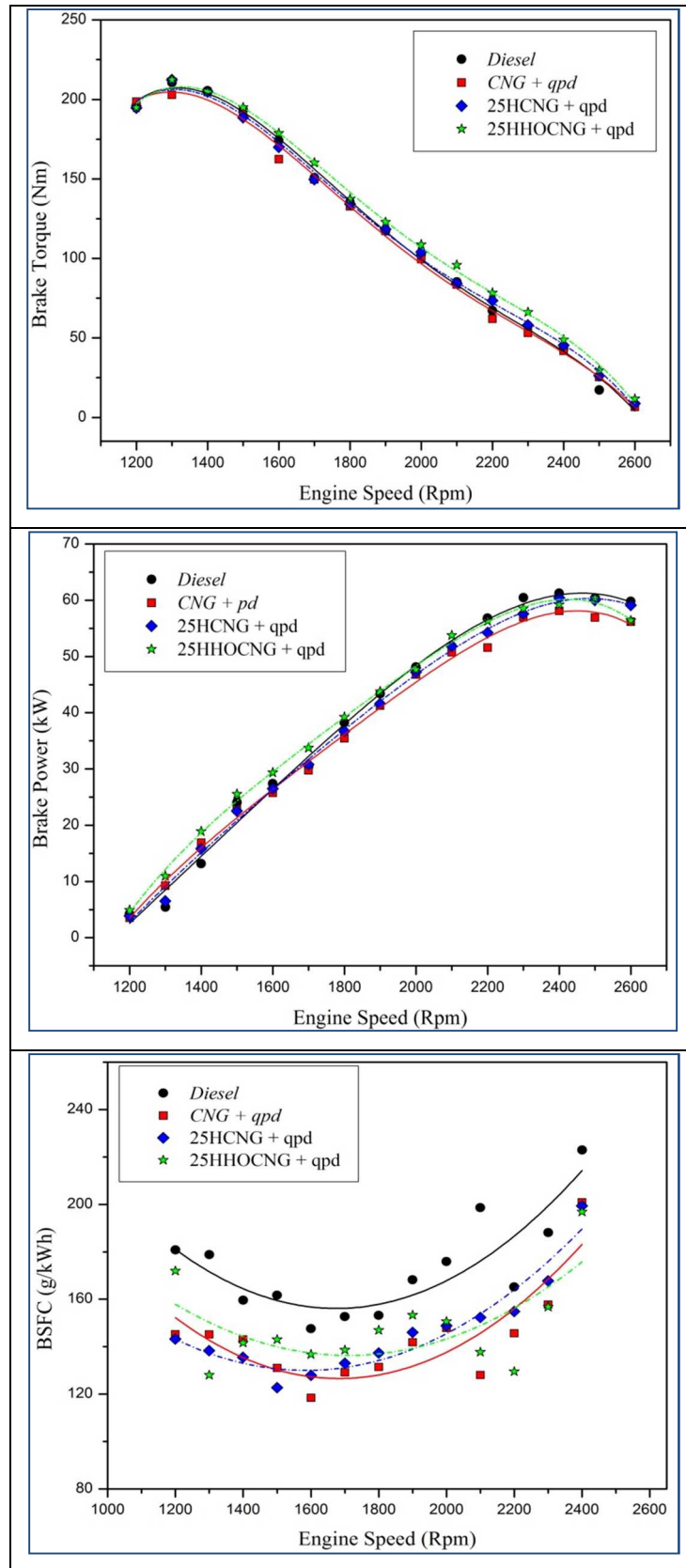


Figure 4.7. Comparative performance data for Diesel, CNG, 25HCNG, 25HHOCNG

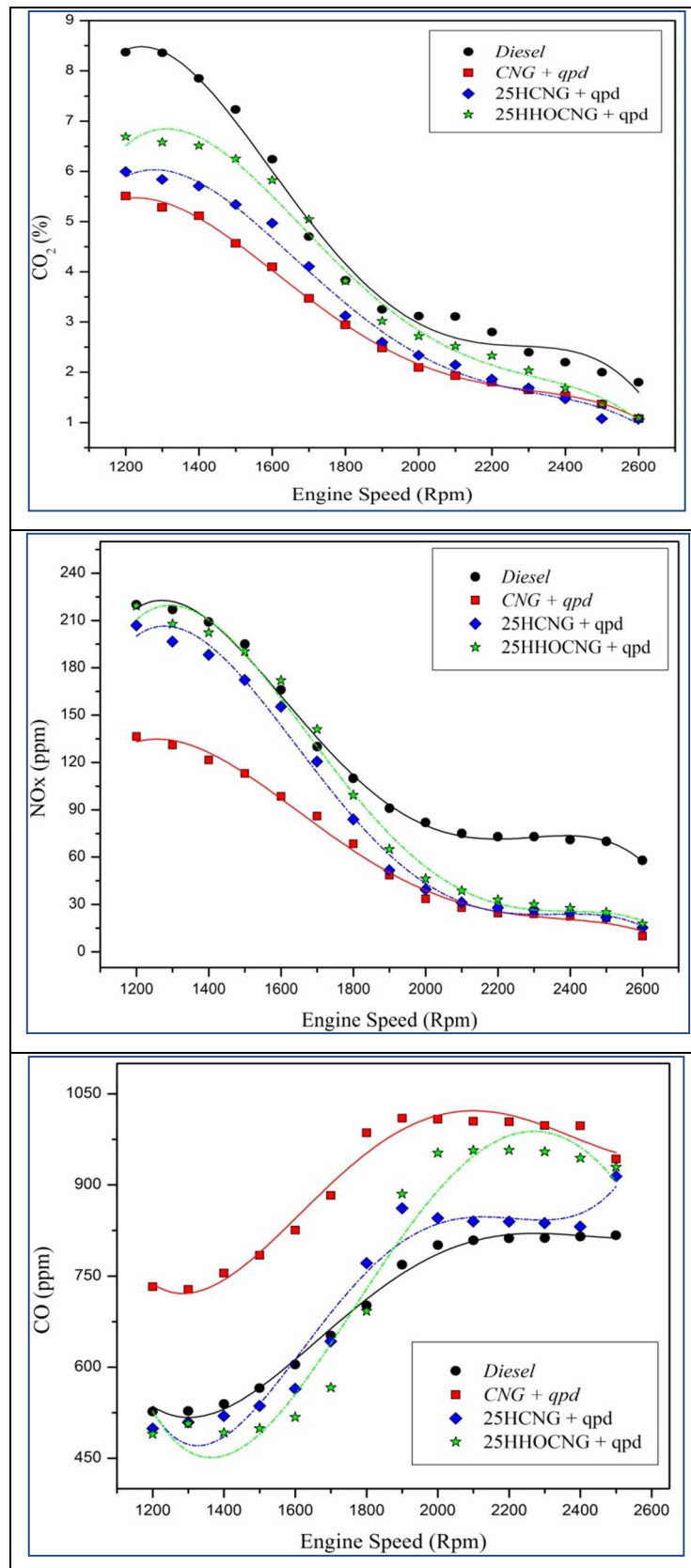


Figure 4.8. Comparative emission data for Diesel, CNG, 25HCNG and 25HHOCNG

Comparison of using 30HCNG vs 30HHOCNG

The performance and emission results of comparison of using 30HCNG vs 30HHOCNG under quarter pilot diesel operation, illustrated in Figure 4.9 and Figure 4.10, respectively. Brake Torque, Brake Power and Brake Specific Fuel Consumption vs engine speed of standard diesel fuel; CNG+qpd; 30HCNG+qpd and 30HHOCNG+qpd fuel mixtures are illustrated in Figure 4.9.

It can be clearly seen from the torque results; HCNG and HHOCNG additives improved the torque values compared the CNG + qpd and neat diesel operation. Hydrogen and extra oxygen that allows more powerful and efficient combustion and the average of 0.5 % and 1.89% brake torque improvement was obtained for 30HCNG+qpd and 30HHOCNG+qpd, respectively.

Similar improvements for brake power and torque are obtained with mixtures at same conditions. Average brake power improvements were 0.04% and 1.5% for 30HCNG+qpd and 30HHOCNG+qpd, respectively.

It is ocularly CNG, HCNG and HHOCNG mixtures were decreased the BSFC with 19.2%, 17.5% and 15.1%, for CNG, 30HCNG and 30HHOCNG, respectively.

Figure 4.10, illustrated the variation of CO₂, NO_x and CO emission as a function of engine speed for standard diesel fuel; CNG+qpd; 30HCNG+qpd and 30HHOCNG+qpd fuel mixtures.

It is clearly seen that, gaseous fuel mixtures were decreased the CO₂ emission values with 41%, 31% and 32.1% for CNG, 30HCNG, 30HHOCNG, respectively.

NO_x effect could be listed as; 47.4%, 26.8% and 16.8% for CNG, 30HCNG and 30HHOCNG, respectively. The best improvement of NO_x value came from CNG mixtures because of the hydrogen's worse effect of NO_x parameters. Even, CNG mixture was minimized this effect and decreased the values under standard diesel operation.

CO emission values were increased for CNG, 30HCNG and 30HHOCNG with 31.02%, 7% and 1.5% when compared with normal diesel fuel operation. This increment was strongly depended on CNG fact.

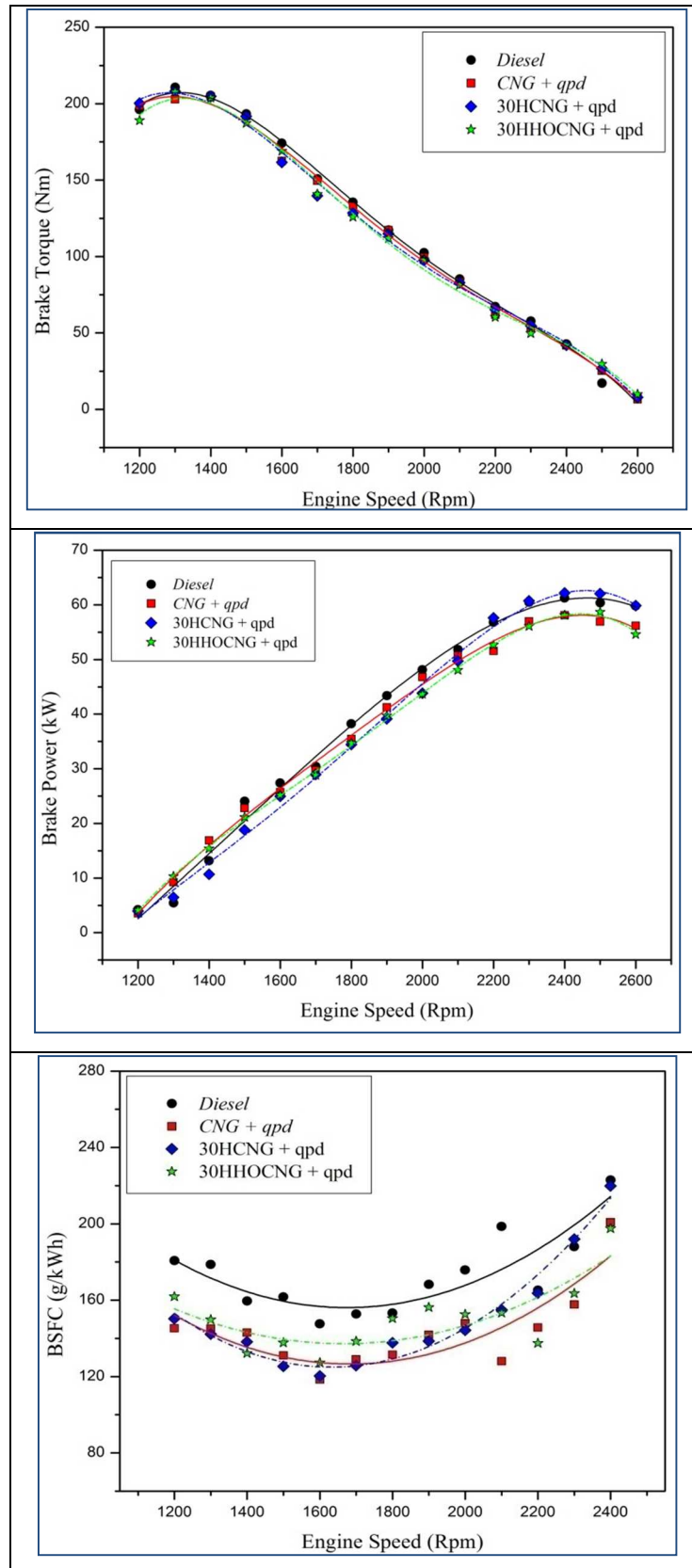


Figure 4.9. Comparative performance data for Diesel, CNG, 30HCNG, 30HHOCNG

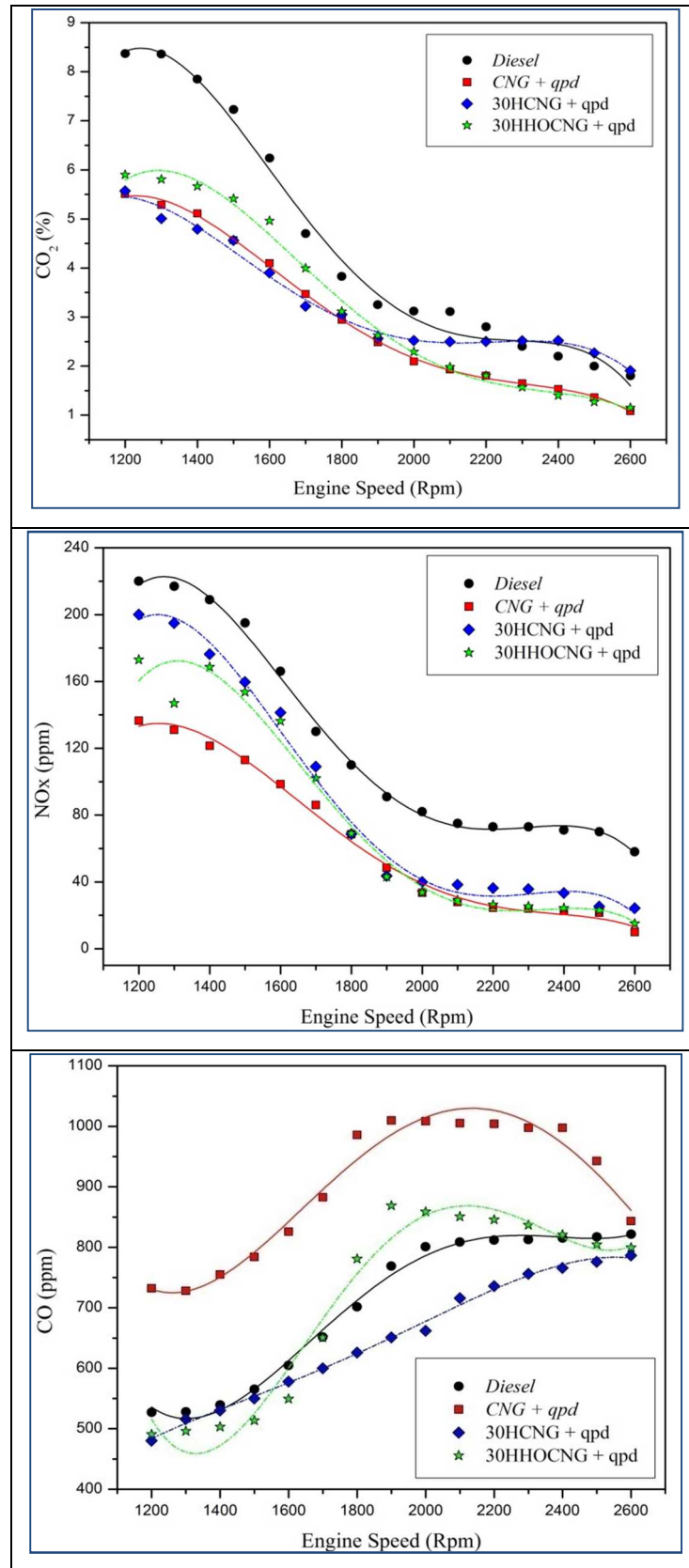


Figure 4.10. Comparative emission data for Diesel, CNG, 30HCNG, 30HHOCNG

4.5. Comparison of HCNG vs HHOCNG under semi pilot diesel operation

Comparison of using 20HCNG vs 20HHOCNG

The performance and emission results of comparison of using 20HCNG vs 20HHOCNG under semi pilot diesel operation, illustrated in Figure 4.11 and Figure 4.12, respectively. Brake Torque, Brake Power and Brake Specific Fuel Consumption vs engine speed of standard diesel fuel; CNG+spd; 20HCNG+spd and 20HHOCNG+spd fuel mixtures are illustrated in Figure 4.11.

It can be clearly seen from the torque results; HCNG and HHOCNG additives improved the torque values compared the CNG + spd and neat diesel operation. Hydrogen and extra oxygen that allows more powerful and efficient combustion and the average of 3.8 % and 5.3% brake torque improvement was obtained for 20HCNG+spd and 20HHOCNG+spd, respectively.

Similar improvements for brake power and torque are obtained with mixtures at same conditions. Average brake power improvements were 6,18% and 7.19% for 20HCNG+spd and 20HHOCNG+spd, respectively.

It is evidently CNG, HCNG and HHOCNG mixtures were decreased the BSFC with 21.1%, 13.9% and 16.5%, for CNG, 20HCNG and 20HHOCNG, respectively.

Figure 4.12, illustrated the variation of CO₂, NO_x and CO emission as a function of engine speed for standard diesel fuel; CNG+spd; 20HCNG+spd and 20HHOCNG+spd fuel mixtures.

It is clearly seen that, gaseous fuel mixtures were decreased the CO₂ emission values with 40.5%, 16.7%, 21.3% for CNG, 20HCNG, 20HHOCNG, respectively.

NO_x effect could be listed as; 31.1%, 7.6% and 4.7% for CNG, 20HCNG and 20HHOCNG, respectively. The best improvement of NO_x value came from CNG mixtures because of the hydrogen's worse effect of NO_x parameters. Even, CNG mixture was minimized this effect and decreased the values under standard diesel operation.

CO emission values were increased for CNG, 20HCNG and 20HHOCNG with 15%, 5.2%, 14.3% when compared with normal diesel fuel operation. This increment was strongly depended on CNG fact.

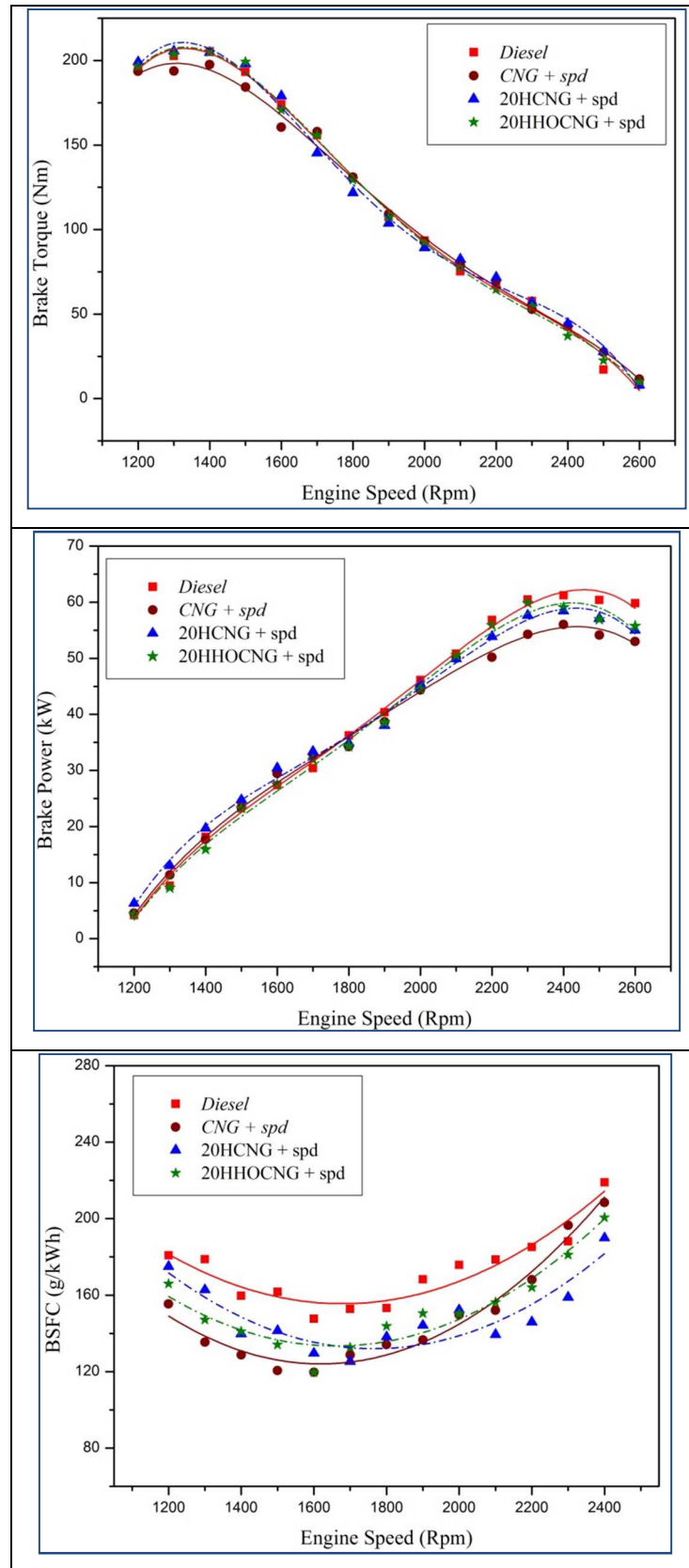


Figure 4.11. Comparative performance data for Diesel, CNG, 20HCNG, 20HHOCNG

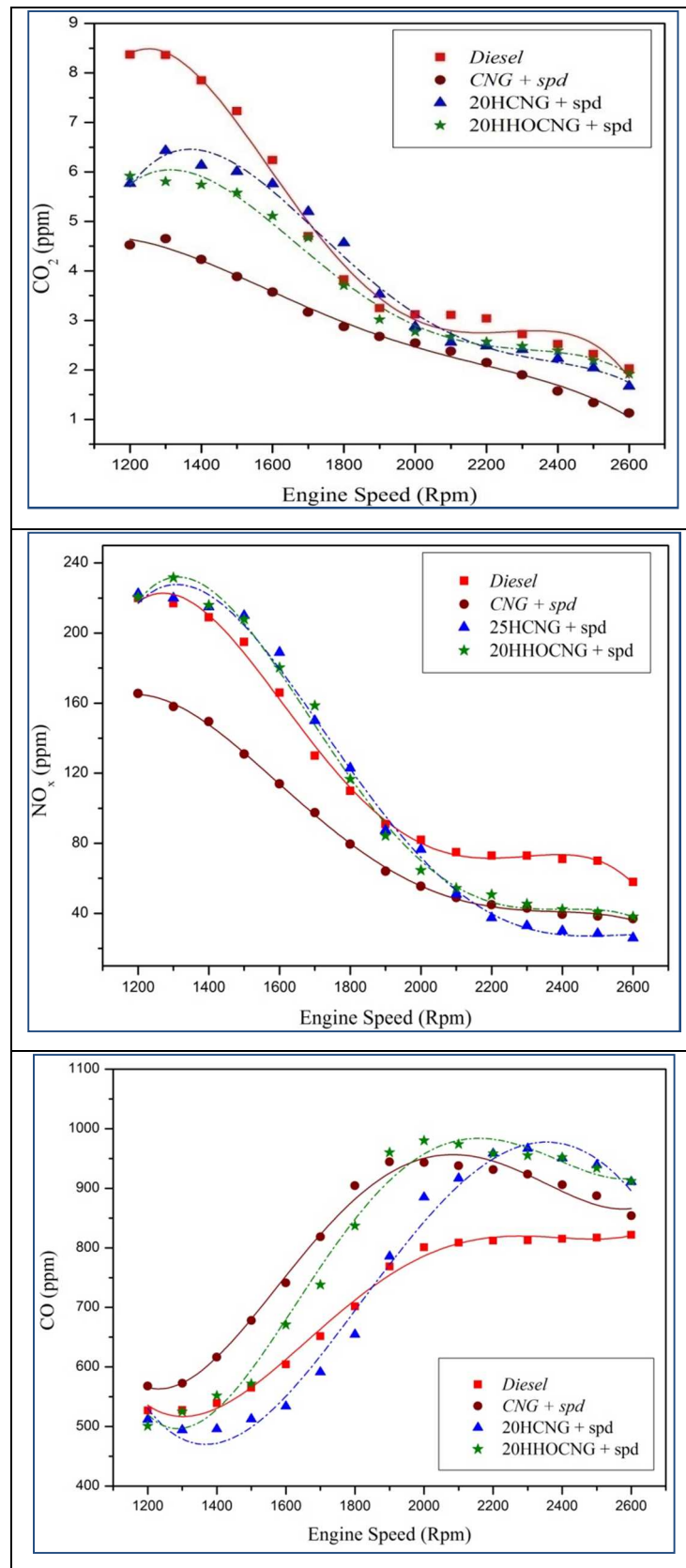


Figure 4.12. Comparative emission data for Diesel, CNG, 20HCNG, 20HHOCNG

Comparison of using 25HCNG vs 25HHOCNG

The performance and emission results of comparison of using 25HCNG vs 25HHOCNG under semi pilot diesel operation, illustrated in Figure 4.13 and Figure 4.14, respectively. Brake Torque, Brake Power and Brake Specific Fuel Consumption vs engine speed of standard diesel fuel; CNG+spd; 25HCNG+spd and 25HHOCNG+spd fuel mixtures are illustrated in Figure 4.13.

