FUEL SAVING WITH HCNG IN THE INTERNAL COMBUSTION ENGINE

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ABSTRACT

Hydrogen and Compressed Natural Gas are great alternatives to the pure fossil fuels. Many researches confirm the advantages of using hydrogen and natural gas blended together for the internal combustion engine in both areas of improving performances and reducing emission levels. In a short to medium range terms, the air pollution around the globe could be significantly reduced by using HCNG in the internal combustion engine and in many other applications with the substitution of using HCNG as a main source of fuel or as a secondary source of fuel such as the dual fuel operation system in the diesel vehicle.

This paper investigates the performance characteristics, emission characteristics, smoke and fuel economy of using HCNG as a secondary source of fuels on a four cylinders D4D commonrail direct injection diesel engine comparing to the original diesel operation with diesel and HCNG blended operation. The experiment has been conducted with minimum pilot diesel injection into the engine and maximum additional HCNG as a secondary source of fuel to the internal combustion engine. It also examined the diesel consumption on the actual road with both pure diesel operation and diesel with HCNG operation on the chosen experimental diesel vehicle. In this experiment, the pilot diesel and HCNG blended were operated with special designed electronic controlled closed loop stepping motor diesel to CNG dual fuel system and hydrogen electrolyzer for the supply of hydrogen.

The results show that horsepower, torques and brake thermal efficiency of the engine increase with the diesel HCNG dual fuel operational mode comparing to the pure diesel operation by the average of 30%. The overall smoke also decreases by 10% with diesel HCNG operation as comparing to pure diesel operation resulting from increases of better engine efficiency and better lean burned combustion stability. With the total mass fuel consumption, the results reported that the distance travel per kilometer increased by 177% comparing to the normal distance travel with pure diesel alone. The results on the emission test in this experiment also indicated that the average CO emission decreased by 12.97%, HC emission decreased by 15.84%, NO_x emission decreased by 1.16% and PM emission decreased by 9.14% with the diesel HCNG dual fuel mode comparing to the pure diesel operation from lowest RPM of 800 rpm to highest RPM of 4000 rpm.

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ABBREVIATIONS

HCNG	=	A mixture of hydrogen and compressed natural gas
DDF	=	Diesel dual fuel
CO	=	Carbon Monoxide
CO_2	=	Carbon Dioxide
HC	=	Hydro Carbon
PM	=	Particulate Matter
NO_x	=	Nitrogen Oxide
LHV	=	Lower heating value
ECU	=	Electronic controlled unit
LPG	=	Liquefied petroleum gas
CNG	=	Compressed natural gas
H_2	=	Hydrogen
GHG	=	Greenhouse gas
BSFC	=	Brake specific fuel consumption
HP	=	Horsepower
TPS	=	Throttle Body Position Sensor
RPM	=	Round per minute
IC	=	Internal combustion engine
SI	=	Spark ignition engine
BTDC	=	Bottom top dead center
TDC	=	Top dead center
$C^{\cdot}$	=	Degree Celsius
$F^{\cdot}$	=	Degree Frarenheit
ECM	=	Electronic Controlled Management
CH_4	=	Methane
EPA	=	Environmental protection agency
CARB	=	The California Air Resources Board
EU	=	European Union
SUV	=	Sport Utility Vehicle

ABBREVIATIONS (CONT.)

NAAQS	=	National ambient air quality standards
PPM	=	Part per million
g	=	Gram
km	=	Kilometer
mi	=	Mile
kW	=	Kilowatt
Mpg	=	Mile per gallon
L	=	Liter
h	=	Hour
EC	=	European Commission
$\dot{m}_f$	=	Mass flow rate in kg per hour
W_f	=	Actual mass of fuel in kg
t	=	Time consumed to burn the actual mass in second
Bsec	=	Brake specific energy consumption in kJ per kW per hour
Q_{HV}	=	Lower heating value in kJ per kg
FP	=	Fuel power in kW
η_{BTH}	=	Brake specific thermal efficiency in percentage (%)
BP	=	Brake power in kW
FP	=	Fuel power in kW
A/F	=	Air fuel ratio per unit of mass fuel
$\dot{m}_a$	=	Volume of air intake into the cylinder in kg/s
$\dot{m}_f$	=	Mass flow rate in kg per hour
SDC	=	Specific diesel consumption in gram per kilowatt per hour
V_d	=	Volume of diesel consumed in cubic meter, cm^3
P_d	=	Specific weight of diesel in kg/l
p	=	Engine power in kW
P_f	=	Power input from fuel in kW
CV_d	=	Calorific value of diesel
f_c	=	Fuel consumed in cm^3 per hour

ABBREVIATIONS (CONT.)

P_g	=	Power from gas in kW
CV_g	=	Calorific value of gas in kJ/Nm^3
g_c	=	Gas consumption in Nm^3 per hour
ds	=	Diesel substitution
W_i	=	Work output
ß	=	Density of CO_2 in gram per ft^3
∀	=	Volume flow rate in ft^3 per minute
F	=	Water condensation in the sample line factor
dt	=	delta time in 1 second
Bsfc	=	Brake specific fuel consumption

CHAPTER I

INTRODUCTION

Background

With ever decreasing fuel resource and constantly increasing air pollution, the fundamental sustainability of present energy system has been a front line question for all nations worldwide. The present reserve of petroleum products is slowly decreasing day by day. This is actually expanding the gap between the global energy supply and energy consumption.

World transportation sector accounts for nearly 50% of the world consumption of petroleum from fossil. Diesel engines make up the largest part in the world transportation sector. These diesel engines consume high portion of diesel petroleum products as they are mostly used in the commercial sector and in many applications distributed widely in countless industries worldwide. There are urgently need to reduce high consumption of petroleum products for these engines as they produce harmful emission leading to all variant of pollutions.

Furthermore, there are very limited applications and technologies to minimize the fuel consumption of diesel engines. Only in the recent years, there has been many alternative ways of using renewable energy sources as a bridging technology to minimize the fuel consumption of the diesel engine and at the same time to lowering emission levels from the operation of these engines in all sort of application and transportation sector.

There are extensive research on alternative fuels such as LPG, CNG, Biodiesel and H_2, that may serve as future energy carriers. CNG is among the most dominant position as its population has grown worldwide in the automobile industry. Hydrogen is the desire source of future energy as it is the most abandon on earth. Currently, natural Gas is an energy source that is widely used in many fields such as residential, industrial, electricity production and transportation as well. The annual consumption of natural gas is steadily increasing in many countries worldwide. The natural gas consumption in transport is growing due to it lower level of pollutions emissions and its very low particles emissions that make it attractive to the intensive use. Furthermore, the lower carbon content in natural gas meets the CO_2 emissions reduction requirements in order to decrease the greenhouse gases (GHG) emissions in the atmosphere.

However, using CNG in the internal combustion engine such as diesel engine; there are still many limitations of incorporating many modifications to the actual mechanical engine to maximize the benefits of using CNG. And moreover, one of the main purposes of improving the combustion process of traditional internal combustion engine is to find out useful way to reduce exhaust emissions without doing major alternation on their mechanical engine but merely installing additional devices to the system.

With the current technologies and in addition to a single alternative fuel operation, diesel dual fuel engines have been a subject of high interest due to their potential to reduce smoke emission and many other significant emissions with improved performance; while utilizing the benefits of using all kind of alternative energy such as hydrogen or CNG in an internal combustion engine. Most of the diesel dual fuel engines today are using gaseous fuel as secondary fuel while either petroleum diesel or biodiesel is only a pilot fuel to start the ignition process. HCNG is among the first choice of any secondary sources for diesel dual fuel engine. Hydrogen blended with natural gas has been viewed as feasible and viable secondary source of fuel to the pilot diesel fuel as it has high flame velocity, possible to store, feasible to set up supporting infrastructures and still contain high potential in many experiments to cut down pollutions.

Previous researches and on-going researches have been conducted with using hydrogen as another potential alternative fuel in the internal combustion engine whether in gasoline or diesel engine. Hydrogen properties are more superior to other alternative sources because of the flame propagation, bursting power and higher octane value and so many other great properties. However, by using hydrogen alone; there are still very limited infrastructure, storage and political economy factor that are preventing hydrogen usages in all kind of application, and especially in the transportation sector.

CNG and Hydrogen both have high ignition temperature but require an ignition source to be used in an internal combustion engine. The diesel fuel which has a much lower ignition temperature must be used as pilot fuel to ignite CNG and hydrogen in dual fuel operation in most of the researches around the world for the design of diesel dual fuel system.

