EFFECT OF FUEL DELIVERY RATIO OF DIESEL-CNG DUAL FUEL ENGINE ON PERFORMANCE AND EMISSIONS

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ABSTRACT

Diesel fuel, which mainly used in transportation produces emission that contributes to global warming. Research advancement showed that the combination of Diesel-CNG fuel is able to reduce exhausts emissions. However, an uncontrolled dual fuel blending ratio with respect to operating load may cause poor engine performance with high hydrocarbon (HC) and carbon monoxide (CO) emissions compared to a diesel engine. The purpose of this study is to quantify the potential CNG fuel substitution at the specific engine load, to identify the blending limit of dual fuel ratio before the occurrence of knock, and to analyse the performance and emission between diesel engine and dual fuel engine. A 2.5 litre four cylinder diesel engine direct injection with common-rail was used as the experiment subject. The fuel ratio tested were 90 % DDF, 80 % DDF and 70 % DDF, which represents the diesel to CNG fuel mass ratio which are 90:10, 80:20 and 70:30 respectively. The result showed the performance of the dual fuel engine is lower than the diesel engine at 1500 rpm engine speed. At higher engine speed, 70 % DDF showed comparable performance as the diesel engine with a reduction of Nitrogen Oxide (NO_X) emission but high HC emission and some occurrences of knock phenomenon. It suggested that the blending limit of CNG fuel ratio should not exceed more than 70:30, and it was found suitable for operation at engine speed higher than 1500 rpm without any knock occurrence.

ABSTRAK

Bahan api diesel umumnya digunakan pada pengangkutan dan menghasilkan pencemaran yang menyumbang kepada pemanasan global. Kajian menunjukkan bahawa gabungan bahan api Diesel-Gas Asli Termampat (CNG) mampu menambahbaik pelepasan gas ekzos. Walaubagaimanapun, nisbah bahan api yang tidak dikawal pada beban enjin tertentu boleh menyebabkan kemerosotan prestasi enjin dengan pelepasan Hidrokarbon (HC) dan Karbon Monoksida (CO) yang lebih tinggi berbanding enjin diesel biasa. Tujuan kajian ini dijalankan adalah untuk mengenalpasti nisbah bahan api CNG yang berpotensi ditambah pada beban enjin tertentu, menentukan had campuran bahan api CNG dan diesel sebelum enjin mencapai fenomena ‘ketukan’, dan menganalisa perbandingan prestasi dan pelepasan gas ekzos diantara enjin diesel dan enjin bahan api berkembar diesel-CNG. Kajian ini menggunakan sebuah enjin diesel empat silinder bersuntikan terus dengan ‘*commonrail*’ yang berkapasiti 2.5 liter. Nisbah bahan api ditentukan dengan 90 % DDF, 80 % DDF dan 70 % DDF merujuk kepada nisbah jisim diesel kepada CNG iaitu, 90:10, 80:20 dan 70:30. Hasil mendapati bahawa prestasi enjin dwi bahan api adalah lemah daripada enjin diesel pada kelajuan 1500 rpm. Pada kelajuan enjin yang lebih tinggi, 70 % DDF menunjukkan peningkatan prestasi yang memberangsangkan berbanding enjin diesel dengan pengurangan pelepasan Nitrogen Oksida (NO_{X}) tetapi menghasilkan Hidrokarbon (HC) yang tinggi disamping berlakunya fenomena ‘ketukan’. Kajian ini mencadangkan bahawa had campuran bahan api CNG adalah tidak melebihi nisbah 70:30 dan ianya sesuai beroperasi pada kelajuan enjin lebih daripada 1500 rpm tanpa berlakunya sebarang ‘ketukan’.

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ABBREVIATIONS AND NOMENCLATURES

ADC	-	Analogue to Digital Converter
B5	-	Biodiesel with 5% PME
B7	-	Biodiesel with 7% PME
BMEP	-	Brake Mean Effective Pressure
BSEC	-	Brake Specific Energy Consumption
BSFC	-	Brake Specific Fuel Consumption
C_2H_6	-	Ethane
C_3H_8	-	Propane
C_4H_{10}	-	Butane
C_5H_{12}	-	Pentane
$C_6+(C6H_{14})$	-	Hexane
CA	-	Crank Angle
CAN	-	Controller Area Network
CH_4	-	Methane
CI	-	Compression Ignition
CN	-	Cetane Number
CNG	-	Compressed Natural Gas
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide
COV	-	Coefficient of Variation
DDF	-	Diesel Dual Fuel
DIN	-	Deutsche Industrienorm
DOHC	-	Dual Over-Head Camshaft
ECU	-	Engine Control Unit
EEPROM	-	Electrically Erasable Programmable Read Only Memory

EEV	-	Energy Efficient Vehicle
EFI	-	Electronic Fuel Injection
EGR	-	Exhaust Gas Recirculation
HC	-	Hydrocarbon
HRR	-	Heat Release Rate
IMEP	-	Indicated Mean Effective Pressure
KOH	-	Potassium Hydroxide
LFL	-	Lower Flammable Limit
LHV	-	Lower Heating Value
LNG	-	Liquid Natural Gas
MAN	-	Maschinenfabrik Augsburg-Nurnberg
MFI	-	Multiport Fuel Injection
MIPS	-	Mega Instructions Per Second
MPa	-	Mega Pascal
MPU	-	Microprocessor Unit
MS	-	Malaysia Standard
N_2	-	Nitrogen
NAP	-	National Automotive Policy
NO_X	-	Nitrogen Oxide
NREL	-	National Renewable Energy Laboratory
O_2	-	Oxygen
OBD	-	On-Board Diagnostic
PME	-	Palm Methyl Ester
ppm	-	Parts Per Million
pS/m	-	Pico Siemens per meter (Conductivity)
RISC	-	Reduced Instruction Set Computing
RM	-	Ringgit Malaysia
RON	-	Research Octane Number
rpm	-	Revolution Per Minute
SAE	-	Society of Automotive Engineers
SI	-	Spark Ignition

STP	-	Standard Temperature and Pressure
TDC	-	Top Dead Centre
UFL	-	Upper Flammable Limit
USA	-	United States of America
WHO	-	World Health Organization
^{o}C	-	Degree Celsius
λ	-	Lambda
ϕ	-	Equivalence Ratio

CHAPTER 1

INTRODUCTION

1.1 Background Study

Fossil fuel is a non-renewable resource and is depleting towards extinction. The combustion of fossil fuel emits pollution, causing global warming, climate change and harmful to creatures and nature. The awareness of this global issue has encouraged researchers to make improvements on alternative fuels since over few decades ago.