It can be clearly seen from the torque results; HCNG and HHOCNG additives improved the torque values compared the CNG + spd and neat diesel operation. Hydrogen and extra oxygen that allows more powerful and efficient combustion and the average of 2.4 % and 5% brake torque improvement was obtained for 25HCNG+spd and 25HHOCNG+spd, respectively.

Similar improvements for brake power and torque are obtained with mixtures at same conditions. Average brake power improvements were 4.18% and 6.29% for 25HCNG+spd and 25HHOCNG+spd, respectively.

It is ocularly CNG, HCNG and HHOCNG mixtures were decreased the BSFC with 19.2%, 16.9% and 14.3%, for CNG, 25HCNG and 25HHOCNG, respectively.

Figure 4.14, illustrated the variation of CO₂, NO_x and CO emission as a function of engine speed for standard diesel fuel; CNG+spd; 25HCNG+spd and 25HHOCNG+spd fuel mixtures.

It is clearly seen that, gaseous fuel mixtures were decreased the CO₂ emission values via 40.5%, 34.4% and 30.6% for CNG, 25HCNG, 25HHOCNG, respectively.

NO_x effect could be listed as; 31.1%, 20.6% and 16.1% for CNG, 25HCNG and 25HHOCNG, respectively. The best improvement of NO_x value came from CNG mixtures because of the hydrogen's worse effect of NO_x parameters. Even, CNG mixture was minimized this effect and decreased the values under standard diesel operation.

CO emission values were increased for CNG, 25HCNG and 25HHOCNG with 15%, 9.7% and 10.9% when compared with normal diesel fuel operation. This increment was strongly depended on CNG fact.

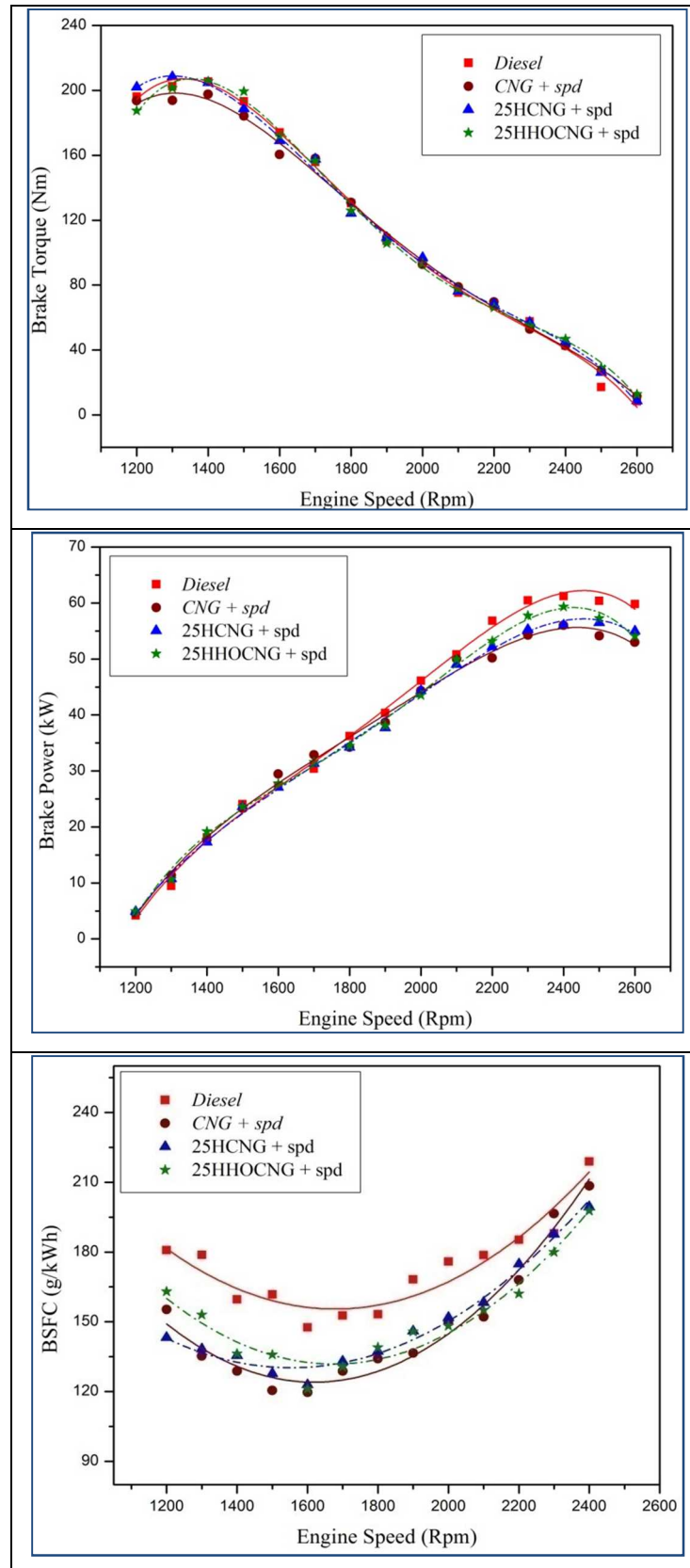


Figure 4.13. Comparative performance data for Diesel,CNG, 25HCNG, 25HHOCNG

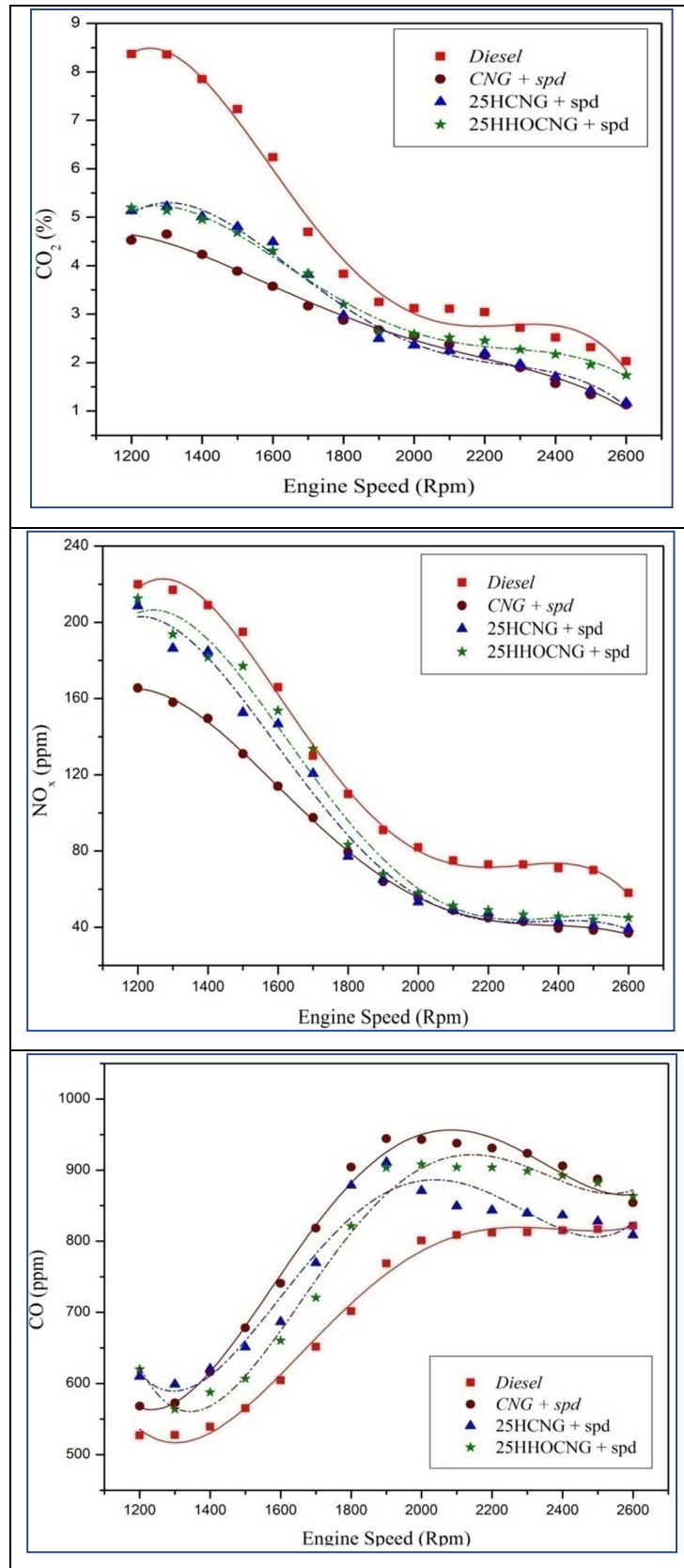


Figure 4.14. Comparative emission data for Diesel, CNG, 25HCNG, 25HHOCNG

Comparison of using 30HCNG vs 30HHOCNG

The performance and emission results of comparison of using 30HCNG vs 30HHOCNG under semi pilot diesel operation, illustrated in Figure 4.15 and Figure 4.16, respectively. Brake Torque, Brake Power and Brake Specific Fuel Consumption vs engine speed of standard diesel fuel; CNG+spd; 30HCNG+spd and 30HHOCNG+spd fuel mixtures are illustrated in Figure 4.15.

It can be clearly seen from the torque results; HCNG and HHOCNG additives improved the torque values compared the CNG + spd and neat diesel operation. Hydrogen and extra oxygen that allows more powerful and efficient combustion and the average of 2.42 % and 4.4% brake torque improvement was obtained for 30HCNG+spd and 30HHOCNG+spd, respectively.

Similar improvements for brake power and torque are obtained with mixtures at same conditions. Average brake power improvements were 2.2% and 5.34% for 30HCNG+spd and 30HHOCNG+spd, respectively.

It is ocularly CNG, HCNG and HHOCNG mixtures were decreased the BSFC with 19.2%, 15.7% and 17.5%, for CNG, 30HCNG and 30HHOCNG, respectively.

Figure 4.16, illustrated the variation of CO₂, NO_x and CO emission as a function of engine speed for standard diesel fuel; CNG+spd; 30HCNG+spd and 30HHOCNG+spd fuel mixtures.

It is clearly seen that, gaseous fuel mixtures were decreased the CO₂ emission values with 40.5%, 34.8%, 28.9% for CNG, 30HCNG, 30HHOCNG, respectively.

NO_x effect could be listed as; 31.1%, 16.6% and 12.7% for CNG, 30HCNG and 30HHOCNG, respectively. The best improvement of NO_x value came from CNG mixtures because of the hydrogen's worse effect of NO_x parameters. Even, CNG mixture was minimized this effect and decreased the values under standard diesel operation.

CO emission values were increased for CNG, 30HCNG and 30HHOCNG with 15%, 9.6%, and 13.7% when compared with normal diesel fuel operation. This increment was strongly depended on CNG fact.

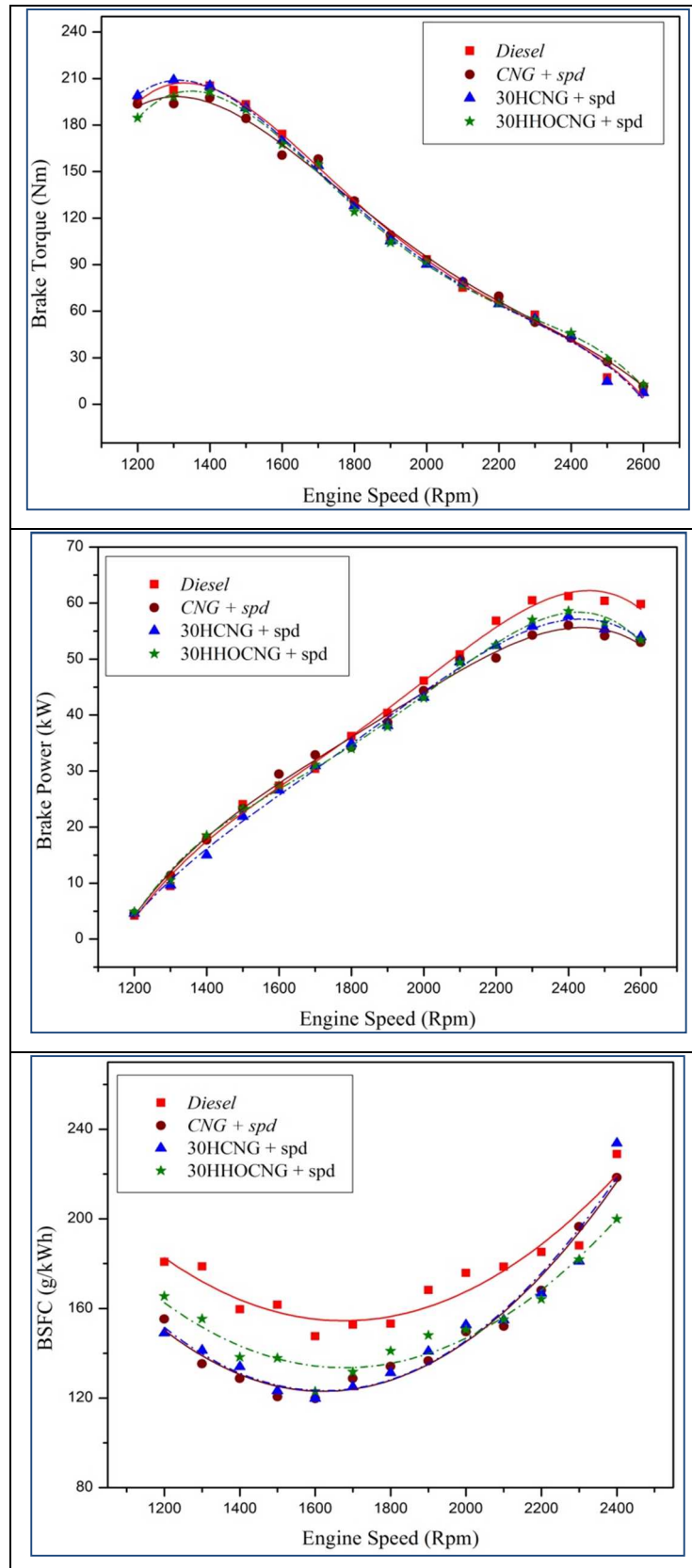


Figure 4.15. Comparative performance data for Diesel, CNG, 30HCNG, 30HHOCNG

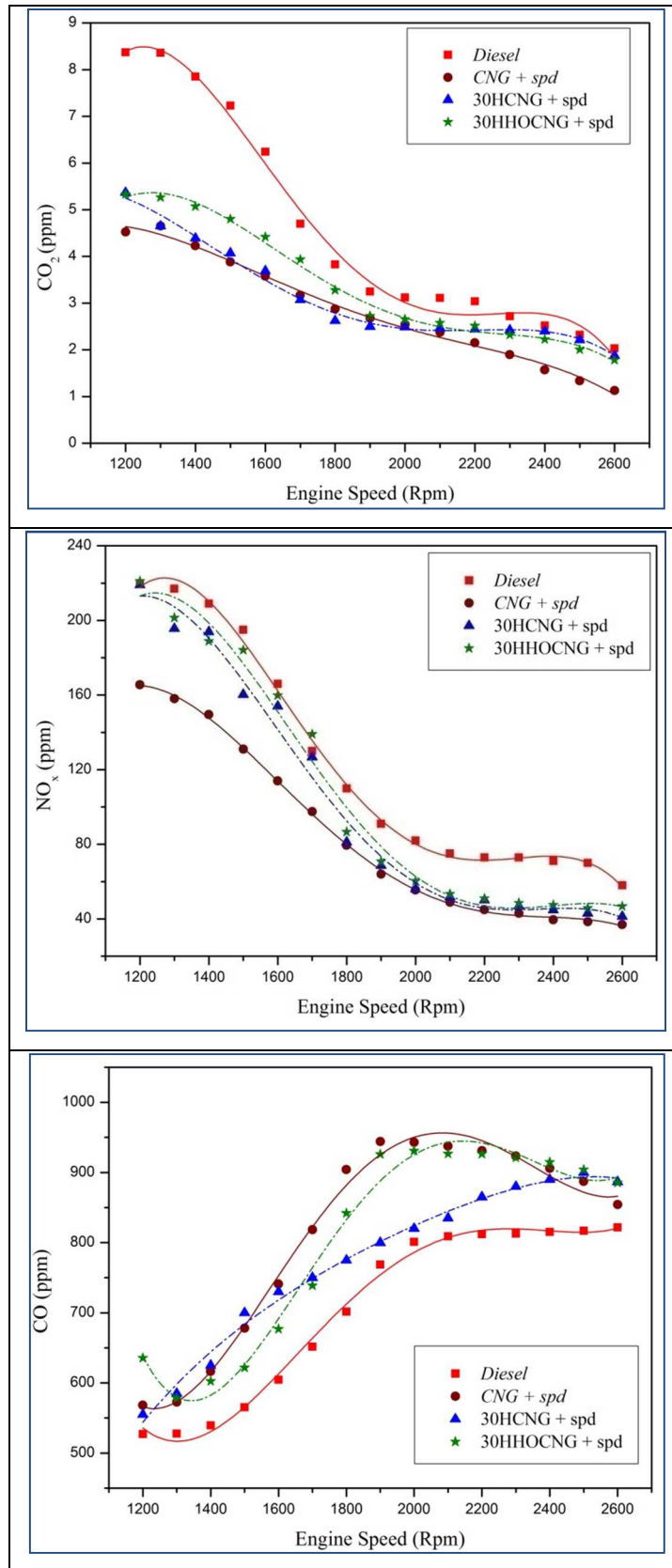


Figure 4.16. Comparative emission data for Diesel, CNG, 30HCNG, 30HHOCNG

4.6. Brake Thermal Efficiency and Exhaust Gas Temperature

Due to the high laminar velocity of combustion and the wide flammability limits of hydrogen, its addition is utilized as a method to shift stable engine operation to leaner mixtures, with positive effects on emissions and thermal efficiency. The use of hydrogen as an additive was also considered as a solution to enhance the combustion rates of some fuels like methane (Chiriac et. al, 2006). The high RON and low lean-flammability limit of hydrogen and natural gas provide the necessary elements to attain high thermal efficiencies in an ICE (White et.al, 2006)

Papagiannakis et al.(2010), mentioned that, the decrease of the total relative air/fuel ratio, which is caused by the increase of diesel fuel supplementary ratio, results to a lower brake thermal efficiency compared to the one under normal diesel operation. The specific deterioration becomes more evident at low and intermediate loads, while at high load and high diesel supplementary ratios the engine efficiency is improved.

Wang et al.(2007), suggested that, two factors due to hydrogen addition influence the variation of thermal efficiency; on one hand, the increase of combustion velocity by hydrogen addition shortens the combustion duration and increases the thermal efficiency, and on the other hand, the heat loss to the chamber wall will be increased by hydrogen addition due to the decreased quench distance and increased combustion temperature, and this will decrease the thermal efficiency. And Park et al (2013) expressed the thermal efficiency, and that of the HCNG engine is superior to that of the CNG engine.

Figure 4.17 shows the variations in the brake thermal efficiency (η_{bth}) as a function of engine speed for the cases of using diesel fuel, CNG + semi pilot diesel; HHO + semi-pilot diesel; 25HCNG + semi-pilot diesel and 25HHOCNG + semi-pilot diesel fuel mixtures. It should be noticed that, in this sample the semi-pilot diesel choose rather than quarter because of the better values.

In results, the averages of η_{bth} improvement of hydrogenated fuels are better than neat diesel operation and CNG usage with between 3.5% - 6.5%. CNG + semi-pilot diesel reduced the η_{bth} with 6.432% vs neat diesel.

These results can be explained by the fact that the high diffusion and flame speeds of hydrogen help improve the charge homogeneity. Besides, the wide flammability of hydrogen also enables the fuel-air mixtures to be burnt completely at lean conditions. Thus, the engine thermal efficiency could be improved after hydrogen addition. Meanwhile, the blending of HHO leads to the increased oxygen concentration in the intake gas, which is also capable of enhancing the combustion completeness for the fuel-air mixtures. η_{bth} results agreement with the previous studies which examined both H_2 and HHO.

As an important point of this section, a critical issue (Lower Heating Value of HHO) has to discuss which directly related with η_{bth} . Thermal efficiency is an important performance indicator in engine performance. In formula form of η_{bth} regenerates from Bauer C.G. (2001), to this thesis can be written as equation 3, adapted for all cases with related changes;

$$\eta_{bth} = \frac{\dot{W}_{bth}}{\dot{m}_{fuel} \cdot \sum \dot{m}_i \cdot LHV_i} \quad (3)$$

where η_{bth} is the brake thermal efficiency; $\dot{W}_{bth}$ is brake power; $\dot{m}_{fuel}$, $\dot{m}_{H_2}$, $\dot{m}_{CH_4}$, $\dot{m}_{C_2H_6}$, $\dot{m}_{C_3H_8}$ is the mass flow rates of all fuels; and LHV_{H_2} , LHV_{CH_4} , $LHV_{C_2H_6}$, $LHV_{C_3H_8}$, LHV_{HHO} is the lower heating values of fuels. In eq.(3), all indices can be known and calculated except $\dot{m}_{HHO}$. In literature there are few different attitudes above this situation. Lounici et.al (2014), noticed this issue the total BSFC is directly calculated from the engine brake power output and fuels mass flow rates. Thus, no consideration of the difference in LHV between natural gas, hydrogen and neat diesel is taken into account. Mariani et.al (2012), reported a review of HCNG blends in ICE and according to them, $LHV_{stoich,mix}$, which is proportional to the engine power output, is negligibly affected by hydrogen addition. Le Anh et.al (2013), touched upon the AFR of HHO and when attributed that, because of HHO gas is water electrolysis product, so the volume of oxygen in this gas is enough for hydrogen combustion process; therefore $(A/F)_{HHO} = 0$ (in theory condition). Insomuch as this attitude, effect the equivalence ratio which we

In this study η_{bth} is calculated under Chiriac's approachment (2006) and mentioned the LHV of HHO transformed to H-H ($2H_2$ and O_2) and use for the thermal efficiency with $0.66 \cdot (m_{H_2} \cdot LHV_{H_2})$. When they noticed this issue they also referred that; presence of oxygen as a product of water electrolysis would not produce a significant change in the engine performance, and the overall effect of the production of hydrogen was found energetically to be not viable over much of the engine operating range and also HHO whose composition includes not only the conventional mixture of hydrogen and oxygen but also, OH, HO_2 , traces of H_2O , and some additional species.

For this study, the maximum EGTs are 571, 535, 530, 500 and 473 for HHO+ semi-pilot diesel; 25HHOCNG + semi-pilot diesel; 25HCNG + semi-pilot diesel; neat diesel and CNG + semi-pilot diesel fuel respectively.