A considerable amount of previous researches, experiments and testing have shown that neither CNG nor Hydrogen alone enhances all desired feature of a diesel dual fuel engine and therefore, it is rational to try blending a mixture of CNG and Hydrogen as a secondary source of fuel which is becoming a very popular research topic on fuel at this point in time. HCNG is by far much more superior source of fuel for internal combustion engine. Especially in the past few years, for the diesel dual fuel engine; HCNG has drawn many researchers from all around the world to discover its high potential and possible rational of replacing previous CNG version into new HCNG version in the near term.

In additional to the selection of secondary fuels, the majority of research works have further suggested a development of a suitable system to control supply of gaseous fuels and diesel in a manner so as to optimize the engine performance over the complete range of operation with least emission outputs.

In summary, there are still urgent prerequisites to develop a new technological change that can bridge yesterday's automotive technology with today's abandon resources of alternative energy such as HCNG to lower emission levels produced from diesel engine. Using diesel dual fuel technique is the only way to bridge these previous technologies from the past to today's technology.

This paper presents an investigation and experiment study of fuel saving with using a mixture of hydrogen and CNG in diesel dual fuel engine. In details, it will examine performance parameters and emission parameters of mixtures between hydrogen and CNG comparing to the original diesel operation. Performance parameters such as brake specific fuel consumption, brake thermal efficiency and brake energy consumption will be thoroughly examined and validated in this report. Emission parameters such as brake NO_x emissions, CO_2 emissions, CO emissions, Hydrocarbon emissions will also be measured and examined along with balancing improving performance and producing least emissions.

Purposes of the study

The purpose of this research project is to examine feasibility of using HCNG in diesel dual fuel engine while at the same time analyzing performance, emission levels and fuel economy of the final DDF system against normal diesel engine operation. Another major interest of this research is also focus on discovering a feasible and affordable diesel dual fuel system without having to modify the vehicle and its original engine at the most affordable investment. In summary, purposes of this research study can be summarized in below points.

1. To determine if HCNG is appropriate source of fuel for diesel dual fuel engine when comparing to only pure diesel operation

2. To investigate the performance characteristics of the engine by using the most affordable HCNG diesel dual fuel system available in Thailand

3. To investigate the emission characteristics of the engine by using the most affordable HCNG diesel dual fuel system available in Thailand

4. To evaluate the fuel economy of using the most affordable HCNG diesel dual fuel system in a EURO IV light duty diesel pick-up truck.

Scope of the study

1. The scope of this research is focusing on identifying an optimum lean burn fuel consumption with a closed loop dual fuel system on combination of HCNG blends with 4 cylinders common rail internal combustion engine; with the extend of measuring limited performance parameters such as Brake specific thermal efficiency, torque and horsepower and limited emission parameters such as NO_x, CO_2, CO, and HC.

2. The experiment will test only in diesel operation and HCNG operation where hydrogen will not be varied but CNG will be varied according to the computerized specially designed for this project

3. Engine load calculations data are measuring only from two sensors, TPS sensor and RPM sensor

4. Fuel saving will be measured from the amount of diesel consumed from running the selected vehicle in normal diesel mode on the real road and comparing the data against the amount of diesel consumed in HCNG DDF mode at constant speed during real road testing.

Limitation of the study

1. This proposed research only investigate, measure, and analyze the effect of mixing hydrogen with methane in the internal combustion engine with constant hydrogen content of 0.5 liters per minute

2. The research will be using a closed loop diesel dual fuel system to operate the diesel engine and measure for performance data and emission levels data of various combinations of different fuels in Toyota Hilux Vigo 4 cylinder D4D common rail engine.

3. In this research, the emission testing will be conducted to determine amount of emission levels in both normal diesel operation and HCNG DDF operation and the results will be compared to the EURO IV standard for diesel vehicle category M.

Key words

HCNG, Diesel Dual Fuel (DDF), Fuel Saving

Benefits of the study

There are certainly many great benefits of this research study. Summary of the benefits are listed below.

1. The benefits of this research include new findings for engine using HCNG dual fuel system

2. Provide suggestions and recommendations for future research in controlling the dual fuel system for internal combustion engine

3. Provide comparisons on performance parameters and emission parameters in each different combination of secondary fuel source.

4. Provide recommendations for balancing the performance and emission output with using different fuel sources under lean burned operations.

5. Provide fuel saving analysis for possibilities of using HCNG DDF system on all sorts of commercial vehicles in the near future.

CHAPTER II

THEORIES AND RELATED LITERATURE

Introduction to internal combustion engine

An internal combustion engine (IC) is one in which the heat transfer to the working fluid occurs within the engine itself, usually by the combustion of fuel with the oxygen of air. In external combustion engines heat is transferred to the working fluid from the combustion gases via such as heat exchanger, steam engines or sterling engines. IC engines include spark ignition (SI) engines using gasoline as a fuel, and compression ignition (CI) engines (usually referred to as diesel engines) using petroleum diesel or biodiesel as a fuel [1].

In these engines, there is a sequence of processes starting from compression, combustion, expansion and finally exhaust process. Fundamentally, four or six stroke basic mechanical designs are the most common designs to achieve these four processes in most common passenger vehicles and light duty vehicles; either in gasoline or diesel passenger vehicles and most pick up diesel trucks in the world. The basic difference between the petrol engine and the diesel engine is in the method of ignition and the combustion process [1].

The diesel engine uses the heat of compression to initiate ignition and burn the fuel that has been injected into the combustion chamber. This contrasts with gasoline engine or gas engine that uses a gaseous fuel as opposed to gasoline, which use a spark plug to ignite an air-fuel mixture. To be more specific, the diesel internal combustion engine differs from the gasoline powered Otto cycle by using highly compressed hot air to ignite the fuel rather than using a spark plug. Gasoline engine is illustrated in figure 1 and diesel engine is illustrated in figure 2.

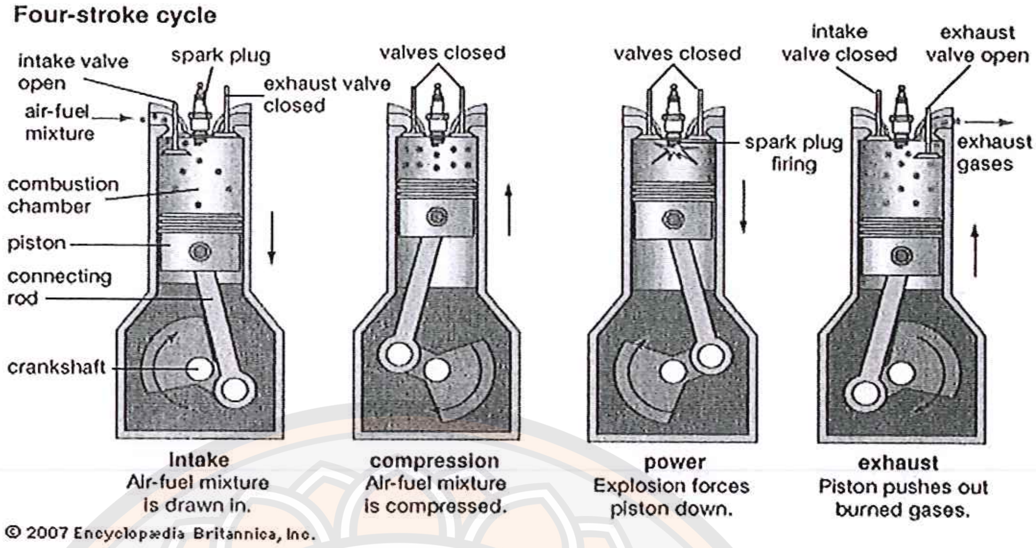

Figure 1 shows basic four stroke processes in gasoline engine

Source: internal-combustion engine: four-stroke cycle. Art. Britannica Online for Kids, June 12, 2014, http://kids.britannica.com/comptons/art-89315

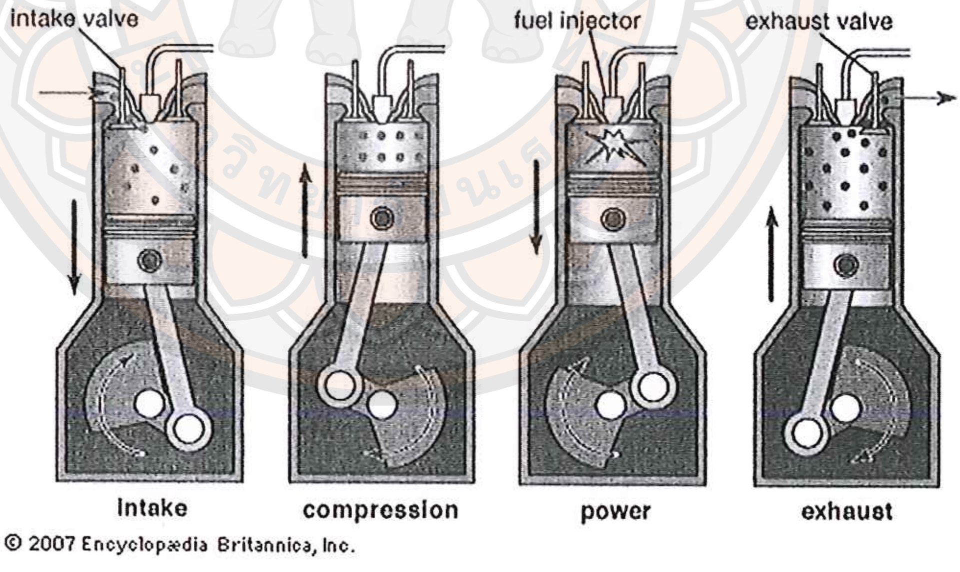

Figure 2 shows basic four stroke processes in diesel engine

Source: diesel engine. Art. Britannica Online for Kids, June 12, 2014, http://kids.britannica.com/comptons/art-167213