The World Health Organization (WHO) emphasizes that the transport sector is the main contributor of black carbon and certain ozone precursors (WHO, 2015). Based on a policy paper by Perschon (2012), there are three actions that can be classified to reduce the emission from transportation sector; AVOID, SHIFT and IMPROVE. The AVOID category is to reduce travel distance by rerouting journeys or relocating buildings through smart urban planning. The SHIFT category is giving priority to use low emission modes of transport in term of reducing total traffic emissions. The IMPROVE category focuses on reducing vehicle emission without affecting the mode of transport by technological approaches such as the innovation of fuel types from diesel to the natural gas. The use of natural gas for fuel alternative is the best way since its most abundant, clean and less polluting compared to common petroleum fuels.

Natural gas fuel is divided into two types, which are Liquid Natural Gas (LNG) and Compressed Natural Gas (CNG). The LNG was converted from the gaseous form to the liquid form by cooling natural gas until it condensed near to the atmospheric pressure. Using the LNG for internal combustion engine, a special storage tank with thermal insulation is used to keep the natural gas in liquid form. The use of CNG for internal combustion engine can be achieved by three types of fuel delivery system; bi-fuel, mono-fuel and dual fuel, depending on the stock ignition system either Spark Ignition (SI) or Compression Ignition (CI). The CNG bi-fuel system is widely used for SI engine because of the CNG requires a source of ignition such as spark plug, similar to gasoline fuel.

However, CNG has a high octane number and it is suitable for high compression engines. When using CNG on the CI engine, the fuel is unable to self-ignite due to the auto-ignition temperature and pressure for CNG is relatively higher than diesel. Therefore, the source of ignition is needed to ignite the combustion.

The conversion from the CI engine to the SI engine can be done through the major modification. However, the installation of ignition system and modification on the compression ratio needing much effort to accomplish. Therefore, an alternative way to avoid this major modification is using the dual-fuel system.

The dual fuel system uses two different fuels for pilot fuel and main fuel. An additional fuel delivery system for CNG fuel can be installed on the existing stock engine without modifying any engine geometry and design. The combination of 10% - 30% of CNG as the main fuel and 70% - 90% of diesel as a pilot fuel is possible to ignite the combustion. Therefore, the conversion process for Diesel-CNG dual fuel engine is worth and more efficient compared to others.

1.2 Problem Statement

In an actual Diesel-CNG dual fuel engine, the fuel ratio substitution is not necessarily constant but dependent on specific engine load. The ignitability of this mixture proportion can easily be achieved by using default mixture preparation method without major modification of the stock diesel engine. However, the dual fuel engines showed poor brake power, poor combustion efficiency, high unburned hydrocarbon (HC) and carbon monoxide (CO) emission (Papagiannakis & Hountalas, 2004). An excessive CNG fuel is one of the culprit lead to the knock occurrence which is a known factor that causes damage to Diesel-CNG dual fuel engine. Therefore, the fuel ratio for this type of engine poses an opportunity for further scrutinization and optimization over a specific range of engine operating load.

1.3 Objectives

The objectives of this study are:

1. To quantify the diesel fuel mass delivered across the whole engine operating range.
2. To identify the blending limit of Diesel-CNG dual fuel ratio before knock phenomenon occurrence.
3. To analyse the engine performance and exhaust gas emissions of diesel single fuel and Diesel-CNG dual fuel.

1.4 Scopes of Study

The scopes of this study are as below:

1. The engine studied is a 4 cylinders 2.5 litre diesel engine with common-rail direct injection (2KD-FTV)
2. The measurement of fuel delivery were made by using the 90:10. 80:20 and 70:30 of diesel to CNG mass fuel ratios within the operating range from 1500 to 3500 rpm engine speed on a chassis dynamometer.
3. The engine performance was determined in terms of power, torque and specific fuel consumption, while the exhaust emission analysed are hydrocarbons (HC), Carbon Monoxide (CO) and Nitrogen Oxide (NO_X).

1.5 Significance of Study

This study explored the dual fuel delivery ratio especially at high load engine operation, which emits high HC and CO pollution. The findings of this study can be used to suggest a suitable fuel delivery options for Diesel-CNG dual fuel vehicles. This study may also be a jumping-off point towards:

1. Reducing the dependency on diesel fuel to achieve a part of the Tenth Malaysia Plan 2010.
2. Increasing energy (fuel) efficiency in transportation to fulfil The National Automotive Policy 2014.
3. Reducing the carbon equivalent environmental pollution to meet The National Green Technology Policy 2009.
4. Help opposing the climate change (Kyoto Protocol 2008-2020).

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Nowadays, the world is facing challenges against the disadvantages of petroleum fuel. The dwindling supplies and high market demand of crude petroleum oil have been causing unstable price recently. Although the crude petroleum price decreases, the refining cost remains high. In addition, the worsening pollution from the combustion of petroleum fuel has encouraged researchers to find other energy resources with the lowest greenhouse gas emissions.

In recent decades, the evolution of diesel engine technology was focused on the prevention of global warming via low CO_2 emission (Nagata, Tanaka, & Yano, 2004). However, this energy resource is unsustainable since it is utilized more than it produced.

As of January 2012, World Proved Reserves of Oil and Natural Gas stated that world natural gas reserved has the capacity of 6.793 billion cubic feet, while oil reserved has the capacity of 1.637 trillion barrels (Oil & Gas Journal, 2012).

Natural gas is not a renewable fuel but it has abundant resources and the lowest average specific CO_2 emission among the non-renewable fossil fuel energy resources (Edenhofer et al., 2012). Therefore, it has a high potential to replace a part of an existing petroleum fuel.

The Malaysian National Green Technology Policy was launched by the Prime Minister of Malaysia on 24th July 2009. This policy aims to minimize the degradation of the environment while conserving the use of energy and natural resources. The target is to reduce 40% of carbon equivalent emission by the year 2020 (National Green Technology Policy, 2009).

Recently, National Automotive Policy 2014 (NAP 2014) was launched in January 2014 with a vision of transforming the competitiveness of Malaysian automotive industry to face the global challenges. One of the objectives of the NAP 2014 is to develop Malaysia as a regional automotive hub in Energy Efficient Vehicles (EEV) (NAP, 2014). Global definition of an EEV is a vehicle that meets a specific limit of carbon emission level (CO_2/km) and fuel consumption (litre/km).

Most shipping and logistic companies, particularly in Malaysia use diesel fuel in their medium-duty, heavy-duty engines and prime mover vehicles. All these vehicles partly contribute to the pollution of our green environment. Alternatively, the exhaust emission from using compressed natural gas (CNG) fuel is more environmentally friendly compared to diesel. A study done by Battelle, NREL and West Virginia University which using CNG on modified diesel trucks was showing a significant improvement in exhaust emission. The CNG engines may produce 25% lower CO, 49% lower NO_X and up to 95% lower Particulate Matter (PM) compared to the standard diesel engine (Chandler et al., 2002). A demonstration done by Addy et al. (2000) also showed the Diesel-CNG dual fuel engine was comparable to the diesel engine with better performance, emissions and economy. With CNG combustion, such emissions are inherently reduced relative to diesel fuelled engines due to the nature of the combustion and the molecular makeup of the fuel (Dahodwala et al., 2014).