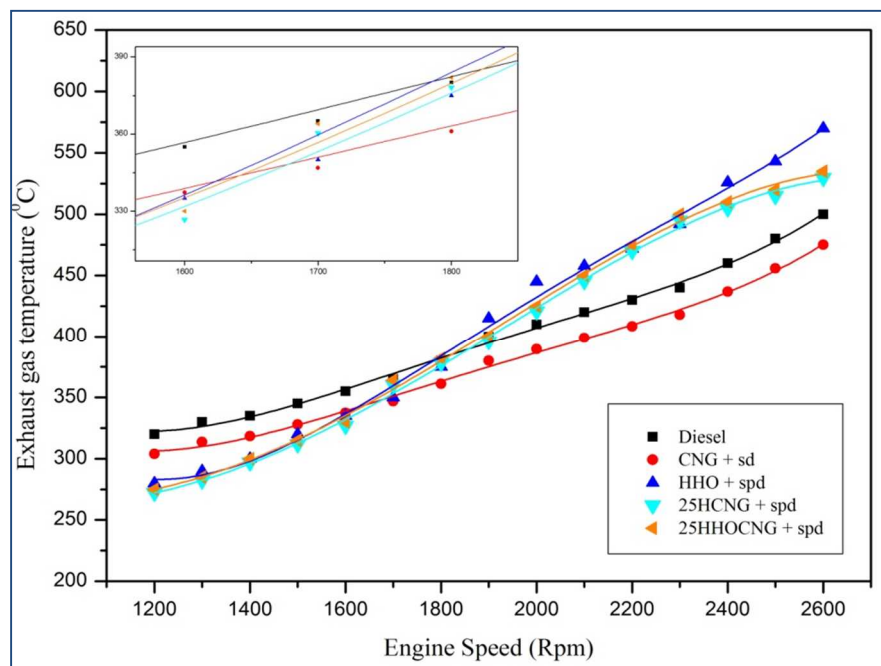
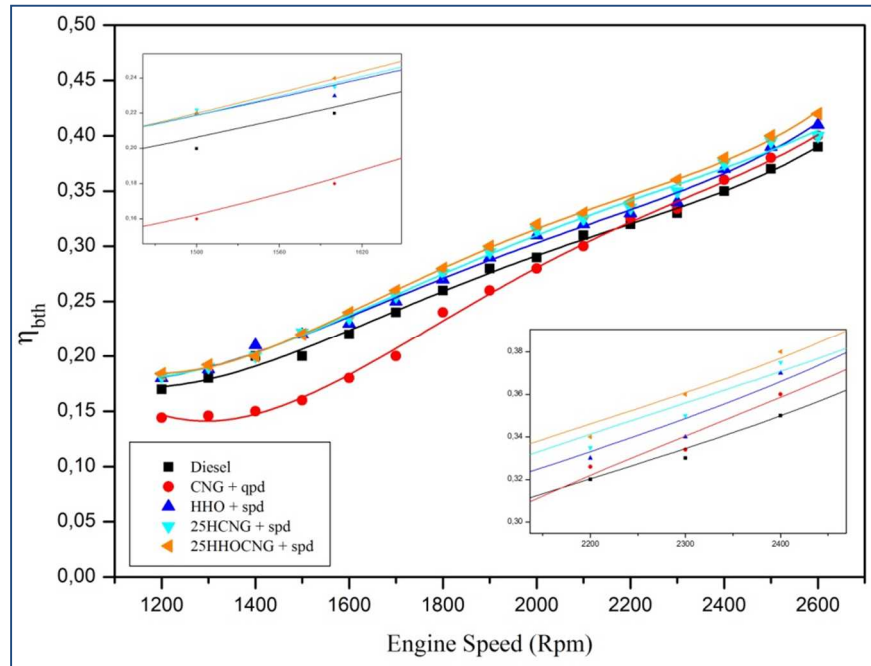


Figure 4.17. Analysis of Brake Thermal efficiency and Exhaust Gas Temperature

4.7. Micro Scale Cost Analysis

As an engineering approach, being only environmentally friendly is not enough. Economical point of this study is briefly explained in this subsection. Equation 4 is presented below by considering current fuel prices for calculation. Instead of converting diesel engine to natural gas engine, which is expensive and needs time consumption, limited modifications on diesel engine is easier and cheaper. Additionally, converted engines are not suitable to work with diesel fuel anymore. Comparison of these two options is illustrated in Table 4.2.

Table 4.2. Approximate investment cost of converting modified diesel engine and present work

Options	Changes/Additions	Approximate investment cost
Converting diesel engine to NG	• Modification on cylinder head and piston • Reduce compression ratio • Incorporate a spark plug • Gas fuel tanks, piping systems and necessary equipment.	\$10.000
Limited modifications on engine	• Mixing chamber before intake manifold • Set up the fuel pump • HHO generator, gas fuel tanks, piping systems and necessary equipment.	\$2700

National current fuel prices are \$1.5 for 1 liter of diesel fuel, \$1 and \$2 for 1m³ of CNG and H₂, respectively. Volumetric flow rates of gaseous fuels are measured from flow meters multiplied by duration of experiment (in unit of minute), meanwhile mass flow rate of liquid diesel fuel is measured and transferred to the computer software simultaneously. Substitution of diesel fuel provided %45 reduction on liquid fuel consumption.

$$\frac{0.000000 \times \$0.0}{0.000000 \times \$0.000000 + 0.000000 \times \$0.000000 + 0.000000 \times \$0.000000} - 1 \times 100 = 0 (\%) \quad (4)$$

η : Percentage of saving in cash

V_{original} : Total amount of diesel fuel consumption during the experiment with original set up of fuel pump (V/ρ).

$V_{\text{substituted}}$: Total amount of substituted diesel fuel consumption during the experiment after fuel pump set up (V/ρ).

Q_{CNG} : Volumetric flow rate of CNG fuel measured by flow meter during experiment (L/min).

Q_{H_2} : Volumetric flow rate of H₂ fuel measured by flow meter during experiment (L/min).

ETP: Experimental Time Period (second).

An explanatory example;

To get a consistent idea, Equation 4 is applied on experimental engine output data which also includes measured gaseous fuel during the test.

$V_{\text{original}} = 0.2$ L, $V_{\text{substituted}} = 0.165$ L, $Q_{\text{CNG}} = 19$ L/min, $Q_{\text{H}_2} = 8$ L/min, **ETP**: 100 sec.

$$\eta = \frac{0.2 \times \$1.5}{0.11 \times \$1.5 + 0.19 \times \frac{\$1}{1000} + 8 \times \frac{\$2}{1000} \times 100 \left(\frac{1}{60}\right)} - 1 \times 100$$

$$= 77\%$$

If a commercial truck is considered which has 30 L/100 km fuel consumption and travels around minimum of 120,000 km/year, fuel cost becomes around \$54,000 (36,000 (L) x 1.5 (\$/L)). It should be noticed that, HHO gas is a free of charge, except for the initial investment cost. For this study, HHO generator cost is \$700 with all equipments and ordered from "Advanced HHO"; a division of Top Energy, LLC, USA. Additionally, even investment cost and constant operating costs included, this experimental usage is extremely advised to protect environment and micro-macro economies. It should be noticed that this is a micro financial analysis which does not includes necessary gas stations or infrastructure preparations.

5. CONCLUSIONS

The goal of this thesis was to investigate the effect of HHO and CNG fuel mixtures on improving engine efficiency while reducing the exhaust emissions with dual fuel mode under quarter and semi pilot injection strategy without any modification of the base engine. The results are summarized in this chapter including all remarkable findings. The contributions made and future suggestion studies resulting from this work are also presented.

Alternative fuels are playing a colossal role in usage of future fuels. The term alternative fuels have come to indicate any fuel that may be used in engine applications other than those conventional liquid fuels, such as gasoline or diesel fuel. Alternative-fueled vehicles and emission-free cars are expected to gain more popularity due in part to enforcement of stricter emission standards, the unmistakable fate of depletion for conventional transportation fuels, and numerous tax incentives for such vehicles.

Alternative fuels have significant importance on engine performance and exhaust emissions. Especially gas fuels (Hydrogen, HHO and CNG) which use in ICE assisted reducing emissions. In order to expand the role of hydrogen in the near term, one option is to use hydrogen for transportation by mixing it with natural gas and use it for use in ICE engines.

From Rudolf Diesel to now, in spite of the dominant position of diesel engines now holds in many applications that it is today the subject of intensive development and capable of improvements.

Fuel research and developments are always possessing importance as much as engine technologies at automotive industry. Common objective is to create more economical and environmental friendly future for both. In CI engines, dual-fuel mode operation gives promotional utilize when use gaseous fuels. The term, dual-fuel diesel operation, describes compression ignition engines that burn *simultaneously* two entirely different fuels in varying proportions. In dual fuel CI engines operating with gaseous fuels as primary fuel and a *óilotô* amount of liquid diesel fuel as an *ignition source*, the gaseous fuel is inducted along with the intake air

and is compressed like in a conventional diesel engine. The mixture of air and gaseous fuel does not auto ignite due to its high autoignition temperature. A small amount of liquid diesel fuel is injected near the end of the compression stroke to ignite the gaseous mixture. Mainly for economic and environmental reasons, the quantity of the diesel fuel pilot needs to be minimized relative to that of the cheaper fuel gases. The pilot quantity of a dual fuel engine represented the major role for balancing of the engine performance and exhaust emissions. As similarly, pilot diesel injection strategy exhibits the factors of *total economy* as lower specific fuel consumption and does not necessary to modify the engine; *environmental issues* as lower undesirable exhaust emissions can be obtained with dual-fuel operation with pilot diesel injection.

The present work investigates of using 20%, 25%, 30% (by volumes) HCNG (Hydrogenated Compressed Natural Gas) and HHOCNG (hydroxy-compressed natural gas) fuel mixtures on a non-modified diesel engine operated with pilot injection experimentally. HCNG and HHOCNG mixtures were used as a replacement fuel in a non-modified diesel engine via intake manifold and reduction of diesel fuel by dint of pilot injection. Reduction of diesel fuel mass was prepared as two different substitutions like quarter and semi-pilot injection controlled by stepping motor devices. 20%, 25%, 30% (by volumes) HHOCNG and HCNG fuel mixture were tested in a 3.6 L, four cylinders, four stroke and water coolant diesel test engine between 1200-2600 rpms. Effects of these two different diesel substitution on engine performance and exhaust emissions parameters were compared and illustrated with graphics as brake power, brake torque, and brake specific fuel consumption; CO, CO₂ and NO_x. Previous studies were also refereed with separated related topics. Experimental procedure and devices were explained detailed. The minimum and optimum quantities of pilot injection at specific engine operational conditions are determined, and the effectiveness of different measures to improve engine performance for various operational conditions are examined. Calibrating and optimizations approaches and with their results, two pilot diesel injection strategies are used in this thesis. One tour (360°) and two tours (720°) of fuel pump plunger gave the best results in engine performance and exhaust emissions. For this reason, in

this thesis experimental investigations and their results were prepared under 360° and 720° pin rotations. Results of this study are given a comparable situation between HHOCNG and HCNG. Also improvement scales of usage these fuel mixtures were described. Additionally, a micro cost analyses of pilot injection diesel engine which fumigated under these fuel mixtures were also examined.

Conclusion of such an investigation benefits the development of effective attraction of HHOCNG and HCNG fuels were explained detail and the following conclusions were obtained below ;

- *First of all, the originality of this thesis* is to investigate the effects of HHOCNG fuel mixtures on a non-modified diesel engine's performance and exhaust emissions with usage of quarter and semi pilot diesel injection. From the point of view; HHOCNG fuel mixture analyses in a conventional diesel engine had been added to literature as an initial study with this thesis and related articles which can be seen in appendix part.
- The goal of this thesis was reached the success result which expected that; improving engine efficiency while reducing the exhaust emissions with non-modification.
- Using the pilot diesel injection with the dint of stepping motor and devices on dual fuel mode, preventing the unnecessary structural modification on test engine.
- For all cases; semi-pilot diesel injection was more preferable than quarter-pilot diesel injection.
- Both quarter and semi pilot diesel injections improved the fuel economy perspective and reduced the specific fuel consumptions.
- As it predicted, gas fuel additives observed noticeable reductions on emission results relative to diesel fuel.

- HHOCNG and HCNG increased the performance parameters compared with single CNG usage on diesel engines. Insomuch that, HHOCNG and HCNG providing the positive performance affect slightly (which decreased the amount of liquid fuel with the substitution of diesel fuel); when compared the standard diesel operation.
- HHO showed the similar characteristic properties with hydrogen on performance base.
- The all test results were adapted with 3E (economical, environmental and efficiency) strategy, except CO exhaust emissions.
- CO₂ and NO_x results have superior outputs when compared with normal diesel operation. Hydrogenated gaseous fuel mixtures emission results were placed between single CNG + pilot diesel operations and standard diesel operations.
- As a sample approach on thermal efficiency, slightly reductions were found on HHOCNG and HCNG fuel mixtures relative to normal diesel operation results. The dominant factor of this reduction depended on the quantity of diesel fuel.
- At higher speeds, hydrogenated gaseous fuel mixtures tented to increase the exhaust gas temperature.
- A minor cost analysis for a heavy duty engine performed and results were very promising when it comes to economy scale.
- All test result were agreement with the previous studies on behalf of the CNG and HCNG experiments which listed in references part with carefully selection.
- During the experiments there has not been faced with any risk of explosion.
- Finally, under the conditions of this thesis, 25HHOCNG fuel mixture with semi-pilot injection operation was obtained the best mix when used as an alternative and additional fuel for run under this test engine.

This study shows the availability of using HHOCNG mixtures as an indicator alternative fuel in diesel engines applications. From the perspective of general results, the HHOCNG mixture helps the improvement of engine performance and decreases the exhaust emissions with very economically gains. Worthwhile the future suggestions will be mentioned for regenerate and improving the current state. For more detailed results, diesel engines with ECU will be regenerated the study with mentioned volumetric ratios. From the environmentally focus, further studies will be run under with EGR capabilities. Determining the HHO's engineering properties will help the scientists for better understanding the HHO usage availability.

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CURRICULUM VITAE

Hüseyin Turan ARAT was born on January 08, 1984 in Kayseri. After completing his education in Nuh Mehmet Küçükçalak Anatolian High School, he enrolled in Mustafa Kemal University Mechanical Engineering Department in 2001. He had graduated from the Mechanical Engineering Department of Mustafa Kemal University with a Bachelor of Science degree in 2006 and Master of Science degree in 2010 in the same university. He had started to Doctor of Philosophy education in Çukurova University with the same department. He has been working as a research assistant in Iskenderun Technical University since 2011. He has published 21 research papers in national & international journals. He has responsible on two different international journal editorial boards. His research areas are; internal combustion engines, alternative gas fuels, heat and mass transfer, nuclear engineering, fluid mechanics, energy sustainability and environmental progress, energy and mechanical engineering subdivisions.

APPENDIX

APPENDIX 1. Papers

The following publications are prepared from this thesis.

PAPER I- OPTIMIZING THE QUANTITY OF DIESEL FUEL INJECTION BY USING 25HHOCNG GAS FUEL MIXTURE

This paper was published in Advanced Engineering Forum Journal, Vol. 14 (2016) pp 36-45

PAPER II- EFFECT OF USING HYDROXY-CNG FUEL MIXTURES IN A NON-MODIFIED DIESEL ENGINE BY SUBSTITUTION OF DIESEL FUEL

This paper was presented at the 6th International Conference on Hydrogen Production, Oshawa, Canada (2015) and was accepted for publishing in International journal of Hydrogen Energy (2016)

PAPER III- EXPERIMENTAL COMPARISON OF PURE HYDROGEN AND HHO (HYDROXY) ENRICHED BIODIESEL (B10) FUEL IN A COMMERCIAL DIESEL ENGINE

This paper was presented at the 6th International Conference on Hydrogen Production, Oshawa, Canada (2015) and was accepted for publishing in International journal of Hydrogen Energy (2016)

PAPER IV- PİLOT PÜSKÜRTME YÖNTEMİYLE MODİFİYE EDİLMEMİŞ DİZEL MOTORDA 20HCNG GAZ YAKITININ PERFORMANS VE EMİSYONLARA ETKİSİ

This paper was presented at the 13th International Combustion Symposium in Bursa, TURKEY (2015) and was placed in symposium CD.

PAPER V- EXPERIMENTAL INVESTIGATION OF USING 30HCNG FUEL MIXTURE ON A NON-MODIFIED DIESEL ENGINE OPERATED WITH VARIOUS DIESEL REPLACEMENT RATES

This paper was published in International journal of Hydrogen Energy, 2016, doi:10.1016/j.ijhydene.2015.12.112

Optimizing the quantity of diesel fuel injection by using 25HHOCNG gas fuel mixture

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Keywords: Hydroxy (HHO), CNG, Fuel injection optimization, performance, emissions.

Abstract. Injection behaviors of internal combustion engines are very substantial fact that provides developments to future strategies about optimizing the engine and fuel parameters. During the combustion process, pilot diesel injection technique is more preferable option while using alternative gas fuels in a diesel engine. In this experimental study, a 3.6 L commercial, four stroke, four cylinders and mechanical fuel pump non-modified diesel test engine operated with hydroxy (HHO) and compressed natural gas (CNG) fuel mixtures under 25% and 75% (vol/vol), respectively. Diesel fuel injection quantities were reduced with the help of steeping motor devices which mounted on mechanical fuel pump plunger pin. Sensitive removes of steeping motor, plunger pin twisted clockwise 360°, 720° and 1080°, respectively. Comparisons of engine performance and exhaust emissions were explained briefly and illustrated via graphs. As a result, 720° clockwise twisted pin is the optimum point for experimental fuel pump plunger while using 25HHOCNG fuel mixtures.

Introduction

In Internal Combustion Engines (ICEs), injection behaviors play an influential and important role that affects the combustion, engine performance and exhaust emissions. Alternative fuels have been getting more attention as concerns escalate over exhaust pollutant emissions produced by ICEs, higher fuel costs, and the depletion of crude oil. Among ICEs applications, one of the most promising options is the diesel derivative dual fuel engine with gaseous fuels as the supplement fuel [1]. Additionally for optimizing the engine performance and exhaust emission parameters; with the ability to reduce oxides of nitrogen (NOx) emissions, carbon dioxide (CO₂) emissions, and particulate matter (PM) emissions, dual-fuel operation is environmentally viable [2]. An effective method for controlling the start of diesel combustion is through pilot fuel injection that

named other words, dual fuel combustion. Dual fuel engines are conventional diesel engines converted to operate on a gaseous fuel while using liquid diesel fuel injection to provide mainly ignition. These engines which tend to have common features with both spark-ignition and diesel engines. There are three different kinds of dual fuel engines according to the means of the induction of the gaseous fuels: 1) Common type of dual fuel engines with pilot injection into homogeneous charge gaseous fuel-air mixture; 2) Dual fuel engines with the timed port injection; 3) Dual fuel engines with both pilot and gaseous fuels injection into high pressure air [3]. The minimum pilot quantities may be different for different combustion chamber structures and operating conditions. Conventional diesel fuel injection systems limit the minimum pilot fuel quantity to not less than 5% of the full load fuel quantity when operating on diesel alone [4]. However, in practical dual fuel engines, the diesel flow is usually not reduced below 10 or 15 percent of the total energy required - in part to maintain the fuel injection system for diesel engine operation and to ensure adequate injection nozzle cooling [3.] Miyake-et al [5] suggested that, "natural gas and pilot liquid diesel fuel were mixed prior to injection and found that 40% pilot diesel fuel was needed for stable ignition". It would be ideal to simply replace diesel fuel with CNG in Compression Ignition (CI) engines, removing the need for significant investment in new trucks and rail freight; however, due to the auto-ignition characteristics of CNG, it cannot be directly substituted without heating the intake because of its relatively high auto-ignition temperatures [6]. Thus, in order to use CNG as a diesel substitute in existing CI engines, dual fuel operation must be employed where the CNG is drawn into the engine through the intake port or directly injected into the combustion chamber and a small diesel pilot, which is injected at the correct timing, is used to initiate the combustion process. This can drastically decrease the overall amount of diesel used, while improving fuel economy through a more homogeneous (and constant-volume like) combustion process [6]. Alternative gas fuels have occurred the same situation either CNG in using CI as a supplementary fuel. Alternative fuels inducted the CI combustion has different situational phenomena. The gas-air mixture is introduced into the cylinder during the intake stroke. Diesel fuel is directly injected into the cylinder during the compression stroke and compression-ignites which in turn ignites the surrounding gas-air mixture. After the period between diesel pilot injection and ignition known as ignition delay, the diesel pilot releases energy and initiates the combustion process. Then, the surrounding gas-air mixture ignites. Finally, the combustion process continues by flame propagation through the remaining lean gas-air mixture [7]. Hydrogen and HHO (oxy-hydrogen, hydroxy) gases are more attractive alternative fuels in ICEs. Alike CNG, these fuels can be combustible in CI engine with dual-fuel mode cause of CI combustion nature. Some researchers, like [1,2,3,4,5,6,7,8,9] related to the use of environmentally friendly fuels like CNG and HHO in diesel engines is seen in intensive way with exertion.

In this experimental study, three different quantities of pilot injection at specific engine operational conditions are determined, and the effectiveness of different measures to improve engine performance and exhaust emissions for various operational conditions are examined. Gaseous fuel mixture affected some

effective results for non-modified diesel engine at dual fuel combustion with pilot injection into diesel combustion both of engine performance and exhaust emissions. 25HHOCNG gas fuel mixture operated in a non-modified diesel engine by substitution of diesel fuel with helped of steeping motor and pilot diesel injection quantities effects are examined. All results and experimental setup is illustrated and explained briefly.

Experimental set-up

Test engine and fuels properties

3.6 L, non-modified, commercial, four cylinders, four-stroke, naturally aspirated, water-cooled direct injection compression ignition engine is used in all test which is placed in Cukurova University Automotive Engineering Laboratories in TURKEY. A Netfren brand hydraulic dynamometer was used for loading the test engine and MRU Delta 1600V gas analyzer was used to measure exhaust gas emissions. Data outputs of dynamometer and gas analyzer were collected via Elimko PR-100 data logger and were transferred to main computer. Table 1 presented the technical specifications of test engine.

Table 1. Test Engine Specifications

Brand	Mitsubishi Canter
Model	4D32 - In line 4
Type	D.I. diesel with glow plug
Displacement	3567cc
Bore x Stroke	104mm x105 mm
Power	89kW @ 3200rpm
Torque	295Nm @ 1800rpm

In this experimental study; CNG and HHO are used as gaseous fuels and commercial diesel is used as a liquid fuel. Fuel properties can be reachable author's previous studies [8]. In this study, CNG is supplied by cryogenic tank under 200 bar pressure which contain 97.372% Methane, 2.327% Nitrogen, 0.230 Ethane and 0.068 Propane. In tests, behind the CNG bottles exist, a check-valve is used for prevent back-flow. After the check-valve, CNG is transferred to regulator in an ex-proof pipeline and that regulator has 2-stage regulation system. 200 bar CNG pressure firstly reduced 12-15 bar in a first stage and secondly regulated to the 0-1 bar for attendance the air-gas mixture chamber. CNG heating-cooling systems are rebuilt using the engine cooling system thought radiator input and output. The quantity of CNG gas flow is controlled by a needle vane after the regulator. CNG gas is entered to ALICAT flow meter for the measurement of the gas flow after needle vane.

HHO system is electrolysis of distilled water with using suitable catalyst. In this experimental study, KOH (potassium hydroxide) is chosen as a catalyser. System contains double parallel connected dry cells, water reservoir, bubbler, solenoid relay, constant current PWM (Pulse Width Modulation), fittings and electrical wires. HHO generator runs with engine battery (24 V), 15-20 amperage

and 500 hertz frequency. When hydroxy gas is generated, gas pours itself into the needle vane and flow meter. For this experiment; (for a single test average) measurement from flow meters, the total average of hydroxy gas was adjusted to 3.04 LPM (Liter Per Minute) and the total average of CNG gas was adjusted to 9.104 LPM during the experiments, and these values indicates give approximate percentages of 25% Hydroxy gas and 75% CNG gas mixture by volume. Additionally this value has a similarity to literature for optimum usage (10-30% HCNG (Hydrogenated Compressed Natural Gas)) of these gas fuels.

Determination of substituted diesel fuel as pilot diesel injection

Optimizing the substituted diesel fuel quantities is the major goal of this study. For this reason substitution of diesel fuel was obtained with the help of stepping motor and devices which mounted on mechanical diesel fuel pump plunger. A bipolar, 1.8 deg/step, 6.2 Nm holding torque stepping motor adjusted to plunger and controlled with Toshiba TA 8435 stepping motor driver. It operated with software in main computer and obtained more sensitive measurement results. Optimizing the quantities of diesel fuel, three clockwise rotations were selected.