Diesel engine technology

In the original diesel engine, only air is initially introduced into the combustion chamber. The air is then compressed with a compression ratio typically between 15:1 and 22:1 resulting in 40-bar pressure compared to 8 to 14 bars in the petrol engine [2]. This high compression heats the air to 550 °C (1,022 °F) [2]. At about the top of the compression stroke, fuel is injected directly into the compressed air in the combustion chamber. This may be into a typically toroidal void in the top of the piston or a pre-chamber depending upon the design of the engine. The fuel injector ensures that the fuel is broken down into small droplets, and that the fuel is distributed evenly. The heat of the compressed air vaporizes fuel from the surface of the droplets. The vapour is then ignited by the heat from the compressed air in the combustion chamber, the droplets continue to vaporize from their surfaces and burn, getting smaller, until all the fuel in the droplets has been burnt completely. The start of vaporization causes a delay period during ignition and the characteristic diesel knocking sound as the vapour reaches ignition temperature and causes an abrupt increase in pressure above the piston. The rapid expansion of combustion gases then drives the piston downward, supplying power to the crankshaft [2].

As well as the high level of compression allowing combustion to take place without a separate ignition system, a high compression ratio greatly increases the engine's efficiency. Increasing the compression ratio in a spark-ignition engine where fuel and air are mixed before entry to the cylinder is limited by the need to prevent damaging pre-ignition [2]. Since only air is compressed in a diesel engine, and fuel is not introduced into the cylinder until shortly before top dead center (TDC) point, premature detonation is not an issue and compression ratios are much higher than the spark-ignition engine [2].

Diesel's original engine injected fuel with the assistance of compressed air, which atomized the fuel and forced it into the engine through a nozzle. The nozzle opening was closed by a pin valve lifted by the camshaft to initiate the fuel injection before top dead center (TDC) point. This is called an air-blast injection. Driving the three stage compressor used some power but the efficiency and net power output was more than any other combustion engine at that time [2].

Diesel engines in service today raise the fuel to extreme pressures by mechanical pumps and deliver it to the combustion chamber by pressure-activated injectors without compressed air. With direct injected diesels, injectors spray fuel through 4 to 12 small orifices in its nozzle [2]. The early air injection diesels always had a superior combustion without the sharp increase in pressure during combustion. Research is now being performed and patents are being taken out to use some form of air injection to reduce the nitrogen oxides and pollution, reverting to Diesel's original implementation with its superior combustion and possibly quieter operation [2]. In all major aspects, the modern diesel engine holds true to Rudolf Diesel's original design that of igniting fuel by compression at an extremely high pressure within the cylinder [2].

A vital component of all diesel engines is a mechanical or electronic governor which regulates the idling speed and maximum speed of the engine by controlling the rate of fuel delivery. Mechanically governed fuel injection systems are driven by the engine's gear train. These systems use a combination of springs and weights to control fuel delivery relative to both load and speed. Modern electronically controlled diesel engines control fuel delivery by use of an electronic control module (ECM) or electronic control unit (ECU) [3]. The ECM or ECU receives an engine speed signal, as well as other operating parameters such as intake manifold pressure and fuel temperature, from a sensor and controls the amount of fuel and start of injection timing through actuators to maximize power, efficiency and minimize emissions. Controlling the timing of the start of injection of fuel into the cylinder is a key to minimizing emissions, and maximizing fuel economy of the engine. The timing is measured in degrees of crank angle of the piston before top dead center. Optimal timing will depend on the engine design as well as its speed and load, and is usually 4° BTDC in 1,350-6,000 HP [3].

Advancing the start of injection results in higher in-cylinder pressure and temperature, and higher efficiency, but also results in increased engine noise due to faster cylinder pressure rise and increased oxides of nitrogen (NO_x) formation due to higher combustion temperatures [3]. Delaying start of injection causes incomplete combustion, reduced fuel efficiency and an increase in exhaust smoke, containing a considerable amount of particulate matter and unburned hydrocarbons [3].

Today, previous diesel engines use a mechanical single plunger high-pressure fuel pump driven by the engine crankshaft. For each engine cylinder, the corresponding plungers of the fuel pump measure out the correct amount of fuel and they determine the timing of each injection. These engines use injectors that are very precise spring-loaded valves that open and close at a specific fuel pressure. Separate high-pressure fuel lines connect the fuel pump with each cylinder. Fuel volume in each cylinder is controlled by a slanted groove in the plunger which rotates only a few degrees releasing the pressure and is controlled by a mechanical governor, consisting of weights rotating at engine speed constrained by springs and a lever [3]. The injectors are held open by the fuel pressure. On high-speed engines the plunger pumps are together in one unit. The length of fuel lines from the pump to each injector is normally the same for each cylinder in order to obtain the same pressure delay [3].

A cheaper configuration on high-speed engines with fewer than six cylinders is to use an axial-piston distributor pump, consisting of one rotating pump plunger delivering fuel to a valve and line for each [3].

Many modern diesel engine systems have a single fuel pump which supplies fuel constantly at high pressure with a common rail to each injector. Each injector has a solenoid operated by an electronic control unit, resulting in more accurate control of injector opening times that depend on other control conditions, such as engine speed and loading, and providing better engine performance and fuel economy [3].

Both mechanical and electronic injection systems can be used in either direct or indirect injection configurations [3].

An indirect injection diesel engine delivers fuel into a chamber off the combustion chamber, where combustion begins and then spreads into the main combustion chamber; assisted by turbulence created in the chamber. This system allows for a smoother and quieter running engine. Mechanical injection systems allowed high-speed running suitable for road vehicles. Indirect injection engines are cheaper to build and it is easier to produce smooth, quiet-running vehicles with a simple mechanical system. In previous diesel engine vehicles, many diesel engine manufacturers most prefer the greater efficiency and better controlled emission levels of direct injection diesel applications [3].

In the past decades, design of diesel engine has included direct injection diesel engines that have injectors mounted at the top of the combustion chamber. The injectors are activated using one of two methods. The first one is hydraulic pressure from the fuel pump, or an electronic signal from an engine controller [3]. Fuel consumption is about 15–20% lower than indirect injection diesels. The extra noise is generally not a problem for industrial uses of the engine, but for automotive industry; buyers have to decide whether or not the increased fuel efficiency would compensate for the extra noise. Electronic control of the fuel injection transformed the direct injection engine by allowing much greater control over the combustion [3].

The most advanced diesel engine today is the common rail diesel engine. In common rail diesel engine systems, the separate pulsing high-pressure fuel line to each cylinder's injector has been eliminated for greater fuel economy and better controlled of the environmental pollutants. A high-pressure pump pressurizes fuel at up to 2,500 bar [3]. The common rail is a tube that supplies each computer-controlled injector containing a precision-machined nozzle and a plunger driven by a solenoid or piezoelectric actuator [3].

Dual Fuel Engine

Dual fuel engine is engine with multi-fuel capability that runs on two fuels or more. On internal combustion engines, dual fuel can be applied to either gasoline engine or diesel engine with a simple conversion system. Dual fuel engine runs on either pure gasoline or pilot diesel and the other is an alternate fuel such as natural gas (CNG), LPG, bio-diesel or hydrogen. The two fuels are stored in separate tanks and the engine runs on one fuel at a time in gasoline engine, or in both fuels for diesel engine. Dual fuel vehicles have the capability to switch back and forth from gasoline or diesel to the other fuel, manually or automatically. The most common technology and alternate fuel available in the market for bi-fuel gasoline cars is Autogas (LPG), followed by natural gas (CNG) and hydrogen. For diesel engine, various alternative fuels such as LPG, CNG, hydrogen and many other alternative fuels are widely used as secondary source of fuel all over the world. Moreover, more researchers have tested possibility of using more alternatives fuels more than two source of fuels that provided higher performance and cleaner emission levels [4][5]. Some new technologies are also being developed daily from available local resources and wasted for the use of dual fuel engine [6]. Many institutions worldwide and major oil companies developed new technology to develop dual fuel for their local production and local market available locally [7, 8].