The cost of CNG fuel and CNG engine maintenance is also more economical compared to the standard diesel engine (Shiraiwa et al., 2013). In Malaysia, after subsidized as of October 2016, the cost of CNG is RM1.05/litre while the cost of diesel is RM1.75/litre. Due to the awareness and long term benefit of green technology and sustainability of using CNG fuel, many companies have started to modify their diesel vehicles to either dual fuel Diesel-CNG vehicles, or mono fuel CNG vehicles.

2.2 Diesel Fuel

Effective from July 2014, the diesel sold in Malaysia contains 5% of biodiesel (B5). Furthermore, the Malaysian government has announced to increase the biodiesel percentage to 7% effective in January 2015 (The Star, 2014). Therefore, currently all diesel fuel sold in Malaysia composed of 93% diesel and 7% biodiesel. In Europe, USA and other parts of the world, such blend, is termed biodiesel. The 5% biodiesel, although having similar energy content, may have a higher viscosity, which cause an atomization problem during small quantity fuel injection. Although that is the case, the use of biodiesel as the pilot fuel is still favourable action to minimize life-cycle CO_2 emission (Kawasaki & Yamane, 2007).

In Malaysia, there is no specific name for biodiesel fuels and was classified as the diesel fuel by Malaysian Standard. In order to ensure the blended diesel fuel fulfilled the requirements set by the government, the first diesel standard MS123:2005 was published by Malaysian Standard in 2005 (Malaysia Standard, 2010). From the onwards, Malaysian Standard keeps updating the diesel standard according to the current blend set by the government. As the government announced to increase the fuel blends, MS123:2014 was published which targets the 7% composition of Palm Methyl Ester (PME) in diesel (Malaysian Standard, 2014). Currently, the latest standard for diesel is MS123:2016 with a revision for a maximum of 7% PME to be included in all diesel fuel (Malaysian Standard, 2016).

In Malaysia's domestic market, there are several types of diesel produced by different manufacturers. The manufacturer also provides diesel with a different properties to fulfil the market demands, whether for vehicle or heavy industries purposes. Same goes to the gasoline with Research Octane Number (RON), the Cetane Number (CN) is used to indicate the combustion quality of diesel. As tabulated in Table 2.1, the different manufacturers produce the different properties of diesel.

Table 2.1 : Properties of diesel available in Malaysia (Petron, 2014; Petronas, 2005)

Properties	**Petronas High Speed Diesel**	**Petronas Dynamic Diesel (Euro 2M)**	**Petron Diesel MAX**
Biodiesel Type	Diesel	Biodiesel B5	Biodiesel B7
Cetane Number, (CN)	55	49	54
Ash, Mass %	0.002	0.01	<0.01
Pour Point, °C	9	15	9
Flash Point, °C	91	60	63
Kinematic Viscosity at 40 °C, mm^2/s	4.0	1.5-5.8	2.9
Copper Corrosion (3 h at 100 °C)	1	1	1
Density at 15 °C, kg/l	0.8443	0.810-0.870	0.8314
Acid Number, mg KOH/g	0.1	0.25	-
Electrical Conductivity, pS/m	-	50	243
Distillation at 95%, °C	365.7	370	369
Total Sulphur, mg/kg	-	500	330
Lubricity, µm	-	460	240

2.2.1 Diesel Direct Injection with Common-rail

Diesel engine is an internal combustion engine and the fuel ignites by compression method. It was developed by Rudolf Diesel in 1897 with cooperation by Maschinenfabrik Augsburg-Nurnberg (MAN). His idea was to design a greater efficient engine than the steam engine which was widely used around that time.

In the beginning of the diesel engine production, its fuel delivery system is fully mechanical controlled. The conventional diesel engine uses a governor to regulate and inject the diesel fuel mechanically to fulfil the engine demand. The passage of time has led inventors to apply the electrical principle on this mechanism in order to control the fuel injection independently.

The latest technology for diesel fuel delivery system is the common-rail system, which adapted from the gasoline EFI system. Compared to the conventional system (governor), the common-rail system is able to supply the fuel at high pressure without being affected by engine speed. This process is important to ensure diesel fuel atomization occurs in the cylinder as early as the engine cold start. Nowadays, the latest diesel common-rail technology is able to supply the high pressurized of diesel higher than 250 MPa by the several improvements as shown in Figure 2.1. Data from the figure was obtained from Flaig et al. (1999), Dohle at al. (2004), Nagata et al. (2004), Kumano et al. (2006) and Matsumoto et al. (2013).

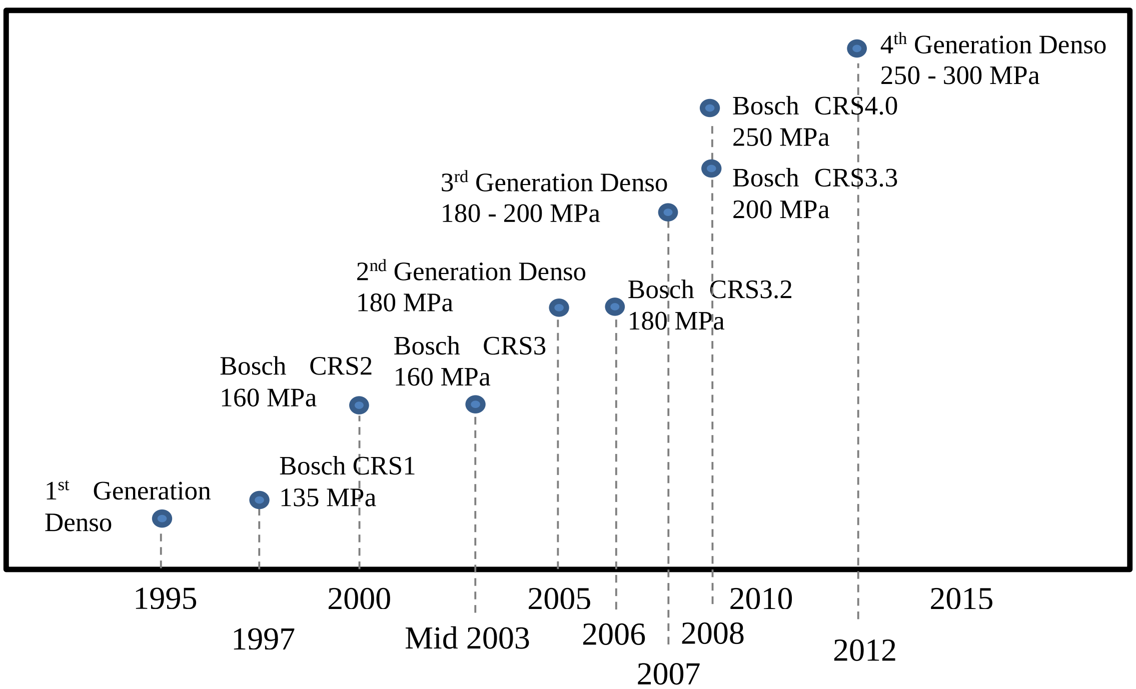

Figure 2.1 : Evolution of diesel common-rail technologies

In the common-rail system shown in Figure 2.2, the diesel fuel is transferred from the fuel tank into the fuel rail. The high pressurized fuel is stored in this rail and distributed to the injector. The injector has a solenoid valve and controlled by the Engine

Control Unit (ECU). Once the ECU received the signal from the camshaft positioning sensor, the ECU triggers that solenoid valve and the fuel is injected into the cylinder.