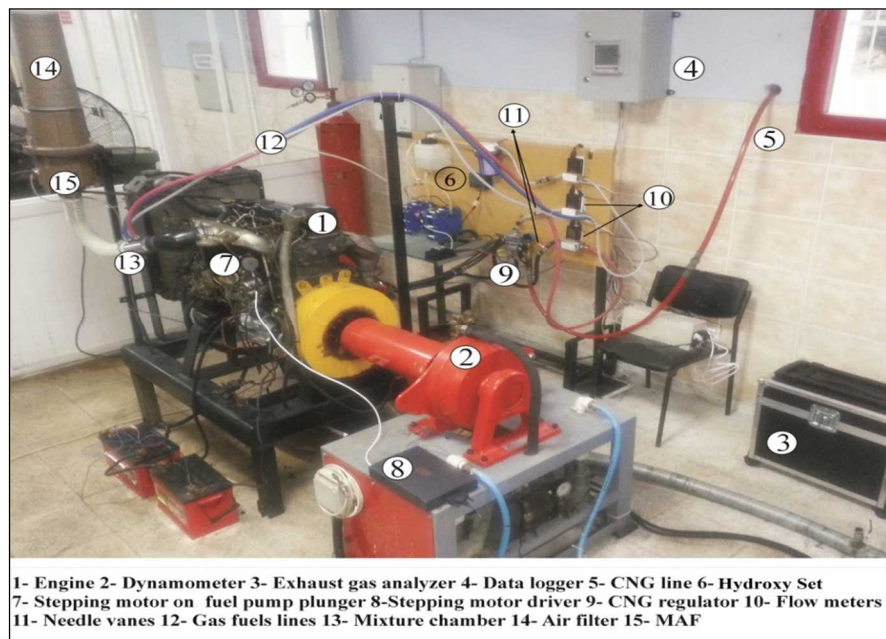


Figure 1. Experimental set-up

Pilot diesel injections occurred with twisting the plunger pin one tour (360°), two tours (720°) and three tours (1080°) of fuel pump plunger pin. Additionally middle degrees of rotations were examined with 540°, 900° and 1440° but half rotation of plunger, 180°, did not show a noticeable decrease in this mechanical fuel pump for using pilot diesel injection quantity. Because of this it was not found necessary for presented of these data. As we mentioned previously, minimum pilot quantities changeable in diesel engines for different combustion

chamber structures and operating conditions. All test apparatus and measurement devices of experimental setup illustrated in figure 1.

Before the tests, the engine was operated for enough time with diesel fuel to reach the operation temperature. Test fuels were tested from 1300 to 2600 rpm with an interval of 100 rpm at full load condition. For optimization of the test results, separately three sets of experiments were performed and average test data were used for the results. The engine was operated with normal diesel fuel and 25HHOCNG gas fuel mixture with various substituted diesel fuel quantities as pilot diesel injection systematic.

Result and Discussion

Engine Performance

One of the main handicaps of gaseous fuels usage in diesel engines, created negative effects in performance parameters. Especially for the CNG fuel used in diesel engines, exhaust gas emissions decreased and affected positively, but in performance up to 15% reduction, CNG was required using in dual-fuel system with hydrogen-enrichment. HCNG improves the diesel performance nearly 10% better than CNG with diesel. In this study HHO is the major player for amelioration the performance of diesel test engine. HHO contains an extra oxygen atom compared to hydrogen that provides the engine more powerful by mixture of air-gas fuels and oxygen before intake manifold. As a general one set average (60 sec), diesel substitution observed with instantaneous fuel consumption for diesel, 360°, 720° and 1080° is 1.75 g/sec, 1.34 g/sec, 1.118 g/sec and 1.59 g/sec respectively. In other word substituted diesel fuel affected like pilot diesel injection reductions handled with 360°, 720° and 1080° is 21%, 30% and 18% respectively.

Fig. 2 presented the Brake Torque as a function of Engine speed. In figure it can be clearly seen that, effect of addition HHO to CNG improves the torque values relative to diesel operation. 25HHOCNG mixture improved the torque values versus diesel engine can be reformed for 360°, 720° and 1080° is 10%, 15% and 13% respectively. Major reason for these improvements is HHO addition into the cylinders. Molar concentration of oxygen in air-gas mixtures occurred more flexible combustion and hydrogen atoms prevented the combustion phases faster. With this situation, CNG has playing critical role for the combustion and due to this faster combustion, CNG combust more willingly. Especially middle and high engine speeds, this factor can be seen expressly.

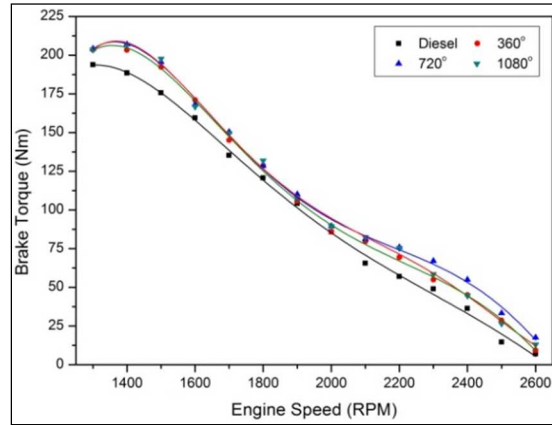


Fig. 2. Brake torque vs engine speed of diesel and various rotations of pilot diesel injection substitution

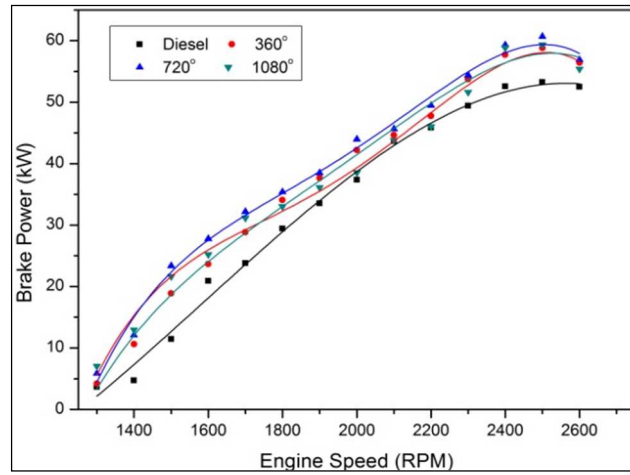


Fig. 3. Brake power vs engine speed of diesel and various rotations of pilot diesel injection substitution

Brake Power as a function of Engine speed graphic is shown in Fig. 3. In figure, similarly brake torque values, 13%, 19% and 15% increases presented for 360°, 720° and 1080° power values compared with neat diesel. Once again, gas fuels combustion properties affected the power development. Brake Specific Fuel Consumption (BSFC) versus Engine speed curve illustrated in Fig. 4. One of the major goals of this study, while improving performance values, decreasing the BSFC values with pilot diesel injection parameters helped of substituting diesel fuel amount. In figure it can be clearly seen that, 25HHOCNG gas mixture with substituted diesel fuel, affected positively in BSFC and forms more lucrative fuel consumption. Decreasing values can be listed for 360°, 720° and 1080° compared to neat diesel is 21%, 29% and 15% respectively.

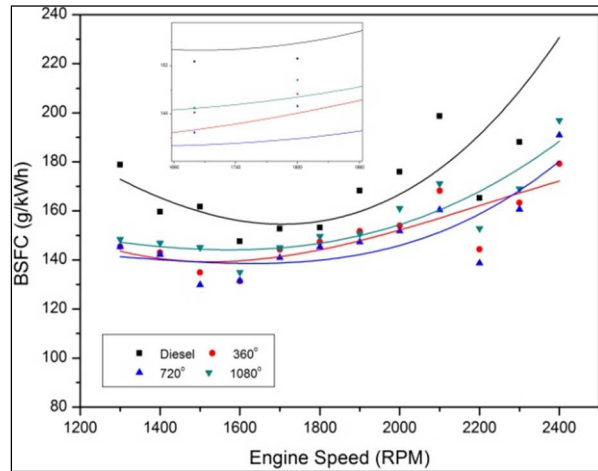


Fig. 4. BSFC vs engine speed of diesel and various rotations of pilot diesel injection substitution

Exhaust Emissions

A precise control of the fuel delivery is needed for increasing stringency of the emission standards for CI engine. Not only to meet the standards for NO_x , PM and other air pollutions, but also to reduce CO_2 emissions with a minimum penalty, in fuel economy and cost [10].

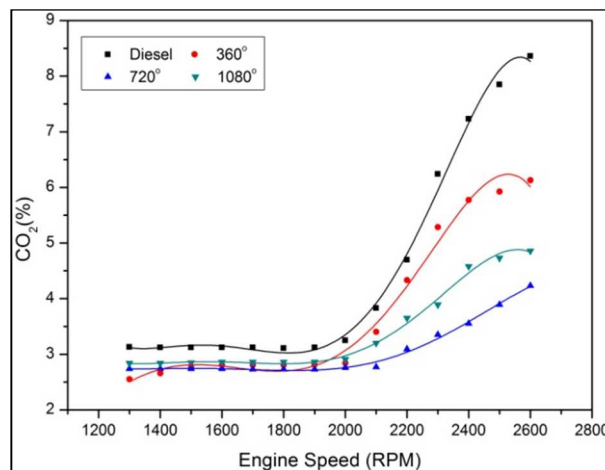


Fig.5. CO_2 vs engine speed of diesel and various rotations of pilot diesel injection substitution

When using alternative gas fuels in a non-modified diesel engine, it is the most important unforgettable thing that; while these gas fuels improve the engine performance, they have to balanced the harmful exhaust emissions values. CO_2

emission curves as a function of engine speed graphic illustrated in Figure 5. It is clearly seen that, 720° clockwise twisted pin position has placed the best CO₂ values. 25HHOCNG mixture with pilot diesel injection has decreased the CO₂ values significantly either neat diesel operation. When we compared the diesel and substituted pilot quantities operated with gas fuels; 360°, 720° and 1080° generated the CO₂ values with; 26%, 32% and 24% respectively. If HHO used singularly in diesel engine as a additive fuel, it increased the NO_x emissions because of higher flammability limits and rapid combustion willing. It is also known that, oxygen concentration, reacting time and in-cylinder gas temperature affected occurring NO_x formation. When increasing the hydrogen content, NO_x emission values are also increased. For all that, CNG plays an important role for reducing NO_x emission values. The amount of hydroxy gas and CNG ratio in the mixture is also affected by this role. Fig. 6 shows NO_x emissions between engine speed of diesel and 360°, 720° and 1080° pilot diesel quantities run under 25HHOCNG mixture. NO_x emission values of mixture fuel are approximately decreased 20%, 21% and 1.5% when compared to normal diesel fuel with 360°, 720° and 1080° respectively.

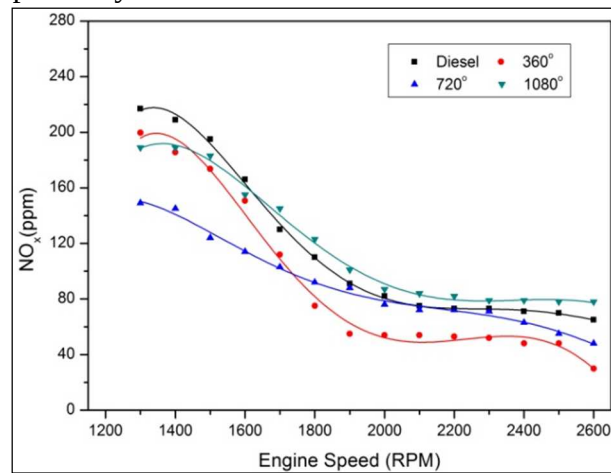


Fig. 6. NO_x vs engine speed of diesel and various rotations of pilot diesel injection substitution

Fig. 7. illustrates CO emissions as a function of engine speed for normal diesel operation and 25HHOCNG mixture with various amounts of pilot diesel injection. CO emission values were decreased soupcon when compared with normal diesel fuel operation. With numbers; CO emission values were decreased 1.05%, 1.17% and 0.55% for 360°, 720° and 1080°, relative to neat diesel operation. The reason for this very little reducing of CO emissions could be result of gas fuel mixtures nature, combustion discontinuity, faster combustion and oxygen concentrations in the cylinders. One of the solutions for these problems is the amount of diesel fuel for pilot ignition, which can be more minimised for the reduction of CO emissions.

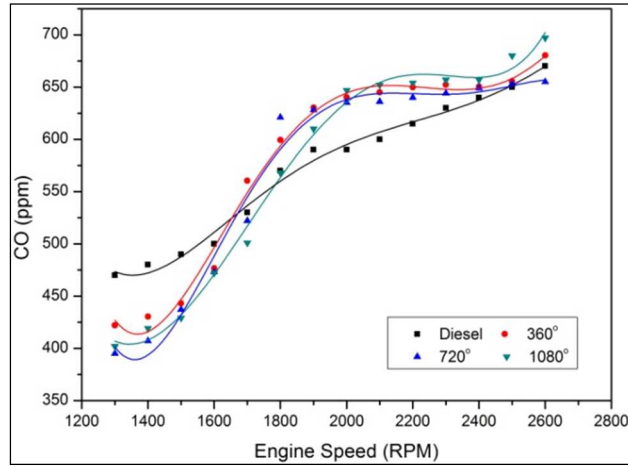


Fig. 7. CO vs Engine speed of diesel and various rotations of pilot diesel injection substitution

Conclusion

In this experimental study, a 3.6 L commercial, four stroke, four cylinders and mechanical fuel pump non-modified diesel test engine operated with hydroxy (HHO) and compressed natural gas (CNG) fuel mixtures under 25% and 75% (vol/vol), respectively. Diesel fuel injection quantities were reduced with the help of stepping motor devices which mounted on mechanical fuel pump plunger pin. Sensitive removes of stepping motor, plunger pin twisted clockwise 360°, 720° and 1080°, respectively. Experimental procedure and measurement devices were also explained briefly. The major goal of this study, while improving combustion values (not only performance also exhaust emissions), decreasing the BSFC values with pilot diesel injection parameters helped of optimizing and substituting diesel fuel amount. As a general result, for this test engine and these studies equipments, 720° clockwise twisted pin is the optimum point for experimental fuel pump plunger while using 25HHOCNG fuel mixtures. 720° point affected the performance improvingly as brake torque and power with 15%, 19% respectively and in BSFC, this point of pilot injection decreased the results up to 29%. On the other hand, 720° point generated and developed the exhaust emissions positively with run under with 25HHOCNG fuel mixtures. 32%, 21% and 1.17% reducing values presented for CO₂, NO_x and CO respectively.

Acknowledgements

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PAPER 2

International Journal of Hydrogen Energy

Gönderen: "Ibrahim Dincer" <Ibrahim.Dincer@uoit.ca>

Tarih: 30 Kas 2015 00:29

Konu: Your Submission - HE-D-15-01640R1

Al̄cē <aratmku@gmail.com>, <htarat@mku.edu.tr>

Ms. Ref. No.: HE-D-15-01640R1

Title: Effect of Using Hydroxy-CNG Fuel Mixtures in a Non-Modified Diesel Engine by Substitution of Diesel Fuel ñInternational Journal of Hydrogen Energyò

Dear Mr. ARAT,

I am pleased to inform you that your paper "Effect of Using Hydroxy-CNG Fuel Mixtures in a Non-Modified Diesel Engine by Substitution of Diesel Fuel" **has been accepted for publication in the International Journal of Hydrogen Energy.**

Thank you for submitting your work to International Journal of Hydrogen Energy.

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Yours sincerely,

Rami S. El-Emam, Ph.D.

Special Issue Guest Editor

International Journal of Hydrogen Energy

EFFECT OF USING HYDROXY-CNG FUEL MIXTURES IN A NON-MODIFIED DIESEL ENGINE BY SUBSTITUTION OF DIESEL FUEL

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ABSTRACT

In this experimental study, Hydroxy (HHO; Oxy-hydrogen) i CNG (Compressed Natural Gas) fuel mixtures were used as an additional fuels in a non-modified diesel engine via intake manifold by substitution of diesel fuel. In experiments 25% Hydroxy and 75% CNG mixture was used as a replacement fuel for a 3.6 L, four cylinders, four stroke diesel engine. The effects of Hydroxy-CNG fuel addition to the engine performance values (Brake Torque, Brake Power and Brake Specific Fuel Consumption (BSFC)) and exhaust emissions (NO_x, CO₂, CO) were investigated in between 1200-2600 rpm engine speeds. Stepping motor used on fuel pump plunger to substitute diesel fuel as similar to pilot diesel injection. Hydroxy-CNG fuel mixtures were affected the engine performance and brake torque and brake power values were increased 5.1%, 6.85% respectively, and BSFC values were decreased 27.2%. NO_x and CO₂ exhaust emission values were decreased 28.4%, 9.65% respectively; however CO emission values were increased 27%.

Keywords: Hydroxy, CNG, Diesel substitute, Engine performance, Exhaust emissions, Pilot diesel injection.

INTRODUCTION

In last two decades, internal combustion engines (ICEs) industry is intentioned greatly to use alternative fuel systems for much effectively combustion and less environmental pollution. As oil prices enlarge, the interest in alternative fuels increases. Alternative fuels in ICEs can be subsume with natural gas, hydrogen, oxy-hydrogen (HHO), biodiesel, bio-alcohol blends, HCNG, propane and other biomass sources [1]. These fuels have significant importance on engine performance and exhaust emissions. Especially gas fuels (Hydrogen, HHO and CNG) which use in ICE supply for improvement of reducing emissions. Additionally CNG and Hydrogen gas mixtures achieve the less greenhouse emissions while any changing the performance scale. In these mixtures, if these gases use singly, they have some disadvantages but when they used a mixture, it can be easily said, they absorbed their disadvantages each other. For this reason many investigators have been studying on this fuel mixtures specifications and usage in ICEs for two decades. Researchers have focused on the systematic usage of gas alternative fuels, effect of engine performance and exhaust emissions, mixture percentages of fuels and induction possibilities of these fuels into combustion systems and effective energy efficiency of gas fuels which some of important references are reviewable on [1,2,3,4,5,6,7].

One of the important ways to reduce CO₂ emissions from an engine is to change the molecular composition of the reacting fuel to one with less or zero carbon content. Fuels such as natural gas and hydrogen are alternative fuels that could provide this molecular benefit [8]. As engineering properties of hydrogen and natural gas, these fuels have important advantages when using as fuel. In ICEs, natural gas usage has continuously increased. According to [9] Globally, there are approximately 15.2 million natural gas

vehicles on the road today (IANGV 2012). In terms of energy use, natural gas is the second most widely used alternative motor fuel after LPG with annual growth of approximately 25% from 2001 to 2011 (IANGV 2012), transportation use of natural gas is increasing in both established and new markets and CNG is the only fossil fuel that can compete with petroleum diesel for vehicle applications

Hydrogen and compounds are the major players in energy world. The heating value of hydrogen is much higher than that of conventional fuels if taken as per unit of weight and hydrogen combustion is completely clean, producing only water vapor in the exhaust gas [2]. Although the most common of all elements, H_2 does not exist in nature, but is bound in water (H_2O), hydrocarbons (C_nH_m) and various other compounds. Electrolysis is the most common method used to split H_2 from water. Currently, 12-15% of hydrogen production globally source is presented by electrolyses [9]. Performance characteristics and applications of hydrogen and natural gas are given in Table 1.

Table 1. Performance characteristics and applications of hydrogen and natural gas [10]

Alternative Fuel	Performance Characteristics	Applications in Heavy-duty Vehicles
Natural Gas	It is a clean burning alternative fuel that is stored onboard a vehicle in either compressed gaseous or liquefied state. Engines can operate solely on natural gas or on a combination of natural gas and diesel fuel (i.e., dual-fuel). Natural gas vehicles can generate significantly lower carbon monoxide, nitrogen oxide, non-methane hydrocarbons, particulate matter, and other toxic emissions, and the fuel is typically less expensive than diesel fuel.	• School bus (CNG) • Shuttle bus • Transit bus • Refuse truck • Delivery van
Hydrogen	It is potentially an emissions-free alternative fuel. Although it is not widely used currently, research is underway to develop hydrogen as a fuel for internal combustion engines and fuel cells. It can also be blended with natural gas to create "Hythane" for use in natural gas engines to offer significant reduction of NO_x .	• Hydrogen fuel cell bus (research) • Fuel cells for auxiliary power generation

In SI (spark-ignition) engines; these gas fuels can be injected to chamber via plug. Air and fuel mixed up in cylinder and compressed by pistons and combust with spark. In SI engines these fuels combustion does not require much more modification in engines. However in CI (compression-ignition) engines; the ignition and combustion situation is not very easy like SI engines when it comes to use gases fuels. CI engines compressed the air and combustion states occur with the injection of diesel fuel. Pilot diesel injection is an opportunity to usage of these gases fuels in CI engines without any modification of engine specifications. Compression-ignition dual-fuel engines use diesel fuel for pilot injection of the natural gas. Direct-injection system can maximize the amount of natural gas substitution but has degraded performance on diesel only. Avoiding the worst performance, hydrogen aided to natural gas, named HCNG fuel has mixed with air and pilot injection by diesel fuel in combustion chamber. Author's previous studies touched upon about the usage of HCNG fuel in CI engines [1].

In this study, hydroxy gas (oxy-hydrogen) and CNG fuel mixtures usage in a non-modified CI engine by substitution of diesel fuel, like pilot diesel injection were investigated. The results of engine performance and exhaust emission parameters were plotted against engine speeds and experimental procedure used in this experimental study was explained.

EXPERIMENTAL SETUP AND METHODOLOGY

This experimental study was carried out in Automotive Engineering Laboratories in Çukurova University, Turkey. In tests; CNG and Hydroxy gas mixtures were used on diesel engine with substitution of diesel fuel. A non-modified, commercial, four cylinders, four-stroke, naturally aspirated, water-cooled direct injection compression ignition engine (Mitsubishi Canter- 4D32) was used in experiments. Engine has 17.5:1 compression ratio

and mechanical direct injection fuel pump. Technical specifications of engine were given in Table 2. A Netfren mark hydraulic dynamometer was used for loading the test engine and MRU Delta 1600 V gas analyzer was used to measure exhaust gas emissions. Data outputs of dynamometer and gas analyzer were collected via Elimko PR-100 data logger and were transferred to computer for further processing. The fuel properties of diesel fuel, methane with similarity of CNG and hydrogen with similarity of HHO are given in Table 3. Additionally; CNG is supplied by cryogenic tank under 200 bar pressure which contain 97.372% Methane, 2.327% Nitrogen, 0.230 Ethane and 0.068 Propane.

Table 2. Test Engine Specifications

Table 3. Fuels Properties [11]

Brand	Mitsubishi Canter	Property	Diesel	Methane	Hydrogen
Model	4D32 - In line 4	Molar Mass (kg/kmol)	200	16.04	2.02
Type	D.I. diesel with glow plug	Density (kg/m ³)	840(1)	0.72(g)	0.082(g)
Displacement	3567cc	Stoichiometric air/fuel. weight	14.7	17.2	34.3
Bore	104mm	Auto-ignition Temperature °C	254-285	595	585
Stroke	105mm	Laminar Flame Speed (cm/s)	128	42	230
Power	89kW @ 3200rpm	Lower Heating Value (MJ/kg)	42.61	47.14	120.21
Torque	295Nm @ 1800rpm	Higher Heating Value (MJ/kg)	45.58	52.23	142.18

A check-valve is used for prevent back-flow behind the CNG bottles exist. After the check-valve, CNG is transferred to regulator in an ex-proof pipeline. The regulator has 2-stage regulation system. CNG pressure of 200 bar reduced to the 12-15 bar in a first stage of regulator and regulated to the 0-1 bar in the second stage. The regulator has high pressure shut-off valve and level gauge. CNG heating-cooling systems are rebuilt using the engine cooling system thought radiator input and output. The quantity of CNG gas flow is controlled by a needle vane after the regulator. This needle vane is manufactured by Maxtor and pressure availability is between 0.8-15 Mpa. CNG gas is entered to ALICAT flow meter for the measurement of the gas flow after needle vane.

Hydroxy (HHO; Oxy-hydrogen) system is electrolysis of distilled water with using suitable catalyst. In this experimental study, KOH (potassium hydroxide) is chosen as a catalyser. System contains double parallel connected dry cells, water reservoir, bubbler, solenoid relay, constant current PWM, fittings and electrical wires. HHO generator runs with engine battery (24 V), 15-20 amperage and 500 hertz frequency. When hydroxy gas is generated, gas pours itself into the needle vane and flow meter.