Worldwide Automobile Emission Standards

Automobile emission standards are requirements that set specific limits to the amount of pollutants that can be released into the environment from an automobile. Many emissions standards focus on regulating pollutants released by automobiles and other powered vehicles but they can also regulate emissions from industry, power plants, small equipment such as lawn mowers and diesel generators [9]. The emission standards are different in many countries around the world but the most widely acceptable standards are from the European Union.

In the United States, emissions standards are managed by the environmental protection agency (EPA). The state of California has special dispensation to promulgate more stringent vehicle emissions standards, and other states may choose to follow either the national or California standards. California's emission standards are set by the California Air Resources Board (CARB) [9]. Given that California's automotive market is one of the largest in the world, CARB wields enormous influence over the emissions requirements that major automakers must meet if they wish to sell into that market. In addition, several other U.S. states also choose to follow the CARB standards, so their rulemaking has broader implications within the U.S. CARB's policies have also influenced EU emissions standards.

Federal tier 1 regulations went into effect starting in 1994, and tier 2 standards were being phased in from 2004 to 2009. Automobiles and light trucks such as SUVs, pickup trucks, and minivans are treated differently under certain standards [9]. California was attempting to regulate greenhouse gas emissions from automobiles, but faces a court challenge from the federal government [9]. The EPA had separated regulations for small engines, such as grounds keeping equipment. The states must also promulgate miscellaneous emissions regulations in order to comply with the national ambient air quality standards (NAAQS) started in 2009 [9].

Major standard for automotive emission controlled is the EURO standard. EURO standard is a major standard of reference for emissions of most common vehicle around the world. The European Union has its own set of emissions standards that all new vehicles must meet these requirements. Currently, standards are applied to all road vehicles, trains, barges and tractors. European emission standards define the acceptable limits for exhaust emissions of new vehicles sold in EU member states and many other part of the world. The emission standards are defined in a series of European Union directives staging the progressive introduction of increasingly stringent standards. Currently, emissions of nitrogen oxides (NO_x), total hydrocarbon (THC), hydrocarbons (HC), carbon monoxide (CO) and particulate matter (PM) are regulated for most vehicle types, including cars, lorries, trains, tractors and similar machinery, barges, but excluding seagoing ships and airplanes [9]. For each vehicle type, different standards will be applied accordingly. Compliance to the standard is determined by running the engine at a standardized test cycle. Non-compliant vehicles cannot be sold in the EU and many other countries, but new standards do not apply to vehicles already on the roads. No use of specific technologies is mandated to meet the standards, though available technology is considered when setting the standards. New models introduced must meet current or planned standards, but minor lifecycle model revisions may continue to be offered with pre-compliant engines [9].

European Union automobile emission standards are typically referred to as Euro 1, Euro 2, Euro 3, Euro 4, Euro 5 and Euro 6. The corresponding series of standards for heavy duty vehicles use Roman, rather than Arabic numeral numbers. These series of standards consists of a specific list which the EU directives provide the definition of the standard for different classification of vehicle ranging from different category of weight and different types of engine.

Emission standards for passenger cars and light commercial vehicles are summarized in the following tables from table 1 to table 4. Since the Euro 2 stage, EU regulations introduce different emission limits for diesel and petrol vehicles. Diesels have more stringent CO standards but are allowed higher NO_x emissions. Petrol vehicles are exempted from particulate matter (PM) standards at the Euro 4 stage, but vehicles with direct injection engines will be subject to a limit of 0.005 g/km for Euro

5 and Euro 6 [10]. A particulate number standard (P) or (PN) is part of Euro 5 and 6, but it is not a final tier on the EU standard. The standard will be defined in the near future and at the latest upon entry into force of Euro 6 [10].

Table 1 EURO emission standards for passenger cars (Category M), g/km

Tier	Date	CO	THC	NMHC	NO_X	HC	PM
Diesel							
Euro 1	July 1992	2.72	-	-	-	0.97	0.14
Euro 2	1 January 1996	1	-	-	-	0.7	0.08
Euro 3	1 January 2000	0.64	-	-	0.5	0.56	0.05
Euro 4	January 2005	0.5	-	-	0.25	0.3	0.025
Euro 5	1 September 2009	0.5	-	-	0.18	0.23	0.005
Euro 6	1 September 2014	0.5	-	-	0.08	0.17	0.005
Petrol (Gasoline)							
Euro 1	July 1992	2.72	-	-	-	0.97	-
Euro 2	1 January 1996	2.2	-	-	-	0.5	-
Euro 3	1 January 2000	2.3	0.2	-	0.15	-	-
Euro 4	January 2005	1	0.1	-	0.08	-	-
Euro 5	1 September 2009	1	0.1	0.068	0.06	-	0.005
Euro 6	1 September 2014	1	0.1	0.068	0.06	-	0.005

Table 2 EURO emission standards for light commercial vehicles of less than 1,305 kg (Category N1), g/km

Tier	Date	CO	THC	NMHC	NO_X	HC	PM
Diesel							
Euro 1	July 1992	2.72	-	-	-	0.97	0.14
Euro 2	1 January 1996	1	-	-	-	0.7	0.08
Euro 3	1 January 2000	0.64	-	-	0.5	0.56	0.05
Euro 4	January 2005	0.5	-	-	0.25	0.3	0.025
Euro 5	1 September 2009	0.5	-	-	0.18	0.23	0.005
Euro 6	1 September 2014	0.5	-	-	0.08	0.17	0.005
Petrol (Gasoline)							
Euro 1	July 1992	2.72	-	-	-	0.97	-
Euro 2	1 January 1996	2.2	-	-	-	0.5	-
Euro 3	1 January 2000	2.3	0.2	-	0.15	-	-
Euro 4	January 2005	1	0.1	-	0.08	-	-
Euro 5	1 September 2009	1	0.1	0.068	0.06	-	0.005
Euro 6	1 September 2014	1	0.1	0.068	0.06	-	0.005

Table 3 EURO emission standards for light commercial vehicles between 1,305 kg to 1,760 kg (Category N1-II), g/km

Tier	Date	CO	THC	NMHC	NO_X	HC	PM
Diesel							
Euro 1	July 1992	5.17	-	-	-	1.4	0.19
Euro 2	1 January 1996	1.25	-	-	-	1	0.12
Euro 3	1 January 2000	0.8	-	-	0.65	0.72	0.07
Euro 4	January 2005	0.63	-	-	0.33	0.39	0.04
Euro 5	1 September 2010	0.63	-	-	0.235	0.295	0.005
Euro 6	1 September 2015	0.63	-	-	0.105	0.195	0.005
Petrol (Gasoline)							
Euro 1	July 1992	5.17	-	-	-	1.4	-
Euro 2	1 January 1996	4	-	-	-	0.6	-
Euro 3	1 January 2000	4.17	0.25	-	0.18	-	-
Euro 4	January 2005	1.81	0.13	-	0.1	-	-
Euro 5	1 September 2010	1.81	0.13	0.09	0.075	-	0.005
Euro 6	1 September 2015	1.81	0.13	0.09	0.075	-	0.005

Table 4 EURO emission standards for light commercial vehicles weight more than 1,760 kg to maximum weight of 3,500 kg (Category N1-III), g/km

Tier	Date	CO	THC	NMHC	NO_X	HC	PM
Diesel							
Euro 1	July 1992	6.9	-	-	-	1.7	0.25
Euro 2	1 January 1996	1.5	-	-	-	1.2	0.17
Euro 3	1 January 2000	0.95	-	-	0.78	0.86	0.1
Euro 4	January 2005	0.74	-	-	0.39	0.46	0.06
Euro 5	1 September 2010	0.74	-	-	0.28	0.35	0.005
Euro 6	1 September 2015	0.74	-	-	0.125	0.215	0.005
Petrol (Gasoline)							
Euro 1	July 1992	6.95	-	-	-	1.7	-
Euro 2	1 January 1996	5.22	-	-	-	0.7	-
Euro 3	1 January 2000	2.27	0.29	-	0.21	-	-
Euro 4	January 2005	2.27	0.16	-	0.11	-	-
Euro 5	1 September 2010	2.27	0.16	0.108	0.082	-	0.005
Euro 6	1 September 2015	2.27	0.16	0.108	0.082	-	0.005

Automobiles in other parts of the world are also using and referring automobile emission to the EURO emission standards. In the UK, taxis and licensed private hire vehicles must be using Euro IV or Euro V standard complied vehicle to operate their fleets [10]. For Germany, cars in Germany mostly conform to the Euro IV standard as of January 2009 onward [10]. China adopted Euro III standards and the standards went into effect on July 1, 2007. In January of 2008, China implemented Euro IV standards. Beijing became the first city in mainland China to adopt this standard [10]. In Hong Kong, all new passenger cars must meet either Euro IV or US EPA Tier 2 Bin 5 standard. This legislation in Hong Kong was implemented since Jan 1, 2006 [10]. For India, Euro IV standard was applied since the beginning of 2010 [10]. Stricter emission standards are being applied in Israel. Since January 2012 all vehicles which do not comply with Euro V emission values are not allowed to be imported to Israel [10].