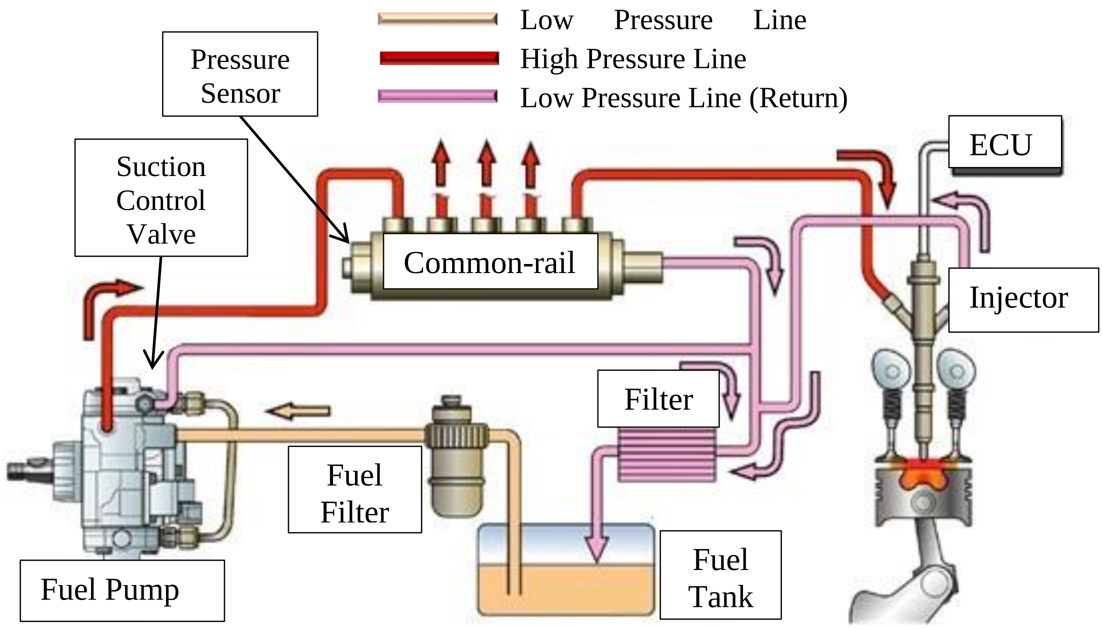

Figure 2.2 : Diesel direct injection with common-rail.

Because this system is fully controlled by the ECU, this system is not affected by the engine speed and load. It can ensure stable high pressure injection at overall engine load, as well as to optimize performance and emission.

2.2.2 Diesel Engine Management System

A modern diesel engine uses electronic control of fuel delivery system which is more flexible compared to mechanically control by a governor. With this, the high pressurized diesel is able to be supplied constantly at the any engine speed, in order to atomize the fuel injected.

An engine management system is a program to control any actuator based on the value from the input sensors as shown in Figure 2.3. The signals from the sensors are transmitted to the ECU. The ECU processes these signals and controls the actuators as it were programmed. The latest technology of engine management system uses closed loop control system. This system uses the feedback signal of each cycle to counter any error by applying a correction value (Denso Corporation, 2004).

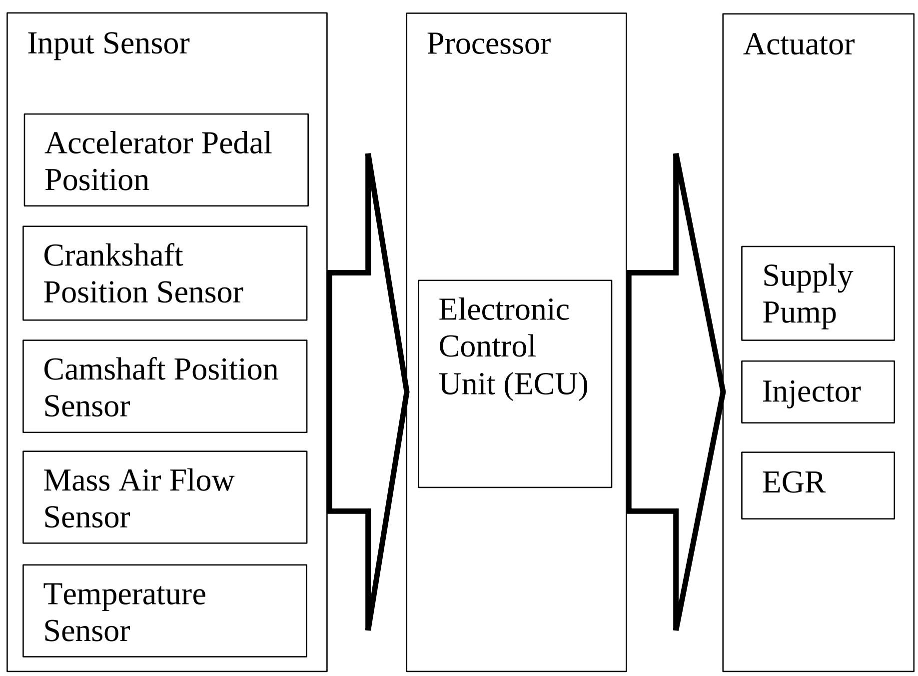

Figure 2.3 : The basic operation of engine management system (Denso Corporation, 2004)

The main component of the engine management system is the ECU which is integrated from several modules such as, microprocessor module, memory module, communication module, sensor driver, actuator driver and the others. Different ECU has different architecture structure, depends on the developers idea and strategy to manage the engine system. Figure 2.4 shows an example of an ECU architecture structure manufactured by Bosch (Walker & Fauvel, 1987).