The amount of Hydroxy and CNG gases supplied to the engine is measured by the flow meters and the amount is controlled by needle vanes. Certain amount of Hydroxy and CNG gases are mixed in a mixing chamber. The amount of gas mixtures are calculated by Equations (1a-b). All experiments were repeated three times and the mixture percentages were collected by the average of these three tests. For this experiment; measurement from flow meters, As a general, the total average of hydroxy gas was adjusted to 5.14 LPM and the total average of CNG gas was adjusted to 15.364 LPM during the experiments, and these values indicates give approximate percentages of 25% Hydroxy gas and 75% CNG gas mixture by volume. Additionally this value has a similarity to literature for optimum usage (20-30% HCNG) of these gas fuels.

$$\text{HHO}(\%) = \frac{\text{Flow of HHO}}{\text{Flow of HHO} + \text{Flow of CNG}} * 100 \quad (1-a), \quad \text{CNG}(\%) = \frac{\text{Flow of CNG}}{\text{Flow of HHO} + \text{Flow of CNG}} * 100 \quad (1-b)$$

Other important issue in the experiments is the substitution of diesel fuel. Mechanical direct injection diesel fuel pump is driven to fuel of the engine. The injection start at 23 deg BTDC and diesel fuel spray amount controlled by fuel pump plunger. A stepping

motor and stepping motor driver were used for substitution of diesel fuel for sensitive measurement. A bipolar, 1.8 deg/step, 6.2 Nm holding torque stepping motor, equipped with Toshiba TA 8435 stepping motor driver for turn around the fuel pump plunger. Plunger pin twisted two rounds clockwise and substituted the amount of diesel fuel injection. This implementation is similar to pilot diesel injection. More detailed information mentioned in BSFC part. All test apparatus and measurement devices are illustrated with experimental setup in Figure1.

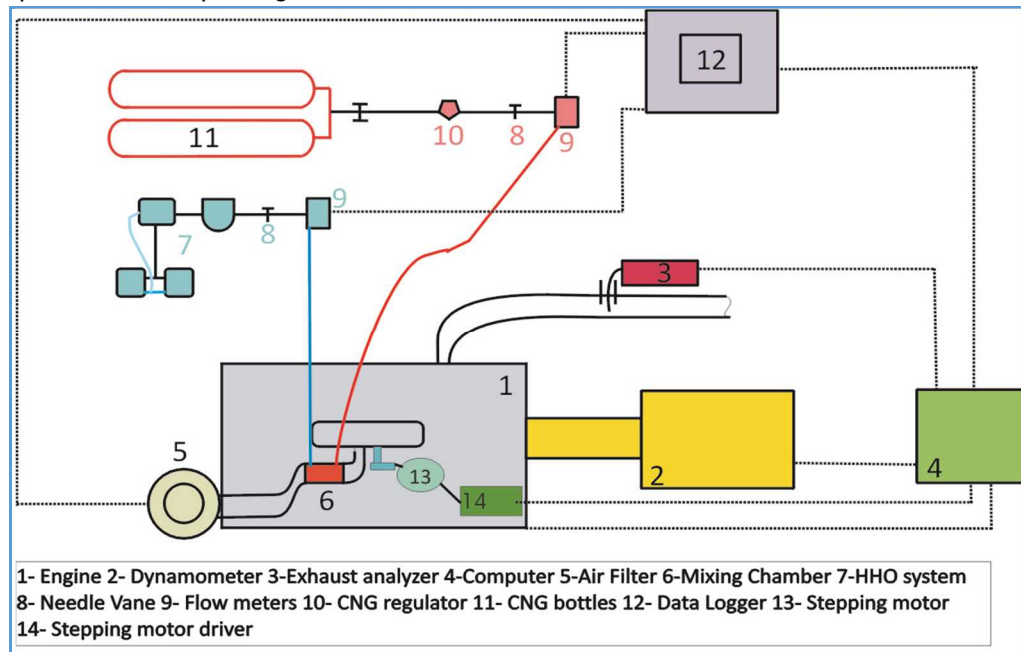


Fig.1: Experimental Setup.

RESULTS AND DISCUSSION

The engine was operated for enough time with diesel fuel to reach the operation temperature before the tests. All tests were implemented with the engine speed between 1200 to 2600 rpm with an interval of 100 rpm at full load condition. Separately three sets of experiments were performed and average test data were used for the results for optimization of the test results. The engine was operated with normal diesel fuel and [(25% Hydroxy + 75% CNG) + Substituted diesel] fuel mixtures. Engine performance and exhaust emission parameters were measured for all tests and compared each other.

Figure 2 illustrates the break torque vs engine speed of pure diesel fuel and (25% Hydroxy+75% CNG) + substituted diesel fuel mixtures. It can be clearly seen from the results that; Hydroxy gas + CNG + substituted diesel fuel mixture was improved engine brake torque significantly over 1500 rpm when compared with diesel fuel. HHO gas contains hydrogen and oxygen that allows more powerful and efficient combustion in the cylinders and the average of 5.1% brake torque improvement was presented. Particularly in middle engine speeds (1200-1700), the substitution of diesel fuel causes the lean burning and more air induction from intake manifold consists of much more CNG and hydroxy gases that combust the mixture fuel optimally.

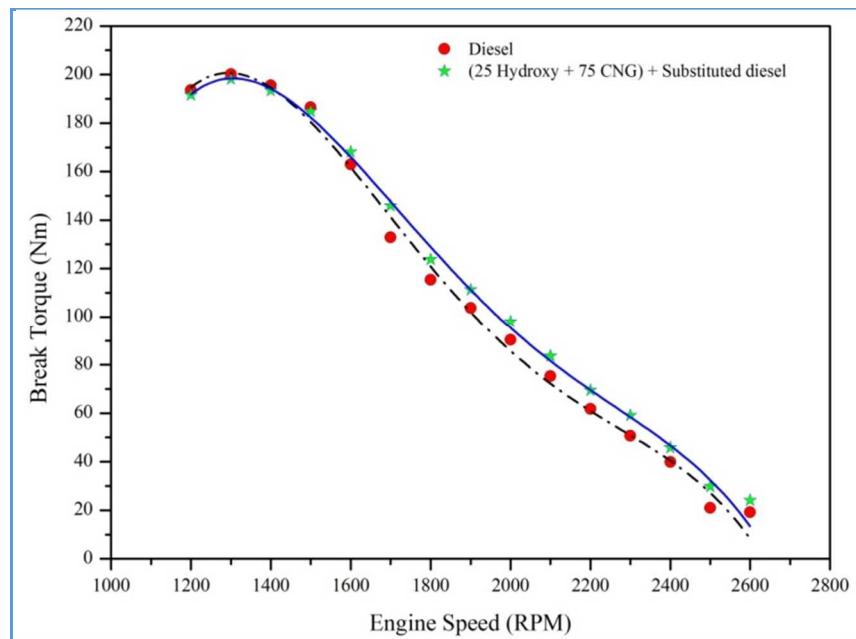


Fig. 2: Break Torque versus Engine Speed of Diesel and (25 Hydroxy+75 CNG) + Substituted Diesel Fuel Mixture.

Break power vs engine speed of diesel fuel and (25% Hydroxy+75% CNG) + substituted diesel fuel mixture graphic is shown in Figure 3. Similarly mixture fuel improved the brake power like brake torque for the same situations and the average brake power improvement is measured as 6.85%. Maximum brake power of 56.86 kW is observed at 2521 rpm.

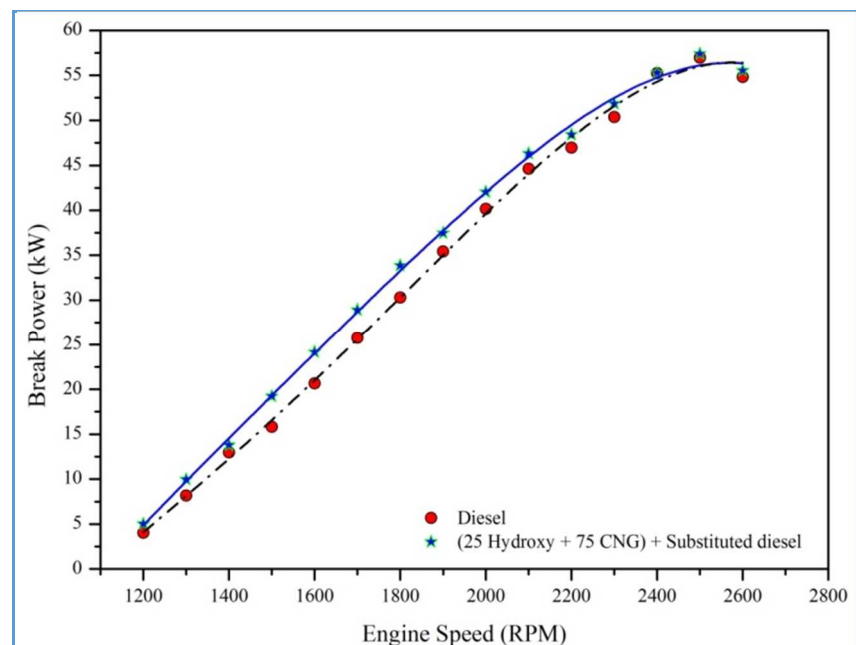


Fig. 3: Break Power versus Engine Speed of Diesel and (25 Hydroxy+75% CNG) + Substituted Diesel Fuel Mixture.

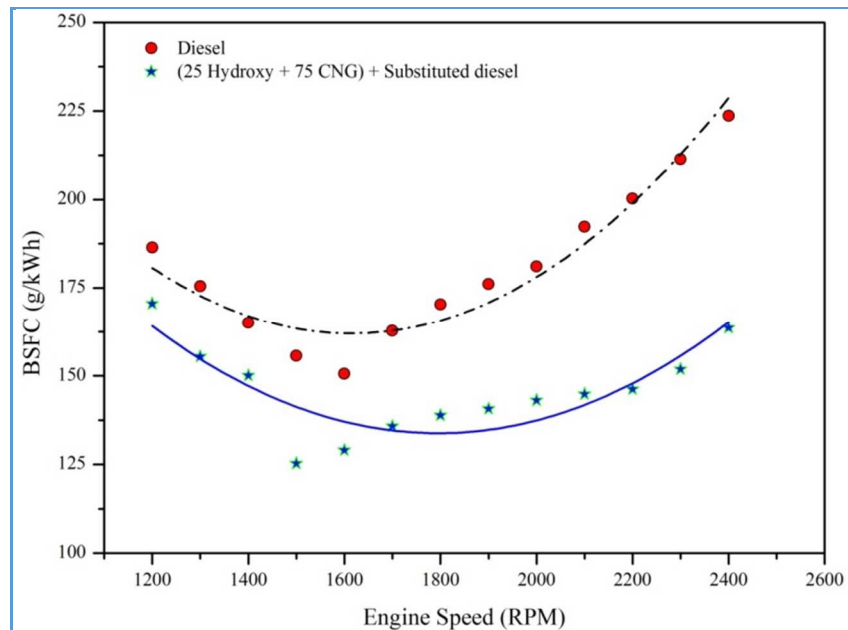


Fig.4: Break Specific Fuel Consumption (BSFC) versus Engine Speed of Diesel and (25% Hydroxy+75% CNG) + Substituted Diesel Fuel Mixture.

Effects of the substitution of diesel fuel forms more lucrative fuel consumption. Figure 4 demonstrates the Break Specific Fuel Consumption (BSFC) of test fuels. It is evidently CNG and hydroxy mixture is decreased the break specific fuel consumption that measured 27.2%. As we mentioned in previous sections, substitution of diesel fuel likes pilot diesel injection is the main factor for the reduction of BSFC. From this result, it can be concluded that, the twisted plunger pin decreased the diesel fuel amount to proximate 30% with two rounds clockwise movement.

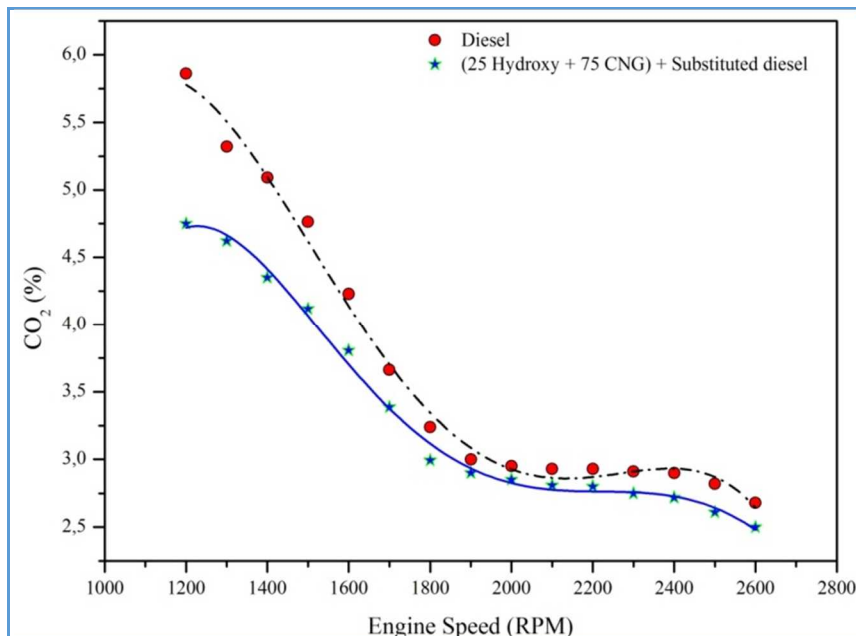


Fig. 5: CO₂ versus Engine Speed of Diesel and (25% Hydroxy+75% CNG) + Substituted Diesel Fuel Mixture. One of the major reasons of usage alternative fuels in ICEs is reducing the exhaust emissions. Many of them can succeed this case with some losses of the engine performance. However hydrogen addition to the alternative fuels can solve this problem because of higher heating value of hydrogen. Even though hydrogen increases the

engine performance as well as it causes less harmful exhaust emissions beside normal diesel operation. Meanwhile CNG plays an important role for reducing exhaust emissions as well. CO₂ emission versus engine speed of diesel and (25% Hydroxy+75% CNG) + substituted diesel fuel mixture is illustrated in Figure 5. It is clearly seen that, mixture fuel was decreased the CO₂ emission values around 9.65%. Similar literature results have been observed compared to the experimental results.

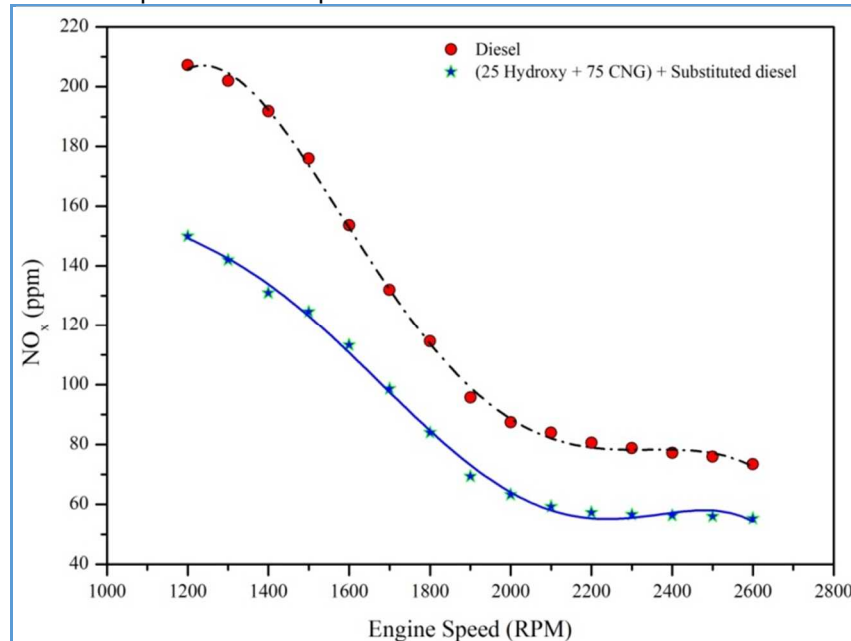


Fig. 6: NO_x versus Engine Speed of Diesel and (25% Hydroxy+75% CNG) + Substituted Diesel Fuel Mixture.

Reducing NO_x emission values of a diesel engine is very important item as environmental issue as optimum combustion. Hydrogen and HHO increased NO_x emission values because of their higher flammability and it is also known that, NO_x formation is affected by oxygen concentration, reacting time and in-cylinder gas temperature. When increasing the hydrogen content, NO_x emission values are also increased. However CNG is one of the major players for reducing NO_x emission values. The amount of hydroxy gas and CNG ratio in the mixture plays very important role for decreasing these values. Figure 6 shows NO_x emissions versus engine speed of diesel and (25% Hydroxy+75% CNG) + substituted diesel fuel mixture. NO_x emission values of mixture fuel are approximately decreased 28.4% when compared to normal diesel fuel. This result has showed a significant reduction of NO_x with usage of hydroxy-CNG mixtures.

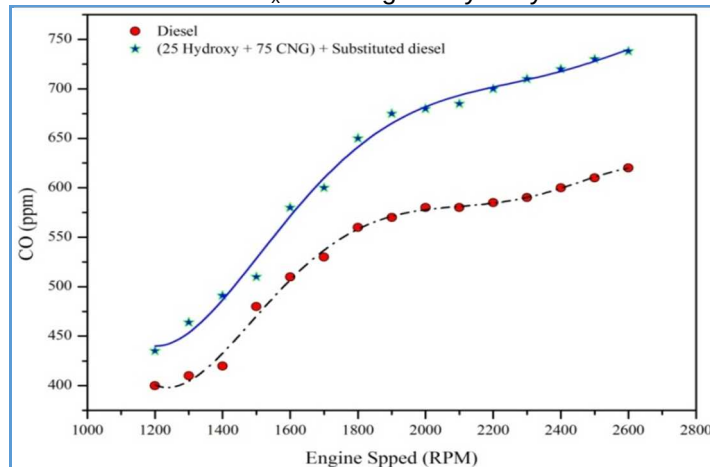


Fig. 7: CO versus Engine Speed of Diesel and (25% Hydroxy+75% CNG) + Substituted Diesel Fuel Mixture.

Figure 7 illustrates CO emissions versus engine speed of diesel and (25% Hydroxy+75% CNG) + substituted diesel fuel mixture. CO emission values were increased when compared with normal diesel fuel operation. The reason for the CO emissions increment could be result of pilot ignition of hydroxy and CNG mixture by diesel fuel. The solution for this problem is the amount of diesel fuel for pilot ignition can be minimised for the reduction of CO emissions.

CONCLUSIONS

Several tests in between 1200-2600 rpm on a four-cylinder, non-modified diesel test engine were performed to investigate the effects of using 25% Hydroxy-75% CNG mixtures with substituted diesel fuel on engine performance and exhaust emissions. The goal of these tests was to identify the changes on engine performance and emissions of Hydroxy-CNG fuels mixture in diesel engine like pilot diesel injection via substitution of diesel fuel. The methodology, experimental set-up and measurement devices were also given in details. The following conclusions can be drawn on the basis of experimental results;

- ❖ Addition of Hydroxy and CNG mixtures to the diesel fuel was increased the engine performance values like break torque and brake power by 5.1%, 6.85% respectively. Hydroxy's gas addition to the CNG was also increased the engine performance, similar to the hydrogen addition.
- ❖ (25% Hydroxy + 75% CNG) + Substituted diesel fuel mixture was decreased the brake specific fuel consumption by 27.2%. Reduction of BSFC and increased engine performance were major goal of this study.
- ❖ Hydroxy and CNG fuel mixture affects the results of emissions like decreasing NO_x and CO₂ emissions by 28.4%, 9.65% respectively, while increasing CO emissions around 27%.

Overall, the results from the study indicate that Hydroxy and CNG fuel mixtures improves the engine characteristics and give more efficient combustion duration especially middle engine speeds.

ACKNOWLEDGEMENT

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NOMENCLATURE

<i>HHO</i>	Hydroxy, Oxy-Hydrogen
<i>CNG</i>	Compressed Natural Gas
<i>ICE</i>	Internal Combustion Engine
<i>HCNG</i>	Hydrogenated Compressed Natural Gas
<i>KOH</i>	Potassium hydroxide
<i>PWM</i>	Pulse Width Modulation
<i>LPM</i>	Liter per Minute
<i>BTDC</i>	Before Top Dead Center
<i>BSFC</i>	Brake Specific Fuel Consumption
<i>IANGV</i>	International Association for Natural Gas Vehicles

Subscripts

<i>l</i>	Liquid
<i>g</i>	Gas

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PAPER 3

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EXPERIMENTAL COMPARISON OF PURE HYDROGEN AND HHO (HYDROXY) ENRICHED BIODIESEL (B10) FUEL IN A COMMERCIAL DIESEL ENGINE

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ABSTRACT

Main objective of this study is to compare performance and emission characteristics of a pilot injection diesel engine with the additions of alternative fuels like pure hydrogen, HHO and biodiesel. In order to achieve this goal, helianthus annuus (sunflower) biodiesel was produced and blended with volumetric ratio of 10% with diesel fuel. Additionally, intake air was enriched with pure hydrogen or HHO via intake manifold without any structural changes except reduction of injected diesel fuel on the 3.6 L, four cylinders, four stroke diesel engine. Amount of Hydrogen fuel supplied to the engine was adjusted to 10 L/min during the experiments. The effects of pure hydrogen and HHO usage with the addition of biodiesel to the engine performance values (Brake Torque, Brake Power and Brake Specific Fuel Consumption) and exhaust emission values (NO_x, CO₂, CO) were investigated in between 1200-2600 rpm engine speeds. Engine performance values were increased with the enriching the intake air with HHO than pure hydrogen compared to the standard diesel fuel operating condition. On the other hand, in terms of exhaust gas emissions, pure hydrogen provided better results than HHO. In both cases, changes on the engine performance results were minimal however improvements on exhaust gas emissions were very promising.

Keywords: Pure hydrogen, HHO (Hydroxy), biodiesel, engine performance, exhaust gas emissions.

INTRODUCTION

It is very well known that environmental and economic criteria push scientists to find out alternative solutions to energy demand. Hydrogen is one of the alternative fuels to create clean and environment friendly future. It is an energy-efficient, low-polluting fuel. When hydrogen is used in a fuel cell to generate electricity or is combusted with air, the only products are water and a small amount of NO_x [1]. In last decades researches have been carried out lots of studies on hydrogen usage in diesel engines. Diesel engine has wide range of using area at transportation. Some of the researchers used pure hydrogen [2-6] and others tried with hydrogen-rich gases (HRG) and hydrogen/oxygen mixture produced by water electrolysis [7-11]. Birtas, A. et al. (2011), mentioned that using pure hydrogen or hydrogen containing gas produced through water electrolysis, are notably different [10]. However, previous studies have a lack of comparison between the using pure hydrogen and hydroxy gas (HHO) in diesel engine. The present experimental study presents a comparison between effects of pure hydrogen and HHO to performance and emissions of a diesel engine. Required pure hydrogen is obtained from hydrogen tank and HHO with processes such as water electrolysis. Prigent, M. (1997), used similar method to produce small amount of hydrogen, or when high-purity hydrogen is required [12]. Water electrolysis is one of the most important industrial processes for hydrogen

production today, and is expected to become even more important in the future [13]. Also it is a practical solution for onboard production of hydrogen, which avoids the storing of heavy pressurized hydrogen tanks [7]. Another way to obtain hydrogen is heavy pressurized (170 bar) commercial tanks which contain hydrogen at 99.99% purity.

Additionally, sunflower biodiesel is used with commercial diesel fuel at a level of 10% volumetric ratio. Lot of different vegetable oils, like canola, palm, cottonseed, soybean, sunflower etc. have been used to produce biodiesel. Vegetable oils offer almost the same power output with slightly lower thermal efficiency when used in diesel engines [14]. Among these, sunflower oil has very good physical properties. Calorific value and Cetane number are higher compared to many others and slightly less than diesel fuel. The sunflower plant can grow all over the Turkey. Biodiesel fuel can effectively reduce engine-out emissions of unburned hydrocarbons, particulate matter, and carbon monoxide in compression ignition (CI) engines. However, a slight increase in emissions of nitrogen oxides has been observed in the use of oxygenated fuels in general [15-18]. High viscosity, a low ignition point, and unsaturated hydrocarbons molecules are the disadvantages of biodiesel fuels.

Biodiesel fuels are non-toxic and do not contain aromatic and can be resolved in nature better than fuels used in the industry and transportation. The most important point is that biodiesel fuel does not contain sulphur [19, 20].

METHODOLOGY

All tests were carried out in the Internal Combustion Engine (ICE) Laboratory of Automotive Engineering Department of Çukurova University. A schematic of experimental set up is shown in figure 1 below. Also technical specifications of the test engine and hydraulic dynamometer are given in table 1 and table 2 respectively. Performance tests were conducted on four cylinders, four-stroke, naturally aspirated, water-cooled direct injection CI engine which connected to a Netfren mark hydraulic dynamometer for loading the test engine. Exhaust emissions were measured by MRU Delta 1600 V gas analyzer. A data logger was used to collect test engine, dynamometer, volumetric flow meters and gas analyzer data. Acquired data was then transferred to host computer from data logger.