Unlike South Africa's own emission standard, the emission regulations are very much different from other countries. South Africa's first clean fuels program was implemented in 2006 with the banning of lead from petrol and the reduction of sulphur levels in diesel from 3000 parts per million (ppm) to 500 ppm, along with a niche grade of 50 ppm. The Clean Fuels 2 standard, expected to begin in 2017, includes the reduction of sulphur to 10 ppm; the lowering of benzene from 5 percent to 1 percent of volume; the reduction of aromatics from 50 percent to 35 percent of volume; and the specification of olefins at 18 percent of volume [10].

Lastly, Japanese automobile emission standards are fairly interesting to study because Japan is the largest automobile manufacturer in the world. Historically, the Japanese emissions standards started in June 10, 1968, when the Japanese Government passed the Japanese air pollution control act which regulated all sources of air pollutants [10]. As a result of the 1968 law, dispute resolutions were passed under the 1970 Japanese air pollution dispute resolution act. As a result of the 1970 law, in 1973 the first four sets of new emissions standards were introduced in that year. Interim standards were introduced on January 1, 1975 and again in 1976. The final Japanese emission standards were introduced in 1978 [10]. While the standards were introduced they were not made immediately mandatory, instead tax breaks were offered for cars which passed them. The standards were based on those adopted by the original US clean air act of 1970, but the test cycle included more slow city driving to correctly reflect the Japanese situation. The 1978 limits for mean emissions during a hot start test of CO, hydrocarbons, and NO_x were 2.1 grams per kilometer (3.38 g/mi) of CO, 0.25 grams per kilometer (0.40 g/mi) of HC, and 0.25 grams per kilometer (0.40 g/mi) of NO_x respectively [10]. Maximum limits are 2.7 grams per kilometer (4.35 g/mi) of CO, 0.39 grams per kilometer (0.63 g/mi) of HC, and 0.48 grams per kilometer (0.77 g/mi) of NO_x [10]. The 10 - 15 Mode Hot Cycle test, used to determine individual fuel economy ratings and emissions observed from the vehicle being tested, use a specific testing regime [10].

In 1992, to cope with NO_x pollution problems from existing vehicle fleets in highly populated metropolitan areas, the Ministry of the Environment adopted the Japanese law concerning special measures to reduce the total amount of nitrogen oxides emitted from motor vehicles in specified areas, called in short the motor vehicle NO_x Law [10]. The regulation designated a total of 196 communities in the Tokyo, Saitama, Kanagawa, Osaka and Hyogo prefectures as areas with significant air pollution due to nitrogen oxides emitted from motor vehicles [10]. Under the law, several measures had to be taken to control NO_x from in-use vehicles, including enforcing emission standards for specified vehicle categories. The regulation was amended in June 2001 to tighten the existing NO_x requirements and to add PM control provisions [10]. The amended rule is called the law concerning special measures to reduce the total amount of nitrogen oxides and particulate matter emitted from motor vehicles in specified areas or in short the automotive NO_x and PM law.

These NO_x and PM law introduces emission standards for specified categories of in-use highway vehicles including commercial goods vehicles such as trucks and vans, buses, and special purpose motor vehicles, irrespective of the fuel type. The regulation also applies to diesel powered passenger cars. In-use vehicles in the specified categories must meet 1997/98 emission standards for the respective new vehicle type [10]. Also, the 1997 and the 1998 new vehicle standards are retroactively applied to older vehicles already on the road [10]. Vehicle owners have two methods to comply with the new law. First, vehicle owners can replace old vehicles with newer cleaner models. Second, vehicle owners can retrofit old vehicles with approved NO_x and PM control devices.

Furthermore, Japanese vehicles have a grace period between 8 and 12 years from the initial registration [10]. The grace period depends on the vehicle type. Light commercial vehicles with gross vehicle weight lesser than 2500 kg have an 8 years limit. Heavy commercial vehicles with gross weight lesser than 2500 kg have a 9 years limit. Micro buses between 11 to 29 seats have a 10 years grace period. Large buses with lesser than 30 seats have 12 years grace period. Special vehicles such as large cargo truck or bus have a 10 years limited. Diesel passenger cars only allow 9 years grace period. The regulation allows fulfillment of its requirements to be postponed by an additional 0.5 to 2.5 years, depending on the age of the vehicle [10]. This delay was introduced in part to harmonize the NO_x and PM Law with the Tokyo diesel retrofit program. The NO_x and PM Law are enforced in connection with Japanese vehicle inspection program, where non-complying vehicles cannot undergo the inspection in the designated areas.

Fuel Economy in automobiles

The fuel economy of an automobile is the fuel efficiency relationship between the distance traveled and the amount of fuel consumed by the vehicle. Consumption can be expressed in terms of volume of fuel to travel a distance, of the distance travelled per unit volume of fuel consumed. Since fuel consumption of vehicles is a great factor in air pollution, and since importation of fuel for transportation sector can be a large part of a nation's foreign trade; many countries impose requirements for fuel economy. Different measurement tests are used to approximate the actual performance of the vehicle. The energy in fuel is required to overcome various losses such as wind resistance, tire drag, and many others in propelling the vehicle, and in providing power to vehicle systems such as ignition or air conditioning.

Generally, fuel economy of a vehicle is mainly losses by many factors. Firstly, engine efficiency; which varies with engine type, the mass of the automobile and its load, and engine speed usually measured in RPM. Secondly, the aerodynamic drag force, which increases roughly by the square of the car's speed and rolling friction. Thirdly, braking is another major cause of higher fuel consumption. Furthermore, losses in the transmission; the manual transmissions can be up to 94% efficient whereas the older automatic transmissions may be as low as 70% efficient

[11]. Automatically controlled shifting of gearboxes that have the same internals as manual boxes will give the same efficiency as a pure manual gearbox. Air conditioning is also another critical cause of fuel economy loss because the power required for the engine to turn the compressor decreases the fuel-efficiency [11]. Moreover, power steering is another major cause. With older hydraulic power steering systems are powered by a hydraulic pump constantly engaged to the engine. Power assistance required for steering is inversely proportional to the vehicle speed so the constant load on the engine from a hydraulic pump reduces fuel efficiency. More modern designs improve fuel efficiency by only activating the power assistance when needed; this is done by using either direct electrical power steering assistance or an electrically powered hydraulic pump.

Also, older cooling systems that used a constantly engaged mechanical fan to draw air through the radiator at a rate directly related to the engine speed can also lower fuel economy. The constant load reduces efficiency. More modern systems are now using electrical fans to draw additional air through the radiator when extra cooling is required by the vehicle.

Vehicle electrical systems are certainly another key factor that effect fuel economy. Turning off headlights, battery charging, active suspension, circulating fans, defrosters, media systems, speakers, and other electronics can also significantly increase fuel consumption because the energy to power these devices causes increased load on the alternator. Since alternators are commonly only 40–60% efficient, the added load from electronics on the engine can be as high as 3 horsepower or approximately about 2.2 kW at any speed including idle [11]. Headlights, for example; consume 110 watts on low and up to 240 watts on high [11]. These electrical loads can cause much of the discrepancy between real world and normal manufacturer tests, which only include the electrical loads required to run the engine and basic climate control.

Fuel-efficiency decreases from electrical loads are most pronounced at lower speeds because most electrical loads are constant while engine load increases with speed. So at a lower speed a higher proportion of engine horsepower is used by electrical loads. Hybrid cars see the greatest effect on fuel-efficiency from electrical loads because of this proportional effect. Various measures can be taken to reduce losses at each of the conversions between chemical energy in fuel and kinetic energy of the vehicle [11]. Driver behavior can also affect fuel economy, even sudden acceleration and heavy braking also wastes energy as well.

Generally, fuel economy can be expressed in two ways. One is the units of fuel per fixed distance and the other one is units of distance per fixed fuel unit. Commonly, unit of expression is miles per gallon (mpg) which is used in the United States, the United Kingdom and Canada. Kilometers per liter (km/L) is more commonly used elsewhere in Europe, Asia and many other parts of Africa.