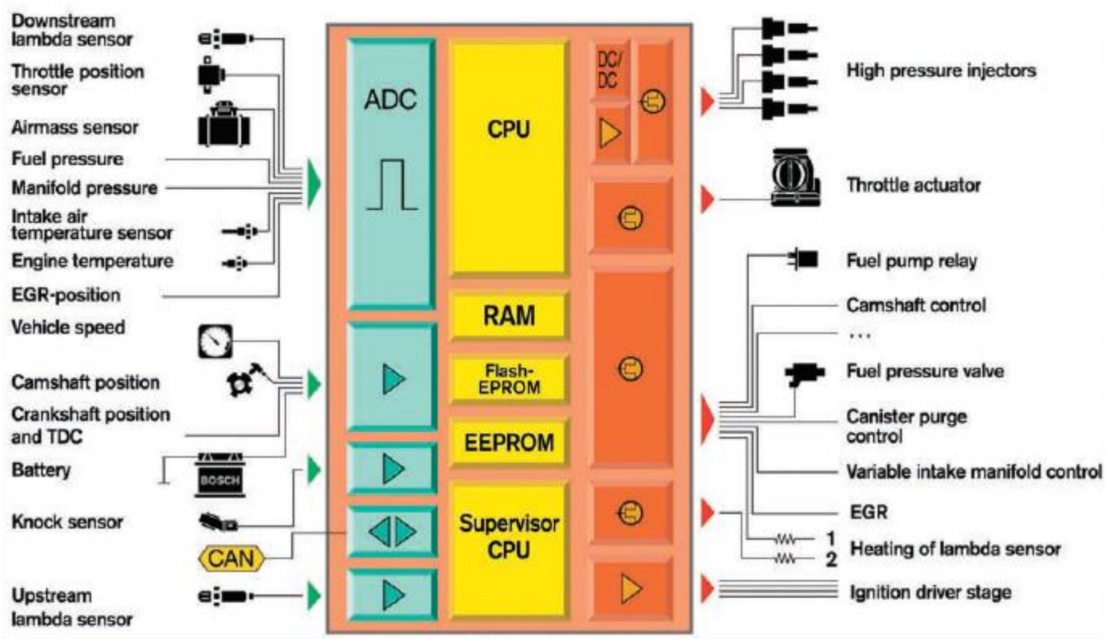

Figure 2.4 : Architecture structure of the Bosch ECU (Walker & Fauvel, 1987)

The main components of the ECU are Microprocessor Unit (MPU) and memory, which act as a system brain. The MPU performance is evaluated by speed operation which has an ability to capture and process data as fast as possible.

The 2nd generation Denso common-rail technology uses a 32bit Reduced Instruction Set Computing (RISC) Core of MPU which is able to operate around 100 Mega Instructions Per Second (MIPS) (Nagata et al., 2004). This MCU is integrated with the Timer Module, Analogue to Digital Converter (ADC) and Crank Angle Counter to achieve the sophisticated injection control strategy. The 4M embedded FLASH memory is used as a memory module and the program is written by Electrically Erasable Programmable Read Only Memory (EEPROM).

The program written in the ECU contains the operating map which reads the value from multiple sensors and gives the signal to actuator as commanded in the programming. The operating map is interpreted in multidimensional graph and the fraction of operating map can be presented in the lookup table as an example shown in Figure 2.5.

Engine Speed (rpm)

Injection Pressure (MPa)

Accelerator Pedal Position (%)	500	1000	1500	2000	2500	3000	4000	5000
0	100	100	85	80	75	65	60	45
5	100	100	90	85	75	65	60	50
10	115	100	100	90	80	70	65	60
15	125	100	100	100	85	80	70	65
20	150	160	[illegible]	[illegible]	[illegible]	85	80	70
30	165	175	[illegible]	[illegible]	[illegible]	90	85	80
40	185	175	175	140	100	100	90	85
50	195	200	195	150	140	100	95	95
60	200	200	200	175	175	160	100	100
70	215	220	220	200	185	175	125	125
80	240	240	220	210	200	175	150	125
100	255	240	220	210	200	175	150	125

Figure 2.5 : Example of lookup table for fuel injection value against the engine speed and accelerator pedal position

Figure 2.5 shows the lookup table for injection pressure against the engine speed and accelerator pedal position. The engine speed and accelerator pedal position are the inputs variable and the injection value is an output. According to Figure 2.5, when the engine runs at 2500 rpm and the accelerator pedal position at 15 %, the injection pressure output is 85 MPa.

2.2.3 Fuel Delivery Map

The fuel delivery map is a main part of the engine management system which controls the engine operation. It controls the actuator likely injectors to deliver fuel as programmed in the operating map such as injection timing and injection quantity.

The terms of 'fuel map' was difficult to understand because of its scarcity in the open literature (Imran et al., 2014). Vora (1997) was defined the 'engine mapping' is a process for characterization of the engine performance through the experiment as a function of the selected variable.

The map can be the ECU set value or experimental result and can be presented as two or three dimension graph and the number of variable is unlimited. The Figure 2.6 showed the example of contour map of BSFC and lambda.

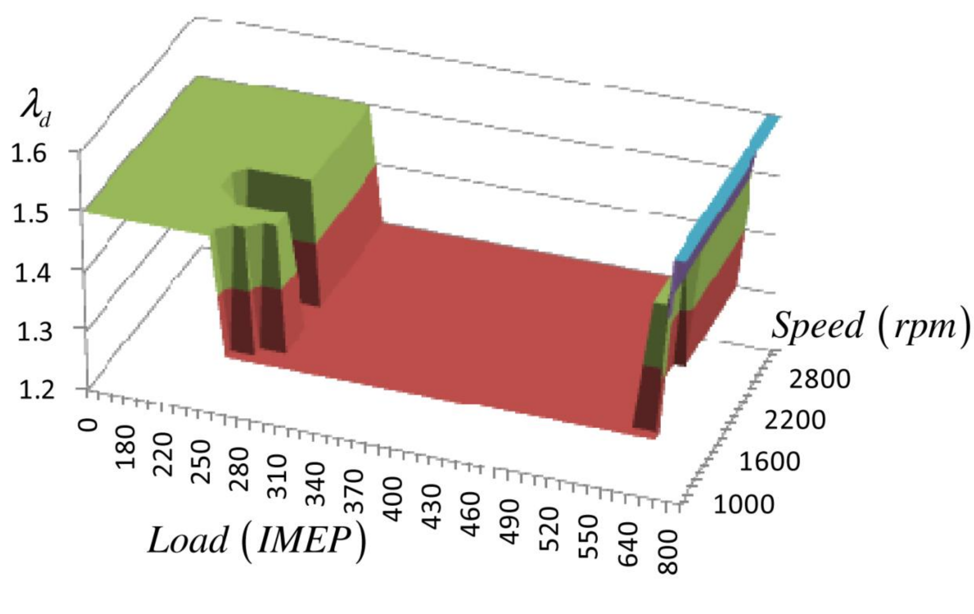

Figure 2.6 : Map of lambda as a function of load and engine speed (Chatlatanagulchai et al., 2010)

2.2.4 Diesel Fuel Injection Quantity

Diesel fuel injection quantity is controlled by the ECU through the input signal from the sensors. The difference between the conventional and common-rail diesel engine is the fuel controller system. The conventional diesel engine uses a mechanical controller such as governor to control and regulate diesel fuel quantity meanwhile the common-rail diesel engine uses an electrical controller.