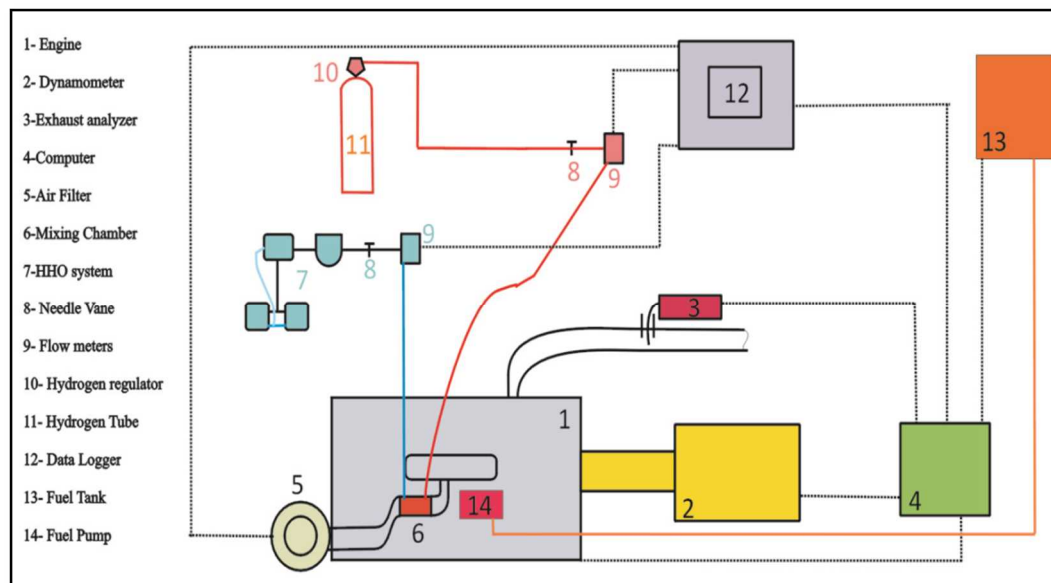


Fig. 1: Schematic view of experimental set up.

Four sets of experiments were performed. First set of experiments was performed with neat diesel fuel, second set of experiments with B10, third set of experiments with pure hydrogen enriched B10 and fourth set of experiments was with hydroxy gas (HHO) enriched B10 fuel. The engine was operated to reach steady state conditions for about 10 minutes at the beginning of each test. All experiments were repeated three times to increase accuracy of results and decrease experimental errors. The engine was subjected constant speed, full load conditions during tests [21]. The engine performance values of brake power, brake torque, and brake specific fuel consumption, and exhaust emission values of carbon monoxide, carbon dioxide and nitrogen oxide were obtained and results were evaluated.

Table 1: Test engine specifications.

Brand	Mitsubishi Canter
Model	4D34 - In line 4
Type	D.I. diesel with glow plug
Displacement	3567 cc
Bore	104 mm
Stroke	105 mm
Power	89 kW @ 3200 rpm
Torque	295 Nm @ 1800 rpm

Table 2: Hydraulic dynamometer specifications.

Brand	Netfren
Torque range	0-1700 Nm
Speed range	0-7500 rpm
Body diameter	250 mm
Torque arm length	250 mm
Torque	295 Nm @ 1800 rpm

Constant rate of 10 L/min pure hydrogen (purity: 99,999%) and HHO mixed with intake air respectively by using mixture chamber which is shown in figure 2. Mixture chamber is placed before the intake manifold entrance as shown below. A, B and C in figure 2, point the pure hydrogen entrance from commercial hydrogen tank with 99,999% purity, hydrogen/oxygen mixture (hydroxyl gas) entrance produced by water electrolysis and intake manifold of the test engine in sequence.

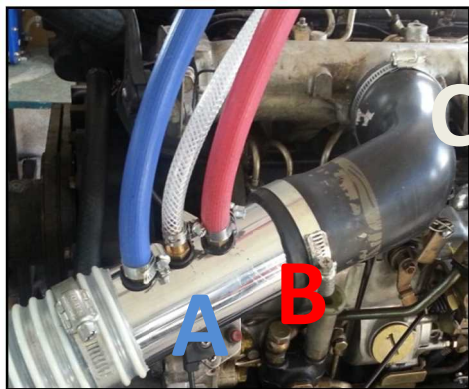


Fig. 2: Mixture Chamber.

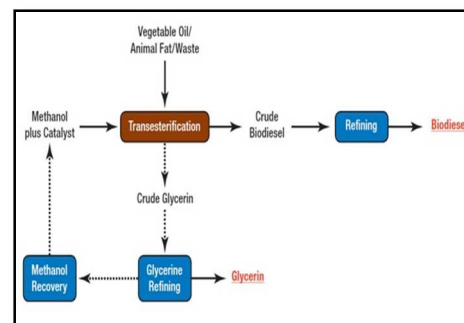


Fig. 3: Schematic view of biodiesel production path [22].

Basically, HHO system is electrolysis of distilled water with electrolyte to any substance containing free ions that make it electrically conductive. In this experimental study, KOH (potassium hydroxide) is chosen as an electrolyte. System contains double parallel connected dry cells with 14 plates total, water reservoir, bubbler, solenoid relay switch, constant current Pulse Width Monitor (PWM) with liquid crystal display, fittings and electrical wires. HHO generator runs with engine battery (24 V). Installed HHO generator

needs 30 amps to achieve 10 LPM of oxy-hydrogen gas. Properties of HHO and hydrogen are very similar to each other therefore HHO has been adopted instead of hydrogen while representing the fuel properties [23]. Some of the important specifications of hydrogen and diesel fuel compression with sunflower biodiesel fuel are shown in table 3 and table 4 respectively. Required amount of sunflower biodiesel is produced by transesterification method in fuel laboratory of automotive engineering. The most common way to produce biodiesel is the transesterification method, which refers to a catalyzed chemical reaction involving vegetable oil and alcohol to yield fatty acid alkyl esters (i.e., biodiesel) and glycerol [24]. A simple biodiesel production path is shown in figure 3 above. B10 fuel is prepared by mixing commercial diesel fuel and produced biodiesel with a volumetric ratio of 90% diesel fuel +10% biodiesel respectively.

Table 3: Fuel Properties of diesel and hydrogen [23, 25].

Property	Diesel fuel	Hydrogen
Density (kg/m ³)	840 (l)	0.082(g)
Limits of flammability in air	-	4-75 vol. %
Auto-ignition Temperature °C	254-285	585
Laminar Flame Speed (cm/s)	128	265-325
Lower Heating Value (MJ/kg)	42.61	120.21

Table 4: Fuels Properties of neat diesel fuel and sunflower biodiesel [26].

Property	Diesel fuel	Sunflower biodiesel	Standards
Kinematic viscosity [mm ² /s]	3.06	4.6	EN ISO 3104
Cetane number	50	49	EN ISO 5165
Pour point [°C]	-	1	ISO 3016
Cold filter plugging point [°C]	-16	-2	EN 116
Flash point [°C]	76	183	EN ISO 3679

RESULTS AND DISCUSSION

All experiments were conducted at full load condition in the range of 1200-2600 rpm and increased by 200 rpm. Experimental results are presented under engine performance and exhaust gas emissions subsections shown below.

Engine Performance

Three figures illustrated in this subsection that contains brake power, brake torque and brake specific fuel consumption. Brake power variations versus engine speed are shown in figure 4. Results show that 10 L/min HHO enrichment of B10 fuel provides an average of 8.31% improvement according to neat diesel fuel. Similar results for pure hydrogen enrichment B10 fuel also are obtained with an average of 4.33% improvement. Maximum improvement was obtained at medium engine speed range around 1750-2000 rpm. Brake power of HHO+B10 enrichment fuel was an average of 13% higher than neat diesel fuel at 1800 rpm.

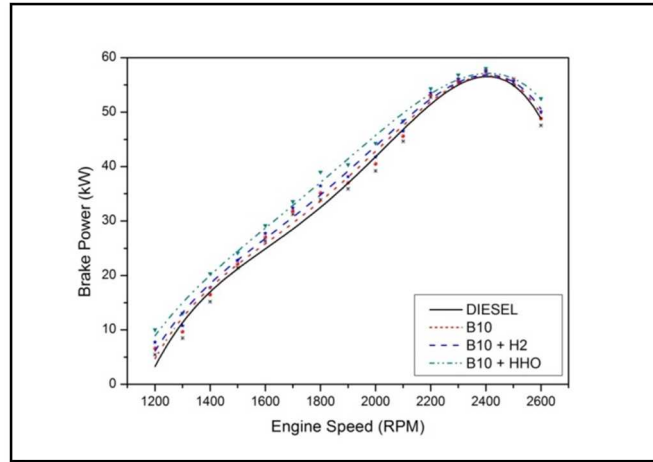


Fig. 4: Brake power versus engine speed.

Using pure hydrogen or HHO in combustion chamber can lead better thermodynamic efficiency. Hydrogen has higher heating value and flame speed compared to conventional liquid fuels. Hence, both of the hydrogen enriched fuels in this study provide better brake torque outputs than neat diesel fuel and B10 as shown in figure 5. Peak points of brake torque values measured at 1400 rpm for all test fuels. Similar to the brake power outputs, maximum brake torque point of 209.57 Nm at 1400 rpm is obtained by HHO+B10 enrichment fuel.

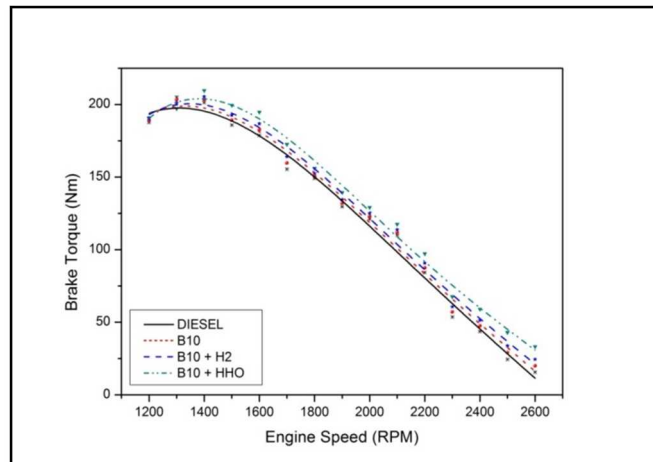


Fig. 5: Brake torque versus engine speed.

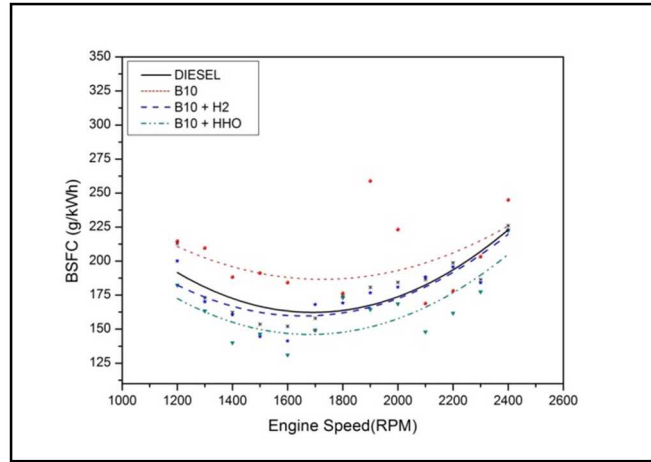


Fig.6. Brake specific fuel consumption versus engine speed.

Brake specific fuel consumption (BSFC) is a measure of the fuel efficiency of any prime mover that burns fuel and produces rotational, or shaft power. It is typically used for comparing the efficiency of ICE with a shaft output. It is the rate of fuel consumption divided by the power produced [27]. BSFC of hydrogen enriched fuels were less than neat diesel fuel and B10 for all engine speeds due to high energy content of hydrogen. BSFC results are demonstrated in the figure 6 above for all the test fuels. H₂+B10 fuel decreased BSFC an average of 2% while decrement for HHO+B10 was 10%. B10 fuel increased the BSFC due to less heating value than neat diesel fuel.

Exhaust Gas Emissions

The biggest advantage of alternative fuels such as biodiesel and hydrogen over diesel fuel is their environmental friendliness. Hydrogen enrichment to the fuels reduces exhaust emission values. Carbon dioxide, carbon monoxide, and nitrogen oxide results of all experiments represented in figures 7-9 in this subsection.

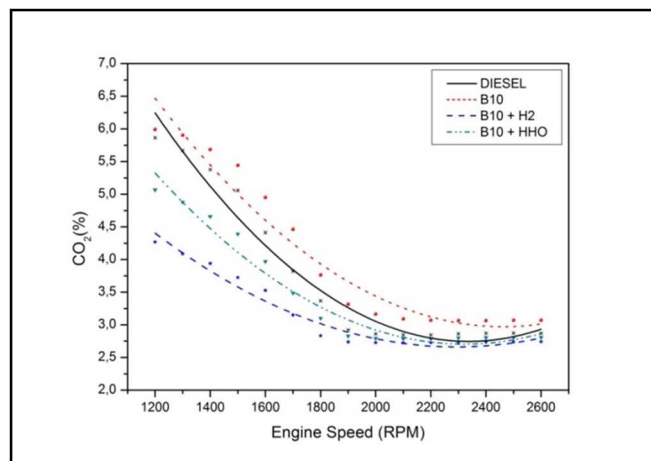


Fig. 7: CO₂ versus engine speed.

CO₂ emission values of H₂+B10 and HHO+B10 decreased at lower engine speed between 1200-1800 rpm compared to the medium or higher engine speeds. Meanwhile B10 fuel increased CO₂ gas emissions at all engine speeds. Improvements by hydrogen enriched fuels were noticeable as shown in figure 7. Maximum decrement of 38% was

achieved using 10 L/min pure hydrogen with B10 fuel at 1300 rpm. Average reductions of CO_2 emissions for H_2 +B10 were 22% while 12% for HHO+B10.

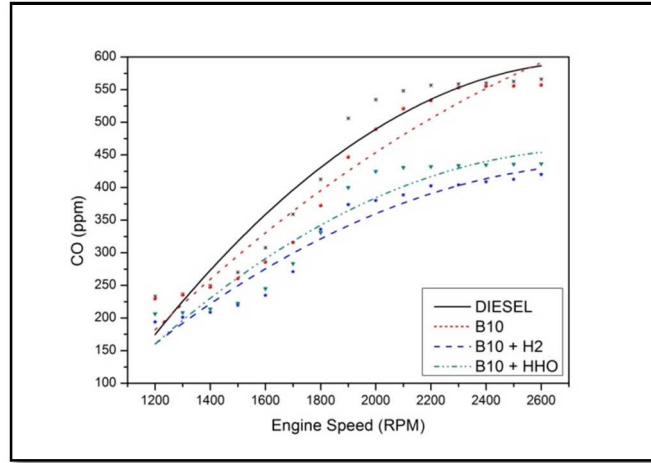


Fig. 8: CO versus engine speed.

CO emission is toxic and an intermediate product in the combustion of a hydro carbon fuel, so it results from incomplete combustion. Emission of CO is greatly dependent on the air-fuel ratio relative to the stoichiometric proportions [15]. As shown in figure 8, observation indicates that neat diesel fuel has higher CO gas emissions than pure H_2 +B10 and HHO+B10 fuels. Higher oxygen content of B10 and small quenching distance of hydrogen improves combustion in the cylinder. As a result CO gas emissions are dropped down for all engine speeds. It is clear in figure 8 that maximum decrement occurred at high engine speeds while there is fast combustion without enough time. H_2 +B10 and HHO+B10 fuels performed the similar characteristics however CO gas emissions H_2 +B10 fuel reduced 5.8% compared to the HHO+B10 fuel. Maximum reduction of CO emissions of 38% using H_2 +B10 fuel was obtained compared to the neat diesel fuel at 2300 rpm.

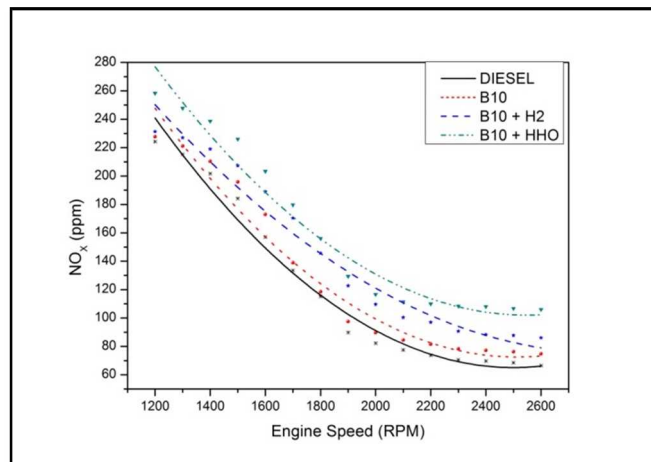


Fig. 9: NO_x versus engine speed.

NO_x is formed during the combustion because of three factors, high temperature, oxygen concentration, and residence time. If these three factors present in a combustion chamber, the NO_x formation is more [7]. When hydrogen is inducted, the enhanced combustion rate increases the temperature and thus the NO emission. This is the main

environmental problem with hydrogen induction [28]. Beside, higher oxygen content of B10 fuel increases the combustion efficiency and the NO_x emissions. As an expected result, higher in-cylinder temperature and oxygen content of B10 are increased NO_x emissions that presented in figure 9. Average increment of NO_x emissions were 20% and 16% for HHO+B10 and H₂+B10 fuels respectively.

CONCLUSIONS

Main point of this experimental study was to investigate the effect of pure hydrogen, hydroxy (HHO) gas and biodiesel addition to the diesel fuel in diesel engines. Experimental results are summarized and simply presented in table 5. Intake air is enriched with 10 L/min of H₂ and HHO before intake manifold without modification on the test engine. Effects of HHO+B10 and H₂+B10 fuels on engine performance and exhaust emissions compared with neat diesel fuel results are presented in table 5.

Table 5: Comparison of experimental results HHO+B10 versus H₂+B10.

	Output	Preference (HHO+B10/H ₂ +B10)	Effect (%)
Emissions	CO (ppm)	H ₂ +B10	5.80 less
	CO ₂ (%)	H ₂ +B10	8.72 less
	NO _x (ppm)	H ₂ +B10	9.70 less
Performance	Brake Power (kW)	HHO+B10	4.33 more
	Brake Torque (Nm)	HHO+B10	2.15 more
	BSFC (g/kWh)	HHO+B10	7.60 less

On the basis of the experimental investigation on diesel engine, conclusions can be drawn below;

- ❖ Enrichment of intake air with pure hydrogen or hydroxy gas gives promising results compared to neat diesel fuel according to the experiments.
- ❖ All other performance and exhaust emissions have improved except NO_x exhaust emissions.
- ❖ According to neat diesel fuel, reductions of CO emission were 29% and 22% via H₂+B10 and HHO+B10 usage respectively.
- ❖ Similar to the CO results, both of the hydroxy gas and hydrogen enriched fuels have provided better CO₂ exhaust emissions than neat diesel fuel. Lesser CO₂ exhaust emissions results have been measured with H₂+B10 fuel usage compared to the HHO+B10 and neat diesel fuels (8.72% and 22.3% respectively).
- ❖ On the other hand, HHO+B10 fuel has performed higher engine performance results compared to the H₂+B10 and neat diesel. While brake power and torque outputs have improved and BSFC values have decreased which has inverse ratio with fuel efficiency.
- ❖ As an overall result, HHO+B10 usage in diesel engines is preferable because of easy and safety assembles to commercial transportation vehicles. Additionally low operation and consumables cost according to H₂+B10.

ACKNOWLEDGEMENT

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PİLOT PÜSKÜRTME YÖNTEMİYLE MODİFİYE EDİLMEMİŞ DİZEL MOTORDA 20HCNG GAZ YAKITININ PERFORMANS VE EMİSYONLARA ETKİSİ

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ÖZET

Dünyada fosil yakıt kullanımı çevresel faktörler, petrol rezervlerinin azalması ve buna bağlı olarak petrol fiyatlarının artmasıyla birlikte önemli bir sorun haline almaktadır. Bu sorun araştırmacılar alternatif yakıtlar üzerinde çalışmaya itmektedir. Bu çalışmada %20 Hidrojen + %80 sıkıştırılmış doğal gaz (CNG) yakıt karışımının emme manifoldu üzerinde oluşturulan karışım odası vasıtasıyla motora enjekte edilmektedir. Yapılan deneylerde yakıtların performans ve emisyon değerlerine olan etkileri araştırılmıştır. Deneylerde, yakıt pompası plancısı üzerinde akupile edilen step motor yardımıyla dizel yakıt püskürtmesi %20 düşürülerek pilot püskürtme gerçekleştirilmiştir. 3.6 L, 4 silindir, 4 zamanlı hava soğutmalı test dizel motoruna bağlı dinamometre ile testler 1300-2600 dev/dak aralığında gerçekleştirilmiştir. Deneylerde; normal dizel yakıt ile 20HCNG gaz yakıt ile zenginleştirilmiş yakıt karışımının performans bakımından sırayla tork, güç ve özgül yakıt tüketiminde; %5, %2,2, %17; düşüş gözlemlenmiştir. Egzoz emisyonlarında ise CO için %7,5 artış, CO₂ ve NO_x değerleri içinse %4 ile %21 azalış elde edilmiştir. Pilot püskürtme yöntemiyle emisyonlarda ciddi düşüşler elde edilmiş ve diğer çift-yakıt sistemlerine nazaran performansta da çok küçük düşüşler elde edilmiştir. **Anahtar Kelimeler:** Hidrojen, CNG, Pilot Dizel Püskürtme, Performans, Emisyon

EFFECTS OF ENGINE PERFORMANCE AND EXHAUST EMISSIONS OF 20 HCNG GAS MIXTURE USING ON A NON-MODIFIED DIESEL ENGINE WITH PILOT DIESEL INJECTION TECHNIQUE

ABSTRACT

Using of fossil fuel is a major problem in the world cause of environmental factors, depending on the reduction of oil reserves and the

increasing of oil prices. These problems are encouraged to researchers for working on alternative fuels. In this study, 20% hydrogen and 80% compressed natural gas (CNG) fuel mixture is injected by mixture chamber which is placed on the intake manifold. Beside, engine performance and emission were investigated of fuels on a non modified diesel engine with pilot injection technique. In the experiments, substituted diesel fuel injection occurred with the helped of stepping motor which stated on to the fuel pump plunger with 20%. 3.6 L, 4-cylinder, 4-stroke, air-cooled test diesel engine connected to a dynamometer that operated the tests in range of 1300-2600 rev / min. In comparison with 20HCNG enriched gas fuel between regular diesel fuel, in order in terms of performance, torque, power and specific fuel consumption; 5%; 2.2% to 17%; decrease was observed. For emissions, 7.5% increase for CO while CO₂, NO_x values were obtained 4% and 21% reduction respectively. Both serious reductions of emissions obtained from using pilot diesel injection technique and moreover other dual fuel systems; pilot injection observed less reduction in performance scale.

Keywords: Hydrogen, CNG, Pilot Diesel Injection, Performance, Emissions

1. GİRİŞ

Günümüzde yükselen teknoloji eğilimleri ve çevresel faktörlerinde etkinliğiyle otomotiv sanayinde, alternatif yakıtların önemi giderek artmaktadır. Petrol piyasalarındaki arz talep dengesizliği ve azalan petrol rezervleri alternatif yakıtlı motor üretimlerine veya bu yakıtların günümüzdeki motorlarda kullanılması üzerinde çalışmaya itmiştir. Egzoz gazı salınımının açışından fosil yakıtların kullanılmadan daha ziyade daha çevreci yakıtların kullanılmaya geçtikçe daha ehemmiyetli bir hal almaktadır. Özellikle biyo-yakıt ve gaz yakıtların motor teknolojilerinde kullanılmaları hem yakıt tasarrufuna hem de sera gazı salınımına etkilerinden dolayı son dönemlerde tercih sebebi haline gelmiştir. Hidrojen, doğalgaz çakıtı hidrokarbonca zengin alkoller ve bio-yakıtlar alternatif yakıtlar arasında gösterilebilir.