Many fuel economy standards and testing procedures vary in many part of the world. For example, in Australia from October 2008; all new cars had to be sold with a sticker on the widescreen showing the fuel consumption and the CO2 emission [11]. Fuel consumption figures are expressed as urban, extra urban and combined, measured according to UN ECE Regulations 83 and 101 which are based on the European driving cycle [11]. Australia also uses a star rating system, from one to five stars, that combines greenhouse gases with pollution, rating each from 0 to 10 with then being best [11]. To get 5 stars a combined score of 16 or better is needed to fulfill the test requirement, so a car with a 10 for fuel economy and a 6 for emission or 6 for economy and 10 for emission, or anything in between would get the highest 5 star rating [11].

Most of the vehicles being sold to Thailand and the ASEAN countries are mainly Japanese automobiles. Japan has 10-15 mode driving cycle test which is the official fuel economy test and emission certification test for new light duty vehicles [11]. For the Japanese vehicle, fuel economy is expressed in km/L (kilometers per liter) and emissions are expressed in gram per kilometer [11]. The test is carried out on a dynamometer and consist of 25 tests which cover idling, acceleration, steady running and deceleration, and simulate typical urban and expressway driving patterns. The running pattern begins with a warm start, lasts for 660 seconds and runs at speeds up to 70 km/h. The distance of the cycle is 6.34 km with average speed of 25.6 km/h, and duration 892 seconds, including the initial 15 mode segment [11]. In December, 2006, Japan automobile manufacturer implemented a new test for setting a new standard of fuel economy testing [11]. It was called the JC08. This test was supposed to go into effect in 2015 but it is already being used by most of the car manufacturers for new cars at this stage [11]. The JC08 test is significantly longer and more rigorous than the 10-15 mode test. The running pattern with JC08 stretches out to 1200 seconds and there are both cold and warm start measurements and top speed is 82 km/h. The economy ratings of the JC08 are lower than the 10-15 mode cycle, but they are expected to be more appropriate for the real usages [11].

For the European Union, the standard for fuel economy is tested using the two drive cycles, and corresponding fuel economies are reported as urban and extra urban, in 100 kilometer per liter. The urban economy is measured using the test cycle known as ECE-15 introduced in 1970 by EC Directive 70/220/EWG and finalized by EEC Directive 90/C81/01 in 1999 [11]. It simulates a 4,052 meter urban trip at an average speed of 18.7 km/h and at a maximum speed of 50 km/h [11]. The extra urban driving test or EUDC lasts up to 400 seconds at an average speed of 62.6 km/h and a top speed of 120 km/h [11].

Another largest part of automobile manufacture is the United States of America. The United States imposes a much stricter regulation on fuel economy. The energy tax act of 1978 established a gas guzzler tax on the sale of the new vehicles whose fuel economy fails to meet certain statutory levels [11]. The tax applies only to cars and is collected by the IRS. Its purpose is to discourage the production and the purchase of fuel-inefficient vehicles. The tax was phased in over ten years with rates increasing over time. It applies only to manufactures and importers of vehicles, although presumably some or all of the tax is passed along to impose on used car sales. The tax is graduated to apply a higher tax rate for less fuel efficient vehicles. To determine the tax rate, manufacturers test all the vehicles at their laboratories for fuel economy. The US environmental protection agency would then confirm a portion of those tests at an environmental protection agency (EPA) lab [11].

From the past up to 2007, two separate fuel economy tests simulate city driving and highway driving were used to identify fuel economy of automobile in the US [11]. The city driving program or urban dynamometer driving schedule or UDDS that defined in 40 C.F.R. 86 Application I consists of starting with a cold engine and making 23 stops over a period of 31 minutes for an average speed of 32 km/h and with a top speed of 90 km/h [11]. The highway program or highway fuel economy driving schedule is also implemented in the fuel economy test. It defined in 40 C.F.R. 600

Application I and uses a warmed-up engine and makes no stops, averaging 77 km/h with a top speed of 97 kilometer per hour over a 16 kilometer distance [11]. The measurements are then adjusted downward by 10% in the city and 22% in the highway to more accurately reflect real-world results [11]. A weight average of city (55%) and highway (45%) fuel economies is used to determine the guzzler tax [11]. Furthermore, the procedure has been updated to FTP-75, adding a hot start cycle which repeats the cold start cycle after a 10 minute pause [11].

From 2008 until present, US EPA added three new supplemental federal test procedure tests (SFTP) to include the influence of higher driving speed, harder acceleration, colder temperature and air conditioning use [11]. SFTP is a high speed and quick acceleration loop that lasts 10 minutes, covers 13 km, averages 77 kilometer per hour and reaches a top speed of 130 kilometer per hour [11]. Four stops are included during this test, and brisk acceleration maximizes at a rate of 13.62 km/h per second. The engine begins warm and air conditioning is not used. Ambient temperature varies between 20 °C to 30 °C [11].

SFTO SC03 is the air conditioning test, which raises ambient temperatures to 35 °C, and puts the vehicle's climate control system to use [11]. Lasting 9.9 minutes, the 5.8 km loop averages 35 kilometer per hour and maximizes at a rate of 88.2 kilometer per hour [11]. Five stops are included, idling occurs 19 percent of the time. Engine temperatures begin warm. Lastly, a cold temperature cycle uses the same parameters as the current city loop, except that ambient temperature is set to −7 °C [11]. EPA tests for fuel economy do not include electrical load tests beyond climate control, which may account for some of the discrepancy between EPA and real world fuel-efficiency [11].

Performance calculation

Performance calculation of diesel and diesel dual fuel engine has been conducted within many research studies. Most of the performance calculation aimed at calculating performance parameters in fuel power, fuel consumptions, energy consumptions and thermal efficiency of the engine.

For example, Leelanoi, et al. [12] studied the performance of diesel engine using buthanol base diesohol fuel with diesel. They had presented diesel engine performance calculations for their experimental study which are useful for the calculation of performance parameters in diesel dual fuel as described below.

1. To find out brake specific fuel consumption of both diesel and dual fuel engines, it can be calculated according to the equation (1) below,

$$Bsfc = \frac{\dot{m}_f \times 3600}{\text{BP}} \quad (1)$$

where Bsfc = brake specific fuel consumption in kg per kW per hour

$\dot{m}_f$ = mass flow rate in kg per hour, which can be calculated according to the equation (2) below,

$$\dot{m}_f = \frac{W_f \times 3600}{\text{t}} \quad (2)$$

where W_f = actual mass of fuel in kg

t = time consumed to burn the actual mass in second

2. To find out brake specific energy consumption of both diesel engine and dual fuel engine, it can be calculated according to the equation (3) below,

$$\text{Bsec} = Q_{HV} \times \text{Bsfc} \quad (3)$$

where Bsec = brake specific energy consumption in kJ per kW per hour

Q_{HV} = Lower heating value in kJ per kg

3. To find out brake fuel power of both diesel engine and dual fuel engine, it can be calculated according to the equation (4) below,

$$FP = \dot{m}_f \times Q_{HV} \tag{4}$$

where FP = Fuel power in kW

Q_{HV} = Lower heating value in kJ per kg

4. To calculate brake thermal efficiency of both diesel engine and dual fuel engine, thermal efficiency can be calculated according to the equation (5) below,

$$\eta_{BTH} = \frac{BP}{FP} \times 100 \tag{5}$$

Where η_{BTH} = brake specific thermal efficiency in percentage (%)

BP = brake power in kW

FP = fuel power in kW

5. To calculate air-fuel Ratio of both diesel engine and dual fuel engine, it can be calculated from the equation (6) below,

$$A/F = \dot{m}_a / \dot{m}_f \tag{6}$$

where A/F = air fuel ratio per unit of mass fuel

$\dot{m}_a$ = volume of air intake into the cylinder in kg/s

$\dot{m}_f$ = mass flow rate in kg per hour

Another important performance parameter for dual fuel is the original diesel substitution. According to the research study in Das, et al. [13], they have presented calculation of diesel substitution with diesel dual fuel engine using producer gas and diesel. To be more specific, they had presented calculations of the engine thermal efficiency, specific diesel consumption and percentage of diesel substitution in their experimental study. Their performance calculation of a diesel engine operated on dual-fuel mode was generally measured in terms of specific diesel consumption, engine thermal efficiency and percentage of diesel substitution. These parameters were determined in the following steps,