The engine of Toyota Hilux 2.5 L uses common-rail system in which the fuel quantity is controlled by a programmed ECU as shown in Figure 2.7. The calculated injection fuel quantity consists of the basic injection quantity and maximum injection quantity (Denso Corporation, 2004).

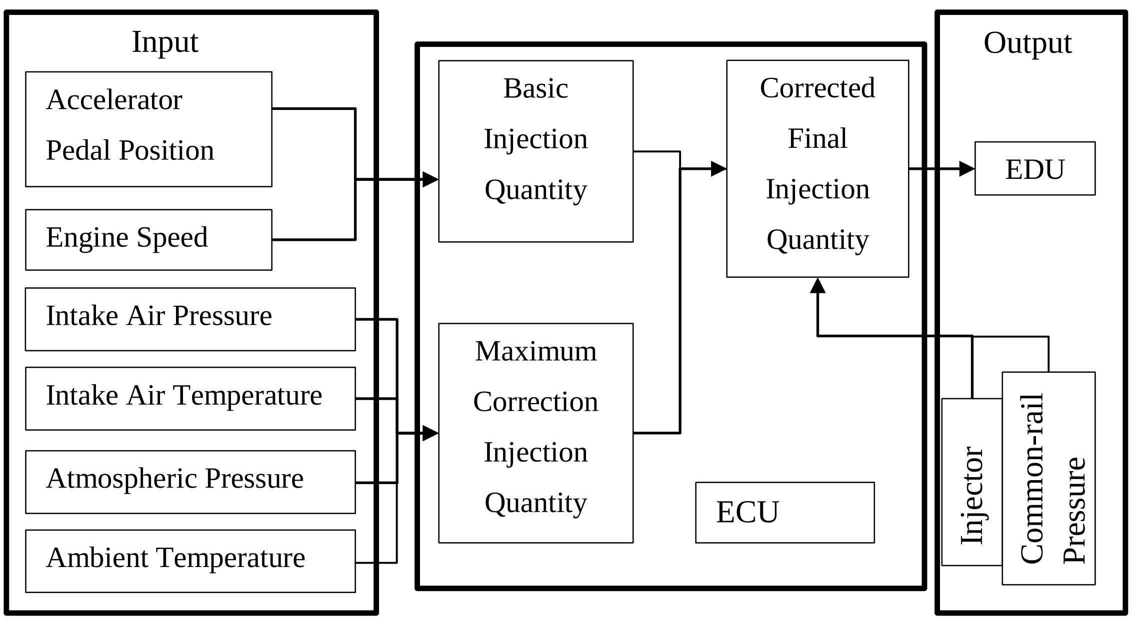

Figure 2.7 : Diagram for controlling injection fuel quantity (Denso Corporation, 2004)

The basic injection quantity is adapted from the governor system pattern and programmed to the ECU. The maximum injection quantity is the correction factor according to the intake air pressure, intake air temperature, atmospheric pressure and ambient temperature. Both basic and maximum injection quantities are combined for final correction. At this final correction, the injection quantity is corrected by a feedback signal from diesel injector and common-rail pressure sensor. The feedback value signal came from the previous engine cycle for the improvement on the next engine cycle.

2.3 Compressed Natural Gas (CNG)

Natural gas is found in petroleum reservoir and a mixture of several types of gases, which contains up to 80% to 90% of methane (CH_4) concentration, ethane (C_2H_6), propane (C_3H_8), Butane (C_4H_{10}), pentane (C_5H_{12}), and other inert gases. This gas is derived by buried animals, plants and microorganisms since over millions ago, similar to petroleum and coal. Natural gas is colourless, pungent odour and not irritating to skin and eyes (Gas Malaysia, 2015). The composition of natural gas is shown in Table 2.2.

Table 2.2 : The Composition of Natural Gas (Doijiode et al., 2013)

Composition	**Formula**	**Percentage (%)**
Methane	CH_4	92.69
Ethane	C_2H_6	3.43
Propane	C_3H_8	0.71
Iso-Butane	i-C_4H_{10}	0.12
N-Butane	n-C_4H_{10}	0.15
Pentane	C_5H_{12}	0.09
Nitrogen	N_2	2.18
Carbon Dioxide	CO_2	0.52
Hexane	C_6+(C_6H_{14})	0.11

The properties of natural gas are different based on the particular sources and end-user (Ly, 2002). The study conducted by Steven R. King in 1992 shows the natural gas sold around United States of America (USA) has the different composition and affects the engine performances and emissions (King, 1992). Several samples of gases with different compositions were shown in Table 2.3.

Table 2.3 : Composition and Properties of Different Natural Gas (King, 1992).

	A (%)	**B (%)**	**C (%)**	**D (%)**	**E (%)**	**F (%)**	**G (%)**	**H (%)**	**I (%)**	**J (%)**	**K (%)**	**L (%)**
CH_4	94.2	88.7	95.3	75.8	90.0	84.2	65.1	46.5	89.0	100	0.0	0.0
C_2H_6	2.8	4.7	2.6	11.2	4.9	8.6	2.2	1.6	11.0	0.0	100	0.0
C_3H_8	0.6	1.3	0.5	0.9	2.2	3.7	16.4	28.7	0.0	0.0	0.0	100
C_4H_{10}	0.1	0.4	0.2	0.1	1.1	2.1	0.3	0.2	0.0	0.0	0.0	0.0
C_5H_{12}	0.1	0.1	0.1	0.0	0.4	0.0	0.1	0.1	0.0	0.0	0.0	0.0
C_6+(C_6H_{14})	0.0	0.1	0.1	0.0	0.4	0.0	0.1	0.0	0.0	0.0	0.0	0.0
CO_2	0.7	0.7	0.8	2.8	0.7	0.6	0.5	0.4	0.0	0.0	0.0	0.0
N_2	1.5	4.0	0.4	6.9	0.3	0.8	12.3	18.0	0.0	0.0	0.0	0.0
O_2	0.0	0.0	0.0	2.3	0.0	0.0	3.0	4.5	0.0	0.0	0.0	0.0

By using the five samples which were A, B, C, D, and E, the equivalence ratio and emission show the different results as shown in Table 2.4.

Table 2.4 : The Equivalence Ratio and Emission of Different Natural Gas (King, 1992).

	A	**B**	**C**	**D**	**E**
Equivalence Ratio, ϕ	0.680	0.664	0.688	0.596	0.708
NO_X (g/hp-hr)	3.0	2.1	3.6	0.4	5.2
THC (g/hp-hr)	1.3	1.6	1.1	11.8	0.9
CO (g/hp-hr)	1.5	1.6	1.4	2.9	1.3

In Malaysia, the natural gas is produced by Petronas Gas Berhad and the property as proved on 1st May 2015 is shown in Table 2.5.