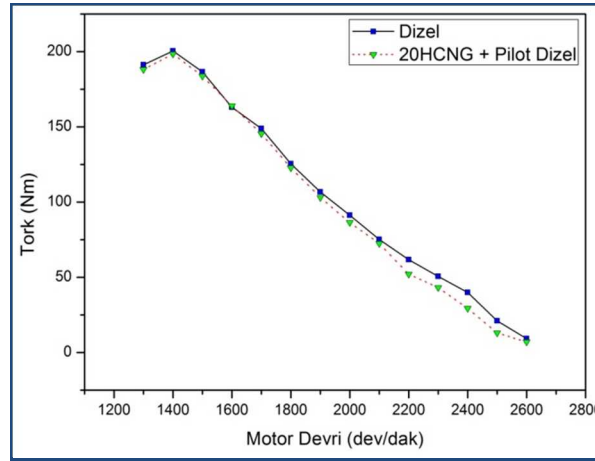
Dünya üzerinde alternatif yakıtların kullanılmalarının artması araştırmacılar bu konular üzerinde daha fazla araştırma geliştirme çalışmalarına zorlamıştır. Günümüz teknolojisiyle bu alternatif yakıtlar için hem farklı motorlar üretilmekte hem de bu yakıtların normal motorlar üzerinde kullanılması için gerekli olan araştırma-geliştirme çalışmaları yapılmaktadır. Son yıllarda bu yakıtlarla ilgili çalışmalar ve gelişmelerden bazılarına değinmek konunun önemi hakkında bize önemli bilgiler verecektir. Örneğin; doğalgazın fosil yakıt olmasına rağmen yanma prosesleri içerisinde alternatif bir yakıt olarak kullanılması ve çevreci olması bakımından; 2006 yılında ABD'de Westport şirketi kurulmuştur. Bu şirket özellikle büyük hacimli motorlarda doğalgazın doğrudan kullanılabilmesi için doğalgaz motoru uygulamasına geçmiştir. Özellikle kullandıkları yakıt enjektörlerinde pilot püskürtmeye benzer bir metotla dizel yakıt ile doğalgaz yakıtını aynı enjektörden püskürterek; daha net ifadeyle dizel yakıtın tutukurucu olarak kullanarak doğalgazlı motoru kullanmışlardır. Diğer yandan farklı araştırmalara bakacak olursa, dikkat çeken gaz yakıt karışımlarına örnek olarak HCNG (hidrojen ile zenginleştirilmiş sıkıştırılmış doğalgaz) verilebilir. Hidrojen ile doğalgazın mühendisliksele özellikleri yanma süreçlerinde motor performans ve emisyonlara etkileri açısından bu gaz yakıtların kullanılmaları yaygınlaşmaktadır. İçten yanmalı motorlarda hidrojenin ve doğalgazın birlikte yakıt karışımı olarak kullanılmaları araştırmacılar tarafından ilgi odağı olmuştur. Yazarlar bundan önceki çalışmaları [1] HCNG yakıtın dizel motorlarda kullanılması ile ilgili bir derleme çalışması yapmışlar ve HCNG'nin yakıt özellikleri, dizel motor performans ve emisyonlara etkileri, kullanım aşamaları avantaj ve zorlukları hakkında detaylı bilgiler vermişlerdir. Bazı araştırmacılar da; [1,2,3,4,5,6,7,8,9,10] HCNG yakıtının içten yanmalı motorlarda kullanılması üzerinde çalışmalarını sunmuşlar; genel kanı olarak hidrojen ve doğalgazın tekli kullanılmaları halinde yanma prosesinde gösterdikleri dezavantajları beraber kullandıklarında birbirlerinin avantajlarına dönüştürdükleri yönündedir. Özellikle hidrojenin kendi kendine tutukma sıcaklığı ve yanma hızının yüksekliği, doğalgazın düşük

3. ARAŞTIRMA BULGULARI VE TARTIŞMA

Deneylere başlamadan önce, motor standart çalışma sıcaklığına gelinceye kadar sadece dizel yakıt kullanılarak çalıştırılmaktadır. Deneyde kullanılan yakıtlar, 100 dev/dak aralıklarla, 1300 ve 2600 dev/dak arasında tam yükte test edilmiştir. DeneySEL hataları optimize etmek için her bir deney üç defa tekrar edilmiştir ve sonuçlar için bu üç deneyin ortalaması alınmıştır. Motor iki farklı yakıt yüklemesi altında çalıştırılmaktadır. Bunlardan biri normal dizel yakıtı bir diğeri ise 20HCNG+kışmık dizeldir. Normal operasyon ve çift-yakıtlı operasyonlar birbiriyle karşılaştırılarak, deney verileri detaylı bir şekilde analiz edilmiştir.

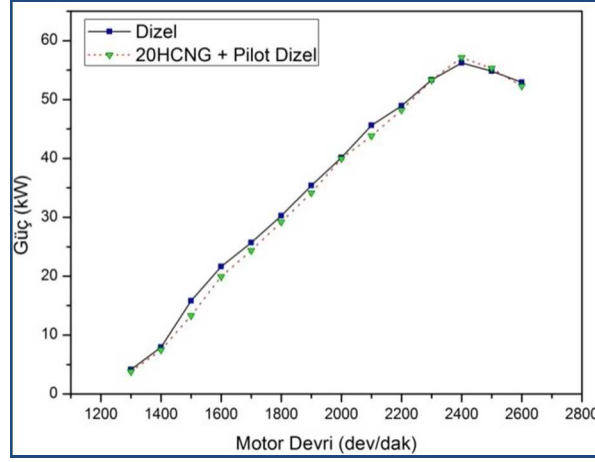
3.1 Performans Sonuçları

Motor performans verileri içerisinde motor torku, motor gücü ve özgül yakıt tüketiminin motor devrine göre karşılaştırmaları irdelenerek grafikleştirilmiştir. Şekil 2’de motor torku i motor devri grafiği görülmektedir. Şekilden de anlaşılabileceği üzere hidrojenle zenginleştirilmiş doğalgaz, orta devirlerden itibaren fakir yanmanın etkisiyle normal dizel verilerine yakınlık göstermiştir. Genel ortalama olarak gaz yakıtların tork değeri normal dizel operasyonuna göre %5 düşük göstermektedir. Sadece doğalgaz ile çalışan dizel motorlarda bu oran %8-10 arasında düşük göstermekte olduğundan hidrojenin olumlu etkisi ile bu durum biraz daha iyileştirilmiştir.



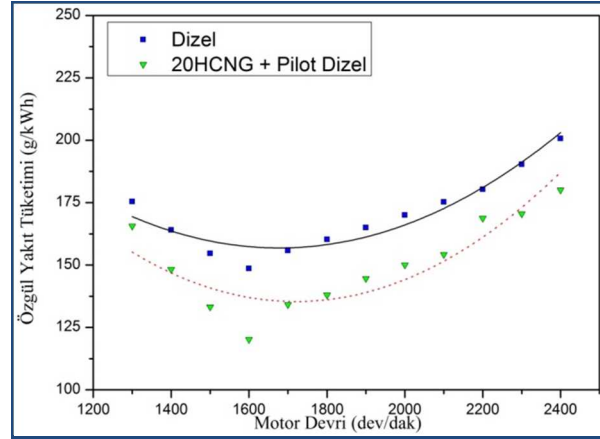
Şekil 2. Tork-Devir grafiği

Şekil 3’de motor gücü ve motor devri grafiği görülmektedir. 20 HCNG + pilot dizel yakıtı normal dizel yakıtı ile karşılaştırıldığında %2.2 gibi düşük bir değer ile azalış göstermiştir. Hidrojenin yüksek yanma verimi ve silindir içerisindeki basınç etkisi sayesinde güç verilerinde çok fazla bir düşüş gözlenmemiştir.



Şekil 3. Güç - Devir grafiđi

Özgöl yakıt tüketimi i motor devri grafiđi ise Şekil 4'te verilmektedir. Diđer grafiklerde de olduđu gibi, normal dizel yakıt kullandın durumun özgöl yakıt tüketimi, pilot püskürtmeli gaz yakıtla kokulun özgöl yakıt tüketimi ile karşılaştırılmaktadır. Silindirlere gönderilen gaz yakıt debileri deneyler boyunca sabit olup H için 5.02 L/min ve CNG için 19,996 L/min olarak ölçülmüştür. Yakıtların üst eşel yanma değelerine yazarların önceki çalışmalarından ulaşılabılır [1,12]. Pilot dizel püskürtme sistemine benzer şekilde yakıt pompasından kışdan dizel yakıtın özgöl yakıt tüketimine etkisi bu grafikten daha net anlaşılmaktadır. Kışaslama yapıldıđında özgöl yakıt tüketimi %17 düşmüştür. Bu düşük yakıt pompası üzerine monte edilen step motor ve ekipmanları sayesinde gerçekleştirilmiştir. Kullandın gaz yakıtlar bu eksilmenin yerine dizel motor performanslarındın olumlu yönde etkilemektedir.



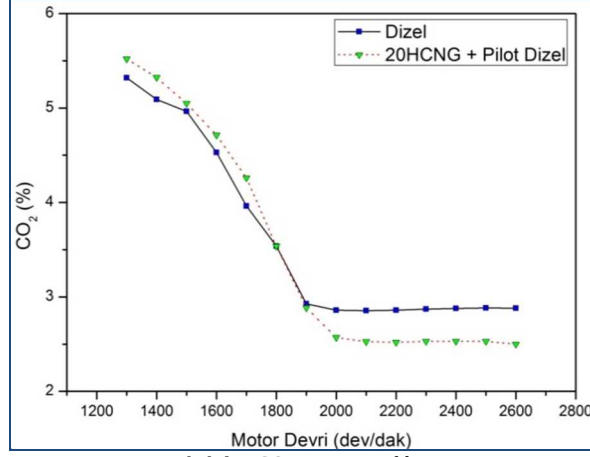
Şekil 4.Özgöl Yakıt Tüketimi - Motor Devri eğrisi

3.2 Emisyon Sonuçları

Kışten yanmalı motorlarda en önemli olgulardan bir tanesi de egzoz emisyonlarındın belirlenmesi ve çevreye olan etkilerinin araştırılmalarıdır. Temiz yanma sağlayan gaz yakıtların bu motorlarda kullanılmaları emisyonlar açısından önem teşkil etmektedir. Özellikle hidrojen ve CNG yakıt karışımlarındın emisyon değelerine olumlu etkileri bulunmaktadır. Bu çalışmada da bu etkileri görmek için egzoz emisyonlarından CO, CO₂ ve NO_x verileri MRU 1600 V egzoz emisyon cihazıyla ölçülmüş, sonuçlar normal dizel operasyonu ile karşılaştırılmaktadır.

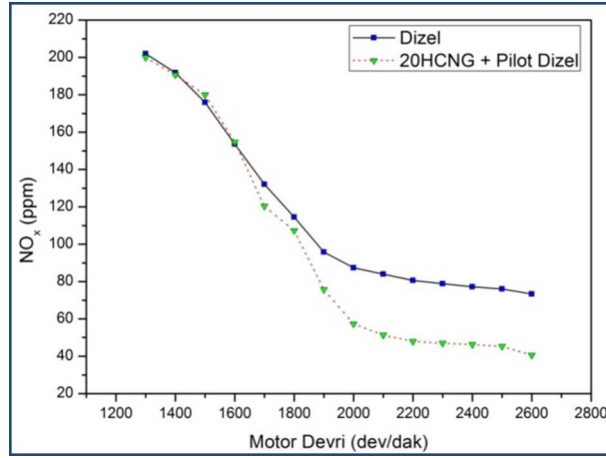
Şekil 5'te CO₂ i Motor Devri grafiđi görülmektedir. Şekilden de anlaşılabılır üzere özellikle yüksek devirlerde gaz yakıt karışımlarındın dizel operasyona göre daha iyi sonuçlar verildiđi görülmektedir. Genel ortalama olarak %4 CO₂ salındın düşük göstermiştir. Özellikle orta devirlerden önce yükselmenin sebebi CNG'nin sistemde oluşturdđu CO₂ salındınındın

sonucudur. Literatür verileri, tekil CNG yakıtı kullanan bir dizel motorunda bu değerin çok daha yüksek olduğunu vurgulamaktadır.



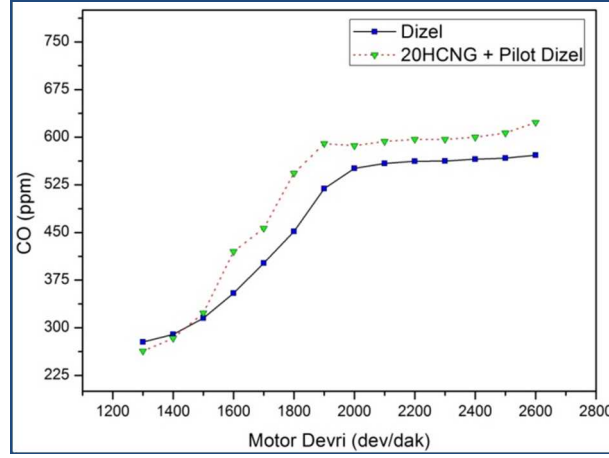
Şekil 5. CO₂ i Devir grafiği

NO_x i Motor devri grafiği Şekil 6'da verilmiştir. Egzoz emisyon salınımının en önemlilerinden bir tanesi olan NO_x in düşürülmesi için alternatif gaz yakıtların kullanılması son derece etkin rol oynamaktadır. Şekil 6'da görüldüğü gibi, %21 seviyelerinde NO_x salınımında düşük görülmüştür. Burada da performansa olumlu etkileyen hidrojenin fazla NO_x salınımına CNG ile karşılaştığında önemli seviyede düşük gerçekleştirmiştir.



Şekil 6. NO_x i Devir grafiği

Şekil 7 de CO i Motor devri grafiği resmedilmiştir. Bu çalışmada sonucunda gaz yakıtlar % 7,5 seviyelerinde CO salınımına arttırmıştır. Bu sonucun sebepleri arasında pilot dizelin daha fazla kışkırtılması ve ortamdaki oksijen konsantrasyonu gösterilebilir.



Şekil 7. CO İ Devir grafiđi

4. SONUÇLAR

Çukurova Üniversitesi Otomotiv Mühendisliđi laboratuvarında gerçekteştirilmik olan bu çalışmada %20 Hidrojen + %80 sıkıştırılmak dođ algaz (CNG) yakıt karışımı emme manifoldu üzerinde oluşturulan karışım odası vasıtası ile motora enjekte edilmektedir. Yapısal değ iklilik yapılmayan dizel motorda pilot püskürtme yöntemi ile yapılan deneylerde yakıtların performans ve emisyon değerlerine olan etkileri araştırılmaktadır. Deneylerde, yakıt pompası plancısı üzerinde akuple edilen step motor yardımıyla dizel yakıt püskürtmesi %20 düşürülerek pilot püskürtme gerçekleştirilmiştir. 3.6 L, 4 silindir, 4 zamanlı hava soğ utmalı test dizel motoruna bađ lı dinamometre ile testler 1300 i 2600 dev/dak aralıđ ında gerçekleştirilmiştir. Deneylerde; normal dizel yakıt ile 20HCNG gaz yakıt ile zenginleştirilmik yakıt karışımında, performans bakımından sırayla tork, güç ve özgül yakıt tüketiminde; %5; %2,2 %17; düşük gözlemlenmiştir. Egzoz emisyonlarında ise CO için %7,5 artış, CO₂ ve NO_x değerleri içinse %4 ile %21 azalış elde edilmiştir. Pilot püskürtme yöntemiyle emisyonlarda ciddi düşüklükler elde edilmik ve diđer çift-yakıt sistemlerine nazaran performansta da çok küçük düşüklükler elde edilmiştir. Özellikle büyük hacimli motorlarda, yapısal değ ikliliđ e gidilmeden bu alternatif yakıtların kullanılması hem performans sonuçlarında çok az bir değ iklime sebebiyet vermesinden hem de egzoz emisyon salınımlarında olumlu etkilerinden dolayı tercih sebebi olabilmektedir. HCNG yakıtın Euro 6 emisyon standartlarına karışması sebebiyle hidrojen ve CNG yakıtın kullanılmasıdaki araştırmaların giderek artması bundan sonraki çalışmalarda üzerine eđ ilinmeye devam eden araştırma konularından biri olacaktır.

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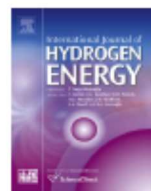
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Experimental investigation of using 30HCNG fuel mixture on a non-modified diesel engine operated with various diesel replacement rates

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ABSTRACT

Pilot diesel injection phenomenon consisted by gaseous fuels such as hydrogen and natural gas; ensure the way of exert fuels without any structural modification in compression ignition engines. This study investigates of using 30HCNG (Hydrogenated Compressed Natural Gas) fuel mixture on a non-modified diesel engine operated with diesel fuel replacement rate experimentally. HCNG was used as an additional fuel with air fumigation in a non-modified diesel engine via intake manifold and reduction of diesel fuel by dint of pilot injection. Reduction of diesel fuel was prepared as two different substitutions like 25 and 50% diesel replacement rates controlled by stepping motor devices. 30% Hydrogen and 70% CNG (Compressed Natural Gas) (by volumes) fuel mixture were tested in a 3.6 L, four cylinders, four stroke and water coolant diesel test engine between 1200 and 2600 rpm. Effects of these two different diesel reductions on engine performance and exhaust emissions parameters were compared and illustrated with graphics as brake power, brake torque, and brake specific fuel consumption; CO, CO₂ and NO_x. Brake thermal efficiency and a minor cost analyses were also performed. It was observed that, 30HCNG fuel mixture with 50% diesel replacement rate affect the engine performance as brake torque, brake power and BSFC values were decreased 4.3%, 8%, 26.8% respectively. Exhaust emission values of NO_x and CO₂ were decreased 47.2%, 16.7% respectively; however CO emission values were increased 8%.

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Introduction

Fuel research and developments are always possessing importance as much as engine technologies at automotive industry. Common objective is to create more economical and

environmental friendly future for both. Some of the important alternative fuels are gaseous fuels, such as hydrogen and natural gas which have rising momentousness of utilization. Especially degradation of exhaust emissions and fuel consumptions can be obtained by using these gaseous fuels in

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1- Introduction

Fuel research and developments are always possessing importance as much as engine technologies at automotive industry. Common objective is to create more economical and environmental friendly future for both. Some of the important alternative fuels are gaseous fuels, such as hydrogen and natural gas which have rising momentousness of utilization. Especially degradation of exhaust emissions and fuel consumptions can be obtained by using these gaseous fuels in internal combustion engines. Gaseous fuels can be used as a fuel for SI (spark ignition), CI (compression ignition) and NG (natural gas) engines. For SI and NG engines these fuels combustions are easier than CI engines. In CI engine combustion state occurs with penetration of diesel fuel to the pressurized air in combustion conditions. Natural gas and hydrogen is favorable couple for using as a fuel in ICE (Internal Combustion Engine). Natural gas has environmental advantages and reserve capacity. Hydrogen has also environmental advantages and significant power inside. Their engineering and combustion properties are very suitable when they become a mixture in certain percentages. Researchers have focused on this point and they mentioned; the optimum usage of mixture percentages as a fuel between 18% - 35% by volumes of these gases [1-5, 15, 16]. Basically, a singular usage effect of NG is reducing emission parameters while causing losses in torque and power. However H_2 is considerable improving power while increasing NO_x exhaust emissions. When they mixed up with each other their disadvantages becomes their advantages. Previous studies showed that it can be more selectable for choosing these mixtures rather than singular usage. Pichayapat K. et al, mentioned that using combinations of hydrogen and diesel mixing together or natural gas and diesel mixing together and even HCNG (Hydrogenated Compressed Natural Gas) blended together in the internal combustion engine will reduce emission levels and provide better overall performances [3].

In CI engines, dual-fuel mode operation gives promotional utilize when use gaseous fuels. In dual-fuel operations mostly two options have been preferred to induct gases into the combustion chamber; generally called fumigation. First one is directly mixed with air and straight the mixture (air and fuel) via intake manifold. The second one is mixed in two fuels in an injector that used gas and diesel [6]. At the first option any kind of structural modification is not required on the engine expect set up to pilot injection system for combustion. Minimum diesel fuel injected towards of air and gas fuel mixtures in combustion chamber. On the other hand; original injectors of engine has to exchange with the new ones for second option. Additionally; in transportation sector, diesel engines recompose like a gases engine with some structural engine modifications. These modifications of diesel engines to gas engines, causes necessary changes of parts with higher costs. Beside, this transformation in CI engines, allowed the system only mono-fuel. Obviating these problems, diesel engines combust with pilot diesel injection by using gaseous fuels without any structural modification.

Cheolwoong Park et al., touched upon and explain the importance of HCNG fuel that, an HCNG engine exhibits a leaner combustion than a CNG (Compressed

Natural Gas) engine, which is possible because of the stable lean combustion characteristics of hydrogen. Consequently, nitrogen oxides (NO_x) and CO₂ emissions can be significantly reduced. [7, 8]. From this point of view, some important previous studies of HCNG fuel experiments can be listed below. Arat H.T. et al, prepared a critical review about HCNG fuel usage in diesel engines. They focused on the usage of HCNG fuel, details on the different mixture formation strategies and fuel properties, analyze their engine performance and their emissions characteristics, and look through the benefits and challenges of HCNG for diesel engines [1]. Papagiannakis R.G., et al., studied NG usage on diesel engines. They examined their tests on a single cylinder, direct injection CI engine with dual fuel, NG and diesel, which operated pilot diesel injection. Test results were worthwhile for exhaust emissions, especially for NO_x results [9, 10]. Cheolwoong P. et al., studied on 11 L, 6 cylinder CNG engine with addition of hydrogen as a supplementary fuel. They mentioned the volumetric ratio of hydrogen to natural gas was maintained at 3:7, which was considered the most appropriate ratio based on their researches. Experiments results showed that proposed operating strategy for satisfying the limit of the EURO-VI standard is effectively in specific spark timing condition [7, 8]. Another study was reached by Fanhu M. et al, studied on performance and emission parameters on a hydrogen-enriched compressed natural gas engine with various hydrogen quantities. They mentioned emission parameters reduce with optimum usages however increasing the hydrogen quantity occur NO_x increase [11].

From the point of view, using hydrogen and/or natural gas as an additive to enhance the conventional diesel engine performance and by the way reducing the exhaust emissions have been investigated by several researchers and the outcomes are very promising. Some of the remarkable studies can be refereed with for HCNG and CNG usage in CI [2, 11-20]. All together touched upon; the important factors of H₂NG vehicles, improving the engine performance (torque, power, brake thermal efficiency, total engine efficiency improvement, lean combustion parameters like higher equivalence ratio and excess air, degradation the engine acoustic, etc.) decreasing the exhaust emission outputs (THC, CO, CO₂ decreases with both and also CNG balanced the unwanted hydrogen's NO_x) and reducing the specific fuel consumption and fuel economy.

In this experimental study, 30HCNG fuel mixtures were used in a non-modified diesel engine and operated with 25 and 50% diesel replacement rates. HCNG was used as a replacement fuel in a non-modified diesel engine via intake manifold and reduction of diesel fuel was obtained by dint of pilot injection. Reduction of diesel fuel was prepared as two different substitutions like 25 and 50% diesel replacement rates and controlled by stepping motor devices. Engine performance and exhaust emissions were plotted and explained in details. Also brake thermal efficiency and minor cost analysis of fuel consumption were performed.

2- Experimental Procedures

2.1 Experimental Setup

All tests are carried out on a 3.6 L, non-modified, commercial, four cylinders, four-stroke, naturally aspirated, water-cooled direct injection compression ignition engine. Test engine has 17.5:1 compression ratio and mechanical direct injection fuel pump with injection starts at 23 deg BTDC (Before Top Dead Center). It should be noted here, the usage of gaseous fuels in a fumigated diesel engine tented to operation under lean limits [18]. In this experiment, combustion operation is under lean limits which calculated results for relative AFR is $\phi=1.35$; equivalence ratio is $\phi=0.74$ and air-fuel ratio is, AFR=21.04. By the way, the stoichiometric AFR of 30HCNG is 16.4 [24]. A Netfren mark hydraulic dynamometer (specifications are presented by [16]) was used for loading the test engine and MRU Delta 1600V gas analyzer was used to measure exhaust gas emissions. Diesel fuel consumption has measured with liquid fuel flow meter which addressed the data to main computer. Additional gas fuels flow parameters controlled and measured with needle vanes and ALICAT mark flow meters respectively. Test engine specifications and accuracies of measurement devices were exposed in Table 1.

Hydrogen and CNG fuels supplied from pressured tanks which has gas capacity of 12.5 m³ and fixed on 200 bar pressure for CNG and 170 bar for hydrogen. A back fire eliminator and CNG check valve used behind the checkout for hinders the reverse flow through the tanks. Regulators were used for reducing the pressures of hydrogen and CNG. Hydrogen regulator that adapted after back fire eliminator regulated the high pressure to atmospheric pressure. Lovato brand CNG regulator kit has 2- stage regulation which throttled in first stage 200 bar to 12-14 bar and the second stage decreased the 12-14 bar to 1-0 bar. Exit from regulators, Hydrogen and CNG pass through the needle valve and flow meters. After controlled and measured the flow of gaseous fuels with needle valves and flow meters, measurement data were collected through the data logger. Air quantity was also gauged with conversation of the air velocity meter which was adapted on air filter. In front of the intake manifold, a mixture chamber was used for the mixing hydrogen, CNG and air. After combustion MRU Delta 1600 V gas analyzer was used to measure exhaust gas emissions. Experimental set-up is illustrated in Figure 1.