1. To calculate specific diesel consumption (SDC), it can be calculated from equation (1)

$$\mathrm{SDC} = \frac{3600 V_d P_d}{1000 t\, p} = 3.6\ \frac{V_d P_d}{t\, p} \tag{1}$$

where SDC = specific diesel consumption in gram per kilowatt per hour

V_d = Volume of diesel consumed in cubic meter, cm^3

P_d = specific weight of diesel in kg/l

t = time required to consume diesel in second

p = engine power in kw

2. Thermal efficiency of diesel engine is calculated according to equation (2)

$$n_t = \frac{Brake\ Power}{Power\ input\ from\ fuel} \tag{2}$$

The Power input from fuel in equation (2) is given in equation (3) in below,

$$P_f = \frac{CV_d \times P_d \times f_c}{3600} \tag{3}$$

where P_f = Power input from fuel in kW

CV_d = Calorific value of diesel = 39 MJ/kg

P_d = density of diesel = 640 kg/m^3

f_c = fuel consumed in cm^3/h

Substituting the values of CV_d and P_d, the equation (3) yields equation (4),

$$P_f = \frac{39 \times 840 \times f_c}{3600} = 9.1\, f_c \quad (4)$$

Using equation (4), equation (2) gives thermal efficiency of pure diesel operation as,

$$n_t = \frac{Brake\ Power}{9.1\, f_c} \quad (5)$$

3. Thermal efficiency of diesel dual fuel is then equal to (6),

$$n_t = \frac{Brake\ Power}{Power\ input\ from\ pilot\ diesel + power\ input\ from\ gas} \quad (6)$$

Power input from gas is given by

$$P_g = \frac{CV_d \times g_c}{3.6} \quad (7)$$

where P_g = power from gas in kW
CV_g = calorific value of gas in KJ/Nm^3
g_c = gas consumption in Nm^3 per hour

Substituting equation (5) and (7) in equation (6), thermal efficiency of a diesel dual fuel engine equal to,

$$n_t = \frac{Brake\ Power}{9.1\, f_c + \frac{CV_d \times g_c}{3.6}} \quad (8)$$

4. Diesel substitution: The percentage of diesel substitution in dual fuel engine is given in equation (9)

$$ds = \frac{D_d \times D_{dg}}{D_d} \times 100 \tag{9}$$

For dual fuel which uses diesel as pilot source of fuel and blending of alternative fuels and used as a secondary source of fuel in diesel engine, Lata, et al. [14] has presented calculation of thermal efficiency for the dual fuel engine in below equation. Their experimental study blended pilot diesel with hydrogen and LPG as a secondary source of fuel. They presented an equation of calculating thermal efficiency for diesel dual fuel with varies LPG blended and hydrogen addition as a secondary source, which uses the following steps below.

1. The indicated power output is calculated as

$$w_i = \sum_{i=1}^{720} \rho_i (v_i - v_{i-1}) \tag{1}$$

where W_i is work output and P_i is pressure and $P_i = W_i(N/2x60)$ where P_i indicated power, N is RPM.

2. Brake thermal efficiency of their calculation is given in equation (2) as

$$n_b = \frac{\text{BP}}{(m_d Q_d + m_{H_2} Q_{H_2} + m_{LPG} Q_{LPG}) \times 1000} \tag{2}$$

where m_d, m_{H_2}, m_{LPG} are the mass flow rate of diesel, hydrogen and LPG respectively, and Q_d, Q_{H_2}, Q_{LPG} are the lowest heat of combustion of diesel, hydrogen and LPG, respectively.

Emission calculation

Calculating automobile emission is meant for the purpose of calculating major harmful emission from an automobile. Lim [10] conducted a study of exhaust emissions from diesel trucks and presented emission calculation for important pollutants to determine the tons of emissions from these trucks. A sample calculation of mass CO_2 is shown in the below equation (1),

$$\text{Mass of } CO_2 = [\beta \cdot \forall \cdot C \cdot dt] / F \quad (1)$$

where:

β = Density of CO_2 in gram per ft^3

$\forall$ = Volume flow rate in ft^3 per minute

C = CO_2 concentration in %

F = water condensation in the sample line factor

dt = delta time = 1 second

Related Literatures

There are many research studies of using alternative fuels in internal combustion engine. Lessons and technical details can be found in many of the literatures over the past years. However, as for the purpose of this research study is on potential development of using HCNG for the diesel engine. Thus, the majority of the literatures are dedicated to reviews in part and components of hydrogen, natural gas, and diesel dual fuel engine.

Early development of experimental study on replacing traditional petroleum fuel can be seen in many business trajectories depending on local circumstances and local resources of the given area. Replacing normal petroleum products such as normal diesel driven vehicle with compressed natural gas (CNG) can be seen in Fontaras, et al. [15]. They conducted an investigation of on road emission tests of EURO V diesel vehicle comparing to pure CNG vehicles. Their experimental results showed advantage of reducing NO_x and PM emissions. But when they had compared to the original diesel operation, pure CNG vehicles had shown decreased in performance efficiency of higher CO, HC and other greenhouse gas emissions. Therefore, with running on pure CNG vehicles may not likely to improve emission levels.

Another interesting area of today's future fuel for the internal combustion engine is the feasibility of bringing hydrogen into the replacement of today's renewable energy. Hydrogen addition to the internal combustion engine is another area of interest among new renewable energies that have been conducted in many laboratories and many major institutions around the world. It is believed that by beginning to implement hydrogen into internal combustion engine, major automobile manufactures will consider building a bridging technology to early trail out blending hydrogen with many other alternative fuels or traditional petroleum fuels in both gasoline and diesel engine [16]. Even new developing country such as Algeria, the research has sought out for combination of hydrogen and compressed natural gas altogether at once without trials in using other alternatives first [17]. India is another example of considering replacing traditional compressed natural gas program with an upgrade version which includes hydrogen addition at the filling station and to ensure an early entry of hydrogen fuel into local infrastructure [18, 19, 20, 21].

In the past years, many research studies have been using LPG as an alternative fuel to blend with petroleum diesel or bio-diesel depending on the given area and the availability of diesel on the given experiments. Results have shown better performance and lower emission level in various applications. However, there are still many problems with inconsistency of fuel economy and emission of NO_x level [14, 22].

Acharya and Jens [23] conducted experimental study of using Karanja oil methyl ester with LPG to improve higher performance of diesel engine. Their results showed positive sign of reducing NO_x and smoke emission while performance of the engine has been increased positively. However, their experimental results suffered from higher HC and higher CO emissions; particularly at lower load level because of the poor ignition.

Poonia, et al. [24] suggested using EGR and larger amount of pilot diesel quantity in low load to improve poor exhaust emissions during low loads in their experimental study of using LPG with diesel in an LPG diesel dual fuel engine.

Saleh [25] investigated LPG diesel dual fuel system by using various LPG compositions with diesel to examine emissions and performance characteristics of the engine. The results had shown that higher LPG composition and lesser diesel injection leads to lower NO_x content levels while it had also reduced CO levels but it happened only in part loads, not in all loads.

There are also many research studies previously chose compressed natural gas over LPG because natural gas is another promising alternative fuel for many reasons. First, it has already been successfully utilized in ground transportation sector in many internal combustion engines such as gasoline and diesel engine. However, for the diesel engine; natural gas cannot be used as the sole fuel because of its high compression ratio and engine knock limitation. Therefore, for diesel engine; natural gas must be used as dual fuel.

Furthermore, many researchers have been trying to find an optimization of the use of natural gas and diesel as it promotes improvement in performance and promise to lower emission levels. But in the past researches, using CNG diesel dual fuel may provide positive results in improving performance to certain levels but emission levels of NO_x and other emission results are still poor as comparing to original diesel engine alone.

Egusquiza, et al. [26] conducted an experimental study of using natural gas and diesel in a diesel dual fuel turbocharged to investigate the performance and emission characteristics of the dual fuel system, and then compared with the original diesel operation. Their results show that diesel dual fuel system improved emission level of NO_x. However, under the low load measurements; the results had indicated poor results on higher CO and HC emissions as well as higher brake specific fuel consumption when compared to the original diesel engine.

Liu, et al. [27] conducted various emission tests on using CNG with diesel in a diesel dual fuel engine. Their results presented interesting improvement in reducing NO_x to 30% as comparing to the original diesel engine. However, hydrocarbon level results of their experiment had been increased at low to medium load level. Moreover, particulate matter (PM) decreased with using natural gas with diesel in a diesel dual fuel engine with less diesel pilot injection but when they tried to increase the amount of pilot diesel injection; PM results also increased when comparing to the original diesel engine.

Ryu [28, 29] studied combustion and emissions characteristics of using biodiesel and compressed natural gas as dual fuel in the diesel engine. Biodiesel was used as a pilot fuel to ignite the engine followed with compressed natural gas to operate in diesel dual fuel mode. The results showed that the combustion of biodiesel-

CNG mode starts later compared to diesel mode but begins and ends earlier if there were more pressures in the pilot injection stage. Also, in the biodiesel-CNG mode; BSFC (brake specific fuel consumption) was higher than those of diesel single combustion. Furthermore, the results showed lower smoke but higher NO_x with more pilot injection pressure in the biodiesel-CNG mode.

Paul, et al. [30] investigated using CNG with diesel and combination of diesel with ethanol blends with CNG. The investigation examines performance characteristics and emission characteristics of using both CNG with diesel and combination of diesel with ethanol blends with CNG.

Their experimental study showed that at excess full load, diesel and ethanol with CNG enrichment increases brake thermal efficiency by 6.32%, brake specific energy consumption increases by 80.18% with the inclusion of more CNG. And on the emission, CO emission increases by 41.37% at 40% load, 70% at 80% load, and 94.21% at 120% load with increasing CNG content. NO_x emission decreased with diesel and CNG combination. With their strategies in the experiment, NO_x emission reduced by 91.29% with using diesel mixed with ethanol and CNG enrichment. Their study has also presented method of calculating calorific value on the basis of base fuels, diesel, ethanol and CNG with using the equation 1 and method of calculating brake specific energy consumption in all base fuels in equation 2.

Below equation is a method of calculating calorific values of a blend between diesel and ethanol in equation (1).

$$\text{Qcal, mix} = \frac{\sum x_i \times \rho_i \times \text{Qcal.i}}{\sum x_i \times \rho_i} = \frac{(x_d \times \rho_d \times Q_{cal.d}) + (x_{eth} \times \rho_{eth} \times Q_{cal.eth})}{(x_d \times \rho_d) + (x_{eth} \times \rho_{eth})} \quad (1)$$

Where,

x_i = Volume percentage of a base fuel in the blend

x_d , x_{eth} = Volume percentage of a base fuel in the blend

ρ_d , ρ_{eth} = Density of diesel and ethanol respectively

$Q_{cal.d}$, $Q_{cal.eth}$ = Calorific value of diesel and ethanol respectively

Below is a method of calculating BSEC (Brake Specific Fuel Consumption) in equation 2 which indicates the efficiency of the engine with which the input energy content of the fuel is utilized by the engine during combustion.

$$\text{BSFC (kJ/kg)} = \frac{M_D \times LHV_D + M_{Eth} \times LHV_{Eth} + M_{CNG} \times LHV_{CNG}}{BP} \quad (2)$$

Where,

M_D , M_{Eth} , M_{CNG} = Mass flow rate of diesel, ethanol and CNG respectively

LHV_D , LHV_{Eth} , LHV_{CNG} = Lower Calorific value of diesel, ethanol and CNG respectively

Carlucci, et al. [31] investigates using natural gas with diesel common rail mono-cylinder to operate in dual fuel mode with new technique of using electronic control to control the whole system of diesel and natural gas operation. The experiment was conducted with defining combustion development and engine exhaust emission in low load and high load with varies amount of CNG injected into the engine. The result shows that comparing low load and high load emission results, the dual fuel is a very effective strategy to reduce unburned hydrocarbons and NO_x.

Similar to other researchers in the field of CNG diesel dual fuel system, Ehsan and Bhuiyan [32] investigated using natural gas with light duty diesel engine, their performance results had shown nearly the same with the original diesel performance nearly 90% close to the original diesel with an impressive 88% replacement of diesel.

On the other hand, Papagiannakis, et al. [33] conducted a study on a direct injection single cylinder CNG diesel dual fuel engine and found that the brake thermal efficiency of this system was lower comparing to normal pure diesel operation. Moreover, their results had also shown that NO_x decreased as compared to normal diesel operation. At the same time, their CNG diesel dual fuel operation provided significant decreases in smoke.

Venkatesan [34] examined diesel dual fuel engine with the use of Jatropa oil methyl ester biodiesel and CNG. The findings from his study provide positive results in both performance improvement and emission level improvement. Similar results were obtained in another CNG diesel dual fuel experiment. This means that faster combustion process and lower exhaust temperature are the reaction of using proper blended and proper amount of pilot and secondary fuel [35].

Many institutions, organizations and private companies are working to develop engines that might efficiently exploit the potential of hydrogen. Researches in using hydrogen with diesel engine have also grown in number previously. The aim is to find energy systems that will be renewable and sustainable, efficient and cost effective, convenient and safe and hydrogen is one of the possible solutions to that.

In addition to single traditional fuel operation, dual fuel operation is also of interest to the automobile manufacturer. The major advantage is the opportunity to refill with a traditional fuel when the hydrogen is not available. But the disadvantage part of this system is the hydrogen storage on board and their management.

Plenty of literature provided positive results in implementing hydrogen addition in diesel engine such as higher brake thermal efficiency when the engine is compared against pure diesel operation [36].

Kumar Bose and Maji [37] investigated using hydrogen as inducted fuel and diesel as injected fuel with exhaust gas recirculation technique to see the performance and emission of the hydrogen diesel dual fuel mode with a single cylinder diesel engine. The results showed that brake thermal efficiency increased by 12.9% with the supply of 0.15 kg/h of hydrogen. And the brake specific fuel consumption is less than operating in pure diesel because higher calorific value of hydrogen and operation of hydrogen fuelled engine under lean burn conditions. Furthermore, the results showed higher engine temperature under hydrogen diesel dual fuel mode. But smoke decreased tremendously 42% comparing to pure diesel operation. CO_2 also decreased by 40.5% and HC emission decreased by 57.69% with hydrogen diesel dual fuel mode. Beyond that, CO emission decreased by 45.8% compared to pure diesel operation under 80% engine load. This investigation reported that low EGR percentage was preferred to lower NO_x concentration as NO_x increased with higher engine temperature.

Boretti [38] reported that hydrogen diesel dual fuel engine has increased engine thermal efficiency close to 40% comparing to the original diesel engine.

Many research studies have found significant enhancement in engine power and decreased in emission levels under hydrogen and diesel dual fuel engine [39][40]. However, some research had pointed out that high percentage of hydrogen addition may cause higher emission levels. In Chaisermtawan, et al. [41], their research study stated that as hydrogen addition to the engine increases, the amount of H_2, CO and CH_4 in the exhaust gas also increased depending on the air and fuel ratios given to the engine.

Other problems are also found in other experimental research studies. Santoso, et al. [42] conducted a study on dual fuel engine with diesel and hydrogen and found that at the low load, hydrogen enhancement reduced the cylinder pressure and also reduced engine efficiency. Higher emission level of NO_x comparing to original diesel operation is another major problem for hydrogen addition [43].

Many research studies have found low percentage of hydrogen to provide better results in mixing with diesel when it comes to operate a diesel dual fuel engine. Szwaja, et al. [44] found that 5% hydrogen addition to the diesel engine shorten ignition time and at the same time decreased temperature of the engine which will enhance engine durability when comparing to only pure diesel operation.

Various results were inconsistent depending on how the research experiment had been conducted, techniques and technologies. SinghYadav, et al. [45] pointed out that using EGR (exhaust gas recirculation) technique will provide better results in lowing emission level and improved performance level when compared to the pure diesel operation. Escalante and Fernandez [46] claimed that higher volume of injection is needed to achieve better results because a low hydrogen density makes larger volume of fuel. Christodoulou and Megaritis [47] reported that hydrogen addition can actually decrease smoke and CO at the expense of higher NO_x emission levels.

An advance experiment has also been conducted with using hydrogen and compressed natural gas or LPG in diesel engine. However, there are still many problems with using this technique. Arat, et al. [48] conducted an experiment using HCNG in diesel engine and found three problems, namely; minor reduction in power output, higher brake specific fuel consumption and storage problem. In Lata and Misra

[49] experimental study, blending both hydrogen and LPG and used them altogether as a secondary source provided better results in performance and emission.

Indeed, HCNG has already been experimented with many spark ignition engines previously. The results of using HCNG in spark ignition engines are still providing unsatisfied results but certainly the results are much better comparing to the normal natural gas engine.

Ma, et al. [50] investigated engine performance and emission of a turbocharged CNG engine fueled by hydrogen and natural gas with 55% hydrogen ratio. The results of this experiment are highly suggested that introducing additional hydrogen can improve combustion, reduce flame propagation duration, increase torque output comparing to using pure CNG in such an engine. Furthermore, the results have shown that high hydrogen ratio can significantly extend the lean burn limit and increases thermal efficiency [51]. Their study has confirmed that high hydrogen ratio increased burning speed of the fuel [52]. The reason for faster burning speed is because the additional hydrogen provides a pool of H and OH radicals which makes the combustion reaction much easier and faster, thus leading to shorter burn duration. Thermal efficiency of high hydrogen ratio obtained in this experiment also improved by 33.7% under the operating conditions of a lambda of 2.4. Beyond that, emission such CO and CH_4 are remarkable reduced with this methodology of high hydrogen ratio but NO_x increased at the same time [53].

Mohammed