Table 2.5 : The Properties of Natural Gas manufactured by Petronas Gas Berhad (Gas Malaysia, 2015)

Methane	92.73 %
Ethane	4.07 %
Other Hydrocarbons	3.20 %
Boiling Point	-162 °C
Vapour Density	0.747 kg/Sm^3 @ 760 mmHg
Specific Gravity	0.61 @ 760 mm Hg
Flash Point	-187 °C
Auto Ignition Temperature	537 °C
Upper Flammable Limit (UFL)	15.4 % vol.
Lower Flammable Limit (LFL)	4.5 % vol.

Natural gas has a high specific heat capacity ratio compare to the air (Imran et al., 2014). The higher number of H/C ratio produces 25% less CO_2 compared to gasoline and diesel. The energy content in a certain volume of stoichiometric air-fuel mixture of CNG is about 10% lower compared to gasoline. The increasing of thermal efficiency can overcome this problem (Unich et al., 2015).

2.4 CNG Fuelled Engine

CNG is being used for internal combustion engine by three common methods such as mono-fuel, bi-fuel, and dual fuel. The application of the methods used is depend on the characteristic of the engine itself in term of the geometry and the stock ignition system.

The CNG mono-fuel engine is widely used on heavy duty CI engines. The conversion from the Diesel cycle to Otto cycle is done through major modification of the engine. Besides the installation of the ignition system, a reduction of the compression ratio is needed to overcome the knocking phenomenon. The redesigning geometry of the piston is required to ensure the stable combustion. An engine with large bore diameter, the pre-chamber ignition system is used for spark plug installation. In the pre-chamber, the spark plug is combined with the injector and igniting the rich air-fuel mixture. Then, this combustion flows into the main combustion chamber turbulent jet formation trough the orifices (Heyne et al., 2011)(Ryan et al., 2015).

A study conducted by Azmir et al. (2013) showed that performance of CNG mono-fuel is lower than the standard diesel engine. The HC, CO and NO_X emission were higher than standard diesel engine but the CO_2 emission showed 38 % reduction as shown in Figure 2.8.

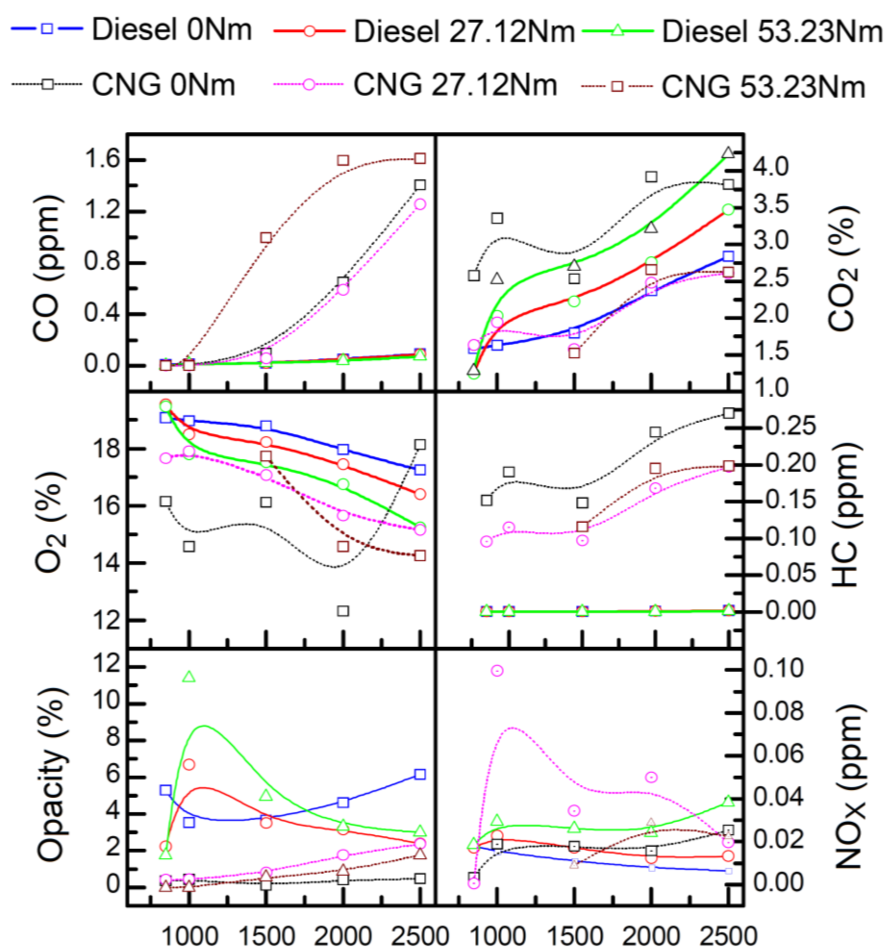

Figure 2.8 : Comparison of CNG mono fuel and diesel engine (Azmir et al., 2013).

The CNG bi-fuel engine is widely used for the SI engine such as a gasoline engine, since the CNG combustion is similar to the Otto cycle. This bi-fuel engine is able to switch between two modes, either 100 % CNG fuel mode or 100 % gasoline fuel mode. The conversion process is done by simple installation for fuel delivery system without any major modification. Since the CNG's performance is quite similar to the gasoline engine, the CNG bi-fuel engine is practically used to reduce the exhaust emission and fuel cost.

Another option to use CNG on the CI engine is by using dual fuel system. This system uses CNG as the main fuel and diesel as the pilot fuel. In this CNG dual fuel system, the CNG as the main fuel enters the combustion chamber premixed with air. Since the CNG has a high octane number, it demands a source of ignition to ignite the combustion. Therefore, a small quantity of diesel is injected into the combustion chamber as the pilot fuel. This pilot fuel will self-ignite as it achieves its auto-ignition temperature and pressure. Then, the pilot fuel combustion will ignite the CNG fuel.

The combustion of dual fuel engine combines the Otto and Diesel cycle (Christopher S. Weaver, 1994). The study conducted by Felt and Steel, they conclude that dual fuel engine was a non-throttled Otto cycle engine which power was controlled by the amount of burned fuel (Felt & Steele, 1962). According to Hakim, Fawzi, & Azmir (2015), the typical fuel ratio of the Diesel-CNG dual fuel engine is about 70% of the CNG and 30% of the diesel due to the ignitability by using this fuel ratio. However, the specific dual fuel ratio depends on the particular engine load. A study by (Dahodwala et al., 2014) showed a possibility to obtain a substitution up to 90% CNG. An experiment conducted by Lim et al. (2012) showed the power output for 90% of CNG substitution was slightly higher than an existing diesel engine.

Christopher S. Weaver (1994) stated that CNG diesel dual fuel engine is highly useful because it can operate interchangeably between diesel single fuel and Diesel-CNG dual fuel engine. The engine is able to operate in the diesel single fuel mode when the CNG supply was not available in certain area. The situation given by him is quite similar to Malaysia where the CNG refuelling station is available in certain areas only.

Because of the dual fuel engine still uses the compression ignition system, the engine conversion is done by installing the CNG fuel delivery system only. Therefore, the time taken for this conversion is shorter than the mono-fuel and the bi-fuel system. Since the ignition system modification is not required, the conversion cost will be lower than the others. A comparison of CNG mono fuel, bi-fuel and dual fuel engine conversion is tabulated in Table 2.6.

Table 2.6 : Comparison of CNG Fuel Delivery System Conversion on Compressed Ignition Engine

	CNG Mono-Fuel	**CNG Bi-Fuel**	**CNG Dual Fuel**
Interchangeable Fuel	**No**	**Yes**	**Yes**
Conversion Process	**Difficult** Need major modification on engine geometry, ignition and fuel delivery system.	**Difficult** Need major modification on engine geometry, ignition and fuel delivery system.	**Easy** Installation of CNG equipment without modifying the engine geometry.
Conversion Cost	**High** Replacing the ignition system and fuel delivery system.	**High** Additional ignition system and CNG fuel delivery system are needed.	**Low** Additional CNG fuel delivery system is needed.

Based on the literature, it can be summarized the method used for CNG fuelling method on the CI engine is depended on the geometry of the engine. The CNG mono fuel and bi-fuel needs the sufficient space for spark plug installation and major modification is required to adapt the ignitability of fuel. The piston profile for CNG mono-fuel and bi-fuel need to be considered due to the original compression ratio is dedicated for diesel fuel properties. Therefore, the conversion of CNG bi-fuel is more difficult than the mono fuel because its compression ratio needs to suit the both the diesel and CNG fuel.

However, the CNG dual fuel method is an easier way to use CNG fuel on the diesel engine. The conversion is done by a simpler installation with lower cost. Furthermore, the CNG dual fuel system is most practical for the transportation where CNG supplies are limited in the certain area.

2.5 Diesel-CNG Dual Fuel Engine

The performance and emission of Diesel-CNG Dual Fuel engine are affected by several factors. Besides fuel delivery method, the main root cause affected the performance and emission are dual fuel quantity and ratio. The other factors such as, pilot injection timing, pilot injection quantity, intake temperature and the others are considered as correction factors.

2.5.1 Fuel Delivery Method

The CNG fuel can be supplied either using an induction method or injection method. The induction method is the conventional system, which had been used around decades ago. The technology developed for the engine management system insists the evolution of the CNG fuel delivery system, from the mechanical to the electronic control. Therefore, the fuel delivery process becomes more flexible to fulfil the engine demands.

The induction method is a technique when the fuel mixture is drawn into the combustion chamber. This method uses a component which referred to as a ‘mixer’ and operated by Venturi effect, similar to carburettor system for gasoline engines. The air flow in the intake manifold produces pressure reduction and drawn the CNG through a Venturi tube. The CNG mixes with air in the intake manifold and inducted into the cylinder.

The injection method is controlled by electronic system which the injectors are an electromechanical element. The injector mechanical valve is controlled by electric current through a solenoid and this valve is of Normally Closed (NC) type.

The direct injection method is similar to diesel direct injection operation where is the gas injector is placed on the combustion chamber. The gas injector is integrated either with diesel injector or glow plug, due to the several limitations on the dimension and geometry of engine design.

The port injection method is similar to the Electronic Fuel Injection (EFI) or Multiport Fuel Injection (MFI) in gasoline engines. The gas injectors are placed at the intake manifold near the inlet valve. According to Doijiode et al. (2013), the CNG port injection method showed better performance compared to induction method as shown in Figure 2.9.

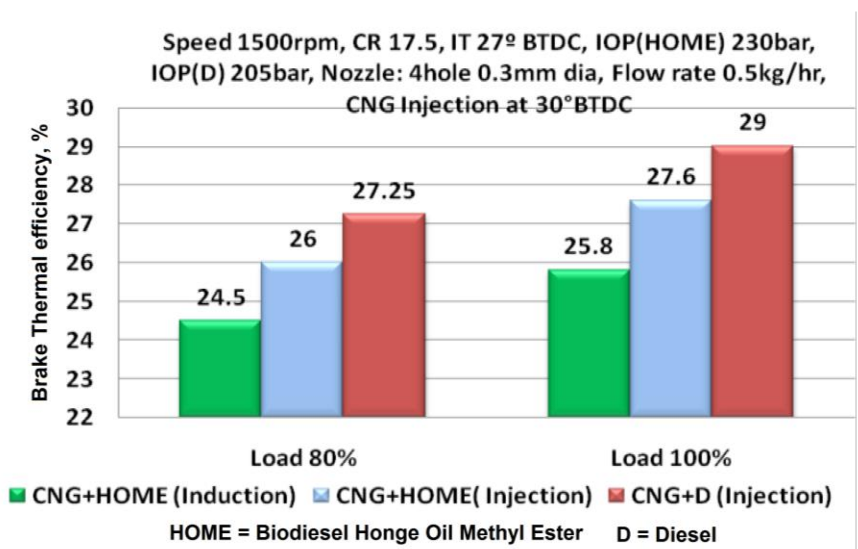

Figure 2.9 : Comparison of brake thermal efficiency between CNG induction and injection method (Doijiode et al., 2013)

The brake thermal efficiency for injection method was better than induction method. The HC emission and CO emission for injection method were lower than induction method. However, the NO_X emission for an injection method was higher than induction method (Doijiode et al., 2013).

2.5.2 Dual Fuel Ratio

As stated in subchapter **1.2**, the fuel ratio for Diesel-CNG dual fuel engine must not be constant but dependant on specific engine load. Hakim et al. (2015) stated the typical ratio of CNG to Diesel was about 70:30 due to the ignitability by using this fuel ratio. Dahodwala et al. (2014) and Lim et al. (2012) showed the possibility to obtain a substitution up to 90 % of CNG fuel with higher power output than a diesel engine.

Researchers used various fuel ratios in their study, according to their objective and method of the experiment. Papagiannakis & Hountalas (2004), Wannatong, Akarapanyavit, Siengsanorh, & Chanchaona (2007) and Lounici et al. (2014) used the following expression to represent the percentages of CNG mass fuel ratio:

$$\%\ \text{CNG}\ (Z) = \frac{\dot{m}_{CNG}}{\dot{m}_{Diesel} \times + \dot{m}_{CNG}} \times 100 \qquad (2.1)$$

Meanwhile, Aroonsrisopon et al. (2009) and Yang, Xi, Wei, Zeng, & Lai (2015) conducted the experiment by modifying the previous equation to express the percentages of the CNG energy fuel ratio. The percentages of the CNG substitution were calculated by an equation:

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