2.2. Fuel properties and Determination of Mixture

In this study; diesel fuel, hydrogen and CNG were used as test fuels. CNG used in this study contains 97.372% Methane, 2.327% Nitrogen, 0.230% Ethane and 0.068% Propane. Methane is the main constituent of the CNG used that; its C/H ratio is also low, resulting in a significant reduction of the specific CO₂ emissions [10]. Hydrogen purity is 99.999%. Diesel fuel is a typical commercial fuel. Fuel properties and contents of mixture proportions under the present experimental investigation are given in Table 2.

Using gas fuels in CI engine and their mixture ratios are very important items in combustion of pilot injection diesel fuel. As we mentioned before, between 18%-35% (vol/vol) ratios of hydrogen to CNG are used for several experiments. In this experiment study, 30HCNG fuel mixtures were used to analyze the engine performance and emission parameters with diesel replacement rates like pilot injection. The volumetric hydrogen content is calculated according to equation 1 [24]. In this experimental study, gas fuel mixtures, used in CI engine with substitution of diesel fuel, are termed by HCNG₁ and HCNG₂ and one test average mass flow rates also given for H₂ and CNG. 30% Hydrogen and 70% CNG gas fuel ratio was not changed in the fuel mixture except diesel fuel ratio. Termed fuels and contents of mixture proportions, and the fuel definitions and quantities were illustrated in Table 2 and Table 3, respectively.

$$\text{Volumetric Hydrogen Content (\%)} = \frac{\text{V}_H}{\text{V}_H + \text{V}_{\text{CNG}}} \quad \text{Eq.1}$$

2.3. Substitution of Diesel Fuel

One of the research experimental goals was to use hydrogen and CNG gas fuel mixtures in an original diesel engine without any modifications. For this reason, substitution of diesel fuel was adjusted with the help of stepping motor and devices. A bipolar, 1.8 deg/step, 6.2 Nm holding torque stepping motor, equipped with Toshiba TA 8435 stepping motor driver was used for adjustment of the mechanical fuel pump plunger pin. Stepping motor driver controlled with software in main computer and obtained more sensitive measurement results. Several optimization experiments were tried for substitution of diesel fuel. As a result, reducing the diesel fuel injection was handled via twisting the plunger pin one tour (360°) and two tours (720°) of fuel pump plunger pin clockwise. In the normal diesel operation conditions, experiments showed that one tour twisted fuel pump plunger pin procured approximately 20-25% reduction of fuel injection. And two tours twisted procured approximately 30-45% reduction in fuel consumption [15]. Engine drivability problem has been observed with more than three and higher twisted rotations. The test engine has a mechanical fuel pump and injection system, therefore more choking of the diesel fuel caused pressure drops in the injection system. Hence fuel droplet size increased with a fuel pressure drop. The self-ignition of the fuel in the combustion delayed and this caused unstable engine running.

Pilot diesel injection phenomenon summarized by Papagiannakis R.G. et al. In dual fuel CI engines operating with gaseous fuels as primary fuel and a pilot amount of liquid diesel fuel as an ignition source, the gaseous fuel is inducted along with the intake air and is compressed like in a conventional diesel engine. The mixture of air and gaseous fuel does not auto ignite due to its high autoignition temperature. A small amount of liquid diesel fuel is injected near the end of the compression stroke to ignite the gaseous mixture [10]. Also some researchers mentioned this small quantity of pilot diesel fuel is between 2-10% by mass [12]. Similar approach with these literatures, 25 and 50% diesel replacement rates were used for substitution of diesel fuel.

3- Experimental Results

The engine was operated for enough time with diesel fuel to reach the operation temperature before the tests. All tests were implemented with the engine speed between 1200 to 2600 rpm with an interval of 100 rpm at WOT and full load condition. Separately three sets of experiments were performed and average test data were used for the results for optimization of the test results. The engine was operated with normal diesel fuel, HCNG₁ and HCNG₂. Engine performance and exhaust emission parameters were measured for all tests and compared each other.

3.1. Performance Characteristics

Performance of 30HCNG fuel mixtures on a non-modified diesel engine with substitution of diesel fuel like pilot diesel injection is discussed with respect to brake torque, brake power and brake specific fuel consumption parameters. These parameters are illustrated in following figures.

Figure 2 illustrates the brake torque of the engine as a function of engine speed of diesel fuel, HCNG₁ and HCNG₂ fuel mixtures. Gaseous fuel mixtures were played a relatively negative role and reduced the torque and power. It is highly probable due to the volumetric efficiency, gas inlet temperature, gas mixture distribution, AFR, net heat release, cylinder pressure and lack of chemical energy conversion to mechanical energy. These criteria occurs incomplete combustion which redirect the researches minimizing this incident. In this study, when brake torque values of fuels were compared, HCNG₁ and HCNG₂ fuels reduced the torque parameters about 6.2% and 4.3% respectively. Although replacement rate of diesel fuel for HCNG₁ is higher than HCNG₂, the hydrogen quantity of HCNG₂ mixture occur more powerful combustion.

Figure 3 demonstrated the break power versus engine speed of diesel fuel, HCNG₁ and HCNG₂. Similarly engine torque values, pilot diesel fuel injection with gas fuel mixtures decreased the brake power of engine using HCNG₁ and HCNG₂ with the ratio of 9% and 8%. Additionally in lean burning period of combustion, HCNG₂ power values were better than HCNG₁ values caused of more hydrogen concentration inducted.

Figure 4 shows the total brake specific fuel consumption (BSFC) variation with engine speed. The BSFC is directly calculated from the ratio between the sum of diesel fuel mass flow rates and the engine brake power output. It should be noticed that; in this study, BSFC performed from liquid diesel engine fuel replacement rates and does not include the gaseous fuel. It can be observed that, 30HCNG fuel variances with substitution of diesel fuel like pilot diesel injection, decreased the BSFC and forms more lucrative fuel consumption. Improvement of fuel consumption in this experimental test engine is observed as 18% and 26.8%

for HCNG₁ and HCNG₂ fuel mixtures, respectively. One of the major intentions of this study was reducing BSFC while minimum torque and power losses. Additionally gaseous fuels consumption and effects of total BSFC have been mentioned in 4th section in cost analyses part.

Due to the high laminar velocity of combustion and the wide flammability limits of hydrogen, its addition is utilized as a method to shift stable engine operation to leaner mixtures, with positive effects on emissions and thermal efficiency. The use of hydrogen as an additive was also considered as a solution to enhance the combustion rates of some fuels like methane [15]. The high RON and low lean-flammability limit of hydrogen and natural gas provide the necessary elements to attain high thermal efficiencies in an ICE [25]. η_{th} thermal efficiency is an important performance indicator in engine performance. In formula form of η_{th} can be written as equation 2;

$$\eta_{th} = \frac{\dot{W}_{br}}{\dot{m}_d \cdot \dot{m}_{CNG} \cdot \dot{m}_{HHO} \cdot \dot{m}_{air} \cdot \dot{m}_{fuel} \cdot \dot{m}_{air} \cdot \dot{m}_{fuel} \cdot \dot{m}_{air} \cdot \dot{m}_{fuel}} \quad \text{Eq. 2}$$

where η_{th} ; is the brake thermal efficiency; $\dot{W}_{br}$ is brake power; $\dot{m}_d, \dot{m}_{CNG}, \dot{m}_{HHO}$ is the mass flow rates of substituted diesel, CNG and HHO respectively; and $\dot{m}_{air}, \dot{m}_{fuel}, \dot{m}_{air}, \dot{m}_{fuel}$ is the lower heating values of fuels.

Figure 5 shows the variations in the brake thermal efficiency (η_{th}) as a function of engine speed for the cases of using diesel fuel, HCNG₁ and HCNG₂ fuel mixtures. In results, the average of η_{th} reduces with 3% and 3.6%, respectively for HCNG₂ and HCNG₁ when compared with neat diesel operation. This can be explained by the fact that the high diffusion and flame speeds of hydrogen help improve the charge homogeneity and tended to increase the efficiency, hence the amount of replacement rate of liquid fuel and quantities of CNG affected the outputs slightly negative. As an additional note; from the characteristics nature of hydrogen, it can be clearly said that; the high flame speed of hydrogen can greatly compensate the low flame speed of CNG. For this reason, open-literature referred that; the η_{th} for HCNG operation is substantially higher with respect to neat CNG operation [24].

3.2. Emission Characteristics

In ICEs, hydrogen and natural gas components have significant environmentally improve when it comes to exhaust emission parameters. For single usage of hydrogen in a diesel engine, due to high flammability limits and increasing the cycle by cycle variation, nitrogen oxides (NO_x) values were increasing. Therewithal only CNG or NG usage in diesel engines, due to lower flammability limits of methane and high C/H ratio, CO parameters were increasing undesirable values. Eliminating of this downbeat situation, HCNG was preferred as a favorable fuel mixture for decreasing the emissions. NO_x emissions were thrilled by some factors like; oxygen concentration, combustion temperature and reacting time. CNG balanced the hydrogen's faster combustion and make more stable

performance [25] and emission outputs especially in lower and middle engine speeds.

NO_x emissions of diesel fuel, HCNG₁ and HCNG₂ fuel mixtures values are plotted versus engine speed in Figure 6. 30HCNG fuel mixtures were decreased the NO_x emissions worthwhile. It was observed that HCNG₁ and HCNG₂ fuel mixtures improved the NO_x emissions with 28% and 47.2%, respectively. Surely, pilot diesel injection assisted this reductions. Also these results are similar and better condition of previous studies [1, 2, 3, 5, 10].

Carbon dioxide (CO₂) concentrations in the atmosphere have been increasing significantly over the past century, compared to the rather steady level of the pre-industrial era [14]. Although it is a product of complete combustion, CO₂ is a major source of air pollution. It can be clearly seen in Figure 7, in dual fuel mode with replacement diesel injection, HCNG₁ and HCNG₂ fuel mixtures decreased the CO₂ values with 11.4% and 16.7%, respectively when compared with the diesel fuel in this experimental study.

Figure 8 shows the plot of carbon monoxide (CO) emissions versus engine speed for diesel fuel, HCNG₁ and HCNG₂ fuel mixtures. It is well known that the rate of CO formation is a function of the available amount of unburned gaseous fuel as well as the mixture temperature, both of which control the rate of fuel decomposition and oxidation [15]. In this experiment, it is obvious that CO emissions under gaseous dual fuel operation are significantly higher. HCNG₁ was increased the CO emission 12% and HCNG₂ was increased the CO emission 8%. The main reason for the CO emissions increment could be result of incomplete combustion of CNG (especially less hydrogen mixture quantity which seen in HCNG₁) and amount of pilot diesel fuel ignition on HCNG mixture. One of the solutions for solving this problem is the amount of diesel fuel for pilot ignition can be minimized for the reduction of CO emissions.

4- Cost Analyses

As an engineering approach, being only environmentally friendly is not enough. Economical point of this study is briefly explained in this subsection. Equation 1 is presented below by considering current fuel prices for calculation. Instead of converting diesel engine to natural gas engine, which is expensive and needs time consumption, limited modifications on diesel engine is easier and cheaper. Additionally, converted engines are not suitable to work with diesel fuel anymore. Comparison of these two options is illustrated in Table 4.

National current fuel prices (*in date: 20.09.2015*) are \$1.5 for 1 liter of diesel fuel, \$1 and \$2 for 1m³ of CNG and H₂, respectively. Volumetric flow rates of gaseous fuels are measured from flow meters multiplied by duration of experiment (in unit of minute), meanwhile mass flow rate of liquid diesel fuel is measured and transferred to the computer software simultaneously. Substitution of diesel fuel provided %45 reduction on liquid fuel consumption.

$$\frac{0.2 \times \$1.5}{0.11 \times \$1.5 + 0.165 \times \$1 + 0.19 \times \frac{\$1}{1000} + 0.08 \times \frac{\$2}{1000} \times 100 \left(\frac{1}{60}\right)} - 1 \times 100 = 34 (\%)$$

(1)

ρ : Percentage of saving in cash

V_{diesel} : Total amount of diesel fuel consumption during the experiment with original set up of fuel pump (ρ / ρ).

$V_{substituted}$: Total amount of substituted diesel fuel consumption during the experiment after fuel pump set up (ρ / ρ).

$\dot{V}_{CNG}$: Volumetric flow rate of CNG fuel measured by flow meter during experiment (L/min).

$\dot{V}_{H_2}$: Volumetric flow rate of H_2 fuel measured by flow meter during experiment (L/min).

ETP : Experimental Time Period (second).

An explanatory example;

To get a consistent idea, Equation 1 is applied on experimental engine output data which also includes measured gaseous fuel during the test.

V_{diesel} : 0.2 L, $V_{substituted}$: 0.165 L, $\dot{V}_{CNG}$: 19 L/min, $\dot{V}_{H_2}$: 8 L/min, ETP : 100 sec.

$$\frac{0.2 \times \$1.5}{0.11 \times \$1.5 + 0.165 \times \$1 + 0.19 \times \frac{\$1}{1000} + 0.08 \times \frac{\$2}{1000} \times 100 \left(\frac{1}{60}\right)} - 1 \times 100 = 34\%$$

If a commercial truck is considered which has 30 L/100 km fuel consumption and travels around minimum of 120,000 km/year, fuel cost becomes around \$54,000 (36,000 (L) x 1.5 (\$/L)). Additionally, even investment cost and constant operating costs included, this experimental usage is extremely advised to protect environment and micro-macro economies. It must be noticed two important assumptions that; firstly, this is a micro financial analysis which does not include necessary gas stations or infrastructure preparations. Secondly, calculations of vehicle fuel consumption such as this approachment, needed to evaluate with transient tests (i.e. world harmonized transient cycle) which is achieved more accomplished results than the steady test data.

5- Conclusion

In this present work, an experimental investigation has been conducted to examine the effect of the performance and pollutant emissions of a non-modified diesel engine operated with liquid diesel replacement rates by using 30HCNG fuel mixtures. Mechanical diesel fuel pump pin was mounted with a stepping motor for substitution of diesel fuel and two different situations were tested. 25% and 50% replacement rates of diesel were feeding with 30HCNG mixture. The cost analyses, methodology, experimental set-up and measurement devices were also given in details. The major conclusions can be drawn on the basis of experimental results;

- ✓ HCNG₂ fuel has significantly preferable fuel mixture rather than HCNG₁ due to engine performance outputs. Although pilot diesel fuel amount was lower than the other, higher hydrogen contents of mixture has improved the results when compared between HCNG₂ and HCNG₁.
- ✓ Comparison with diesel operation; both HCNG₂ and HCNG₁ mixtures decreased the brake torque outputs 4.3% and 6.2 % while brake power outputs decreased 8% and 9% respectively.
- ✓ Brake thermal efficiency follows the similar effect with brake power and decreased 3 and 3.6% for HCNG₂ and HCNG₁ fuel mixtures, respectively when compared the normal diesel operation.
- ✓ BSFC results provided 18% and 26.8% improvement for HCNG₁ and HCNG₂ fuel mixtures, respectively.
- ✓ Cost analysis and economical approach of this experimental study is calculated and supported with an example. Results showed that in case of using non-modified engine with diesel replacement rates, supplied with 30HCNG is approximately 30% profitable than base diesel engine. Meanwhile, it should be remembered that, further vehicle fuel consumption analyses evaluate with additional approaches like WHTC.
- ✓ Very promising improvements obtained for NO_x and CO₂ emissions. Both of the fuel mixtures decreased the NO_x amounts 28% for HCNG₁ and 47.2% for HCNG₂ respectively. While reduction of CO₂ emissions were 11.4% and 16.7% respectively.
- ✓ CO emissions under gaseous dual fuel operation are significantly higher than diesel fuel. Both of the fuel mixtures increased the CO emissions 12% and 8% respectively.

Overall, it can be concluded that, 30HCNG fuel mixtures usage on a non-modified commercial diesel engine has promising improvements for BSFC, CO₂ and NO_x outputs. Especially for this reason, HCNG blends are candidate to be piquant alternative fuel for internal combustion engines.

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Table Captions:

Table 1: Test Engine Specifications and Accuracies of Measurement Devices

Table 2: Fuel Properties and contents of percentages mixtures

Table 3: The fuel definitions and quantities

Table 4: Approximate investment cost of converting modified diesel engine and present work

Figure Captions: Figure 1- Experimental Setup

Figure 2- Brake torque vs engine speed of HCNG₁ and HCNG₂

Figure 3- Brake power vs engine speed of HCNG₁ and HCNG₂

Figure 4- BSFC vs engine speed of HCNG₁ and HCNG₂

Figure 5- BTE vs engine speed of HCNG₁ and HCNG₂

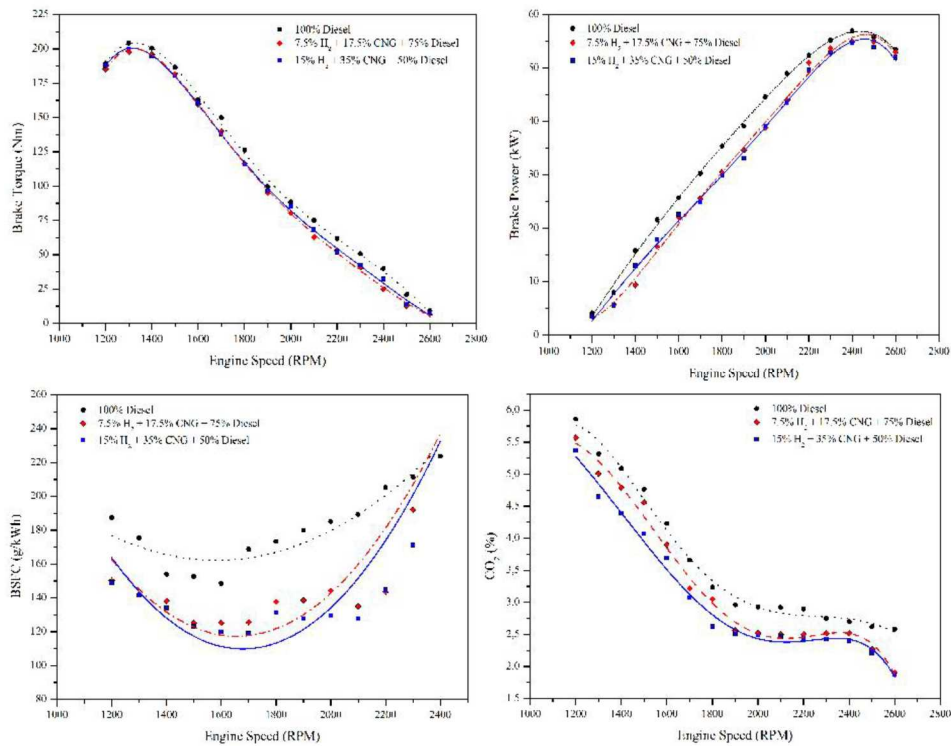
Figure 6- NO_x vs engine speed of HCNG₁ and HCNG₂

Figure 7- CO₂ vs engine speed of HCNG₁ and HCNG₂

Figure 8- CO vs engine speed of HCNG₁ and HCNG₂



1- Engine 2- Dynamometer 3- Exhaust gas analyzer 4- Data logger 5- CNG line 6- Hydrogen tank 7- Stepping motor on fuel pump plunger 8- Stepping motor driver 9- CNG regulator 10- Flow meters 11- Needle vanes 12- Gas fuels lines 13- Mixture chamber 14- Air filter 15- MAF 16- Fuel Flowmeter 17- Dynamometer Control Unit 18- Main Computer



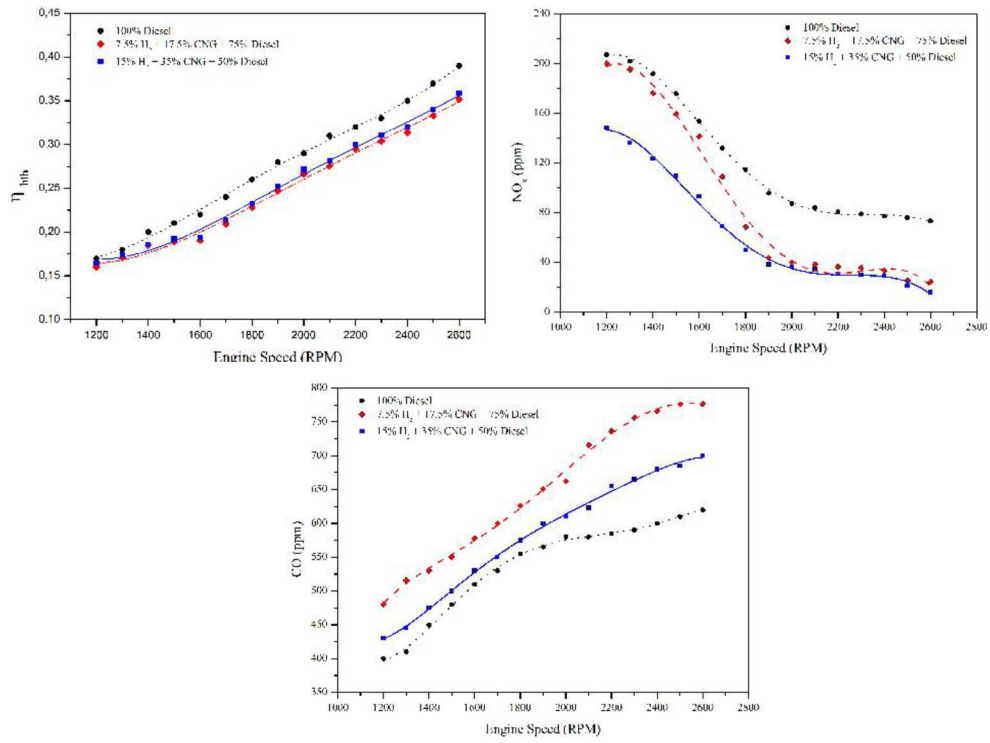


Table 1. Test Engine Specifications and Accuracies of Measurement Devices

Brand	Mitsubishi Canter	Performance	Alicat Flow Meter ±	MRU Delta 1600 v
Model	4D32 - In line 4	Accuracy at calibration conditions	± 0.8%	-
Type	D.I. diesel with glow plug	High Accuracy at calibration conditions	± 0.6%	-
Displacement	3567cc	Repeatability	± 0.2%	-
Bore	104mm	Typical Response Time	10 ms	-
Stroke	105mm	Measuring range-CO ₂ - 0-22%	-	OIML-class 1
Power	89kW @ 3200rpm	Measuring range-NO _x -(0-4000 ppm)	-	OIML-class 1
Torque	230Nm @ 1350rpm	Measuring range-CO - 0-10%	-	OIML-class 1
Hyd. Dynam. Torque/Speed Range	0-1700 Nm / 0-7500 rpm	Lambda	-	0.9-9.99

Table 2. Fuel Properties and contents of percentages mixture

Property	Diesel	Methane	Hydrogen	
Molar Mass (kg/kmol)	≈200	16.04	2.02	1 Diesel
Density (kg/m ³)	840(l)	0.72(g)	0.082(g)	
Stoichiometric air/fuel. weight	14.7	17.2	34.3	2 0.75 Diesel 70 CNG 30 HD
Auto-ignition Temperature °C	254-285	595	585	
Laminar Flame Speed (cm/s)	128	42	230	3 0.5 Diesel 70 CNG 30 HD
Lower Heating Value (MJ/kg)	42.61	47.14	120.21	
Higher Heating Value (MJ/kg)	45.58	52.23	142.18	

Table 3. The fuel definitions and quantities

Fuel	Definition	Liquid Fuel Flow rate*	Gas Fuel Flow rates*	Mass %**	Energy %**	LHV**
Diesel	Non substituted, standard diesel oper.	2.17 g/sec	-	100	100	42.6 MJ/kg
HCNG ₁	7.5% H ₂ +17.5% CNG+75% Diesel	1.53 g/sec	8.2 l/min, 19.57 l/min	4.9	11.2	52.2 MJ/kg
HCNG ₂	15% H ₂ +35% CNG+50% Diesel	1.11 g/sec	8.2 l/min, 19.57 l/min	95.1	88.8	52.2 MJ/kg

* General one set test average (90 sec.) ** Adapted from Munshi S. R. [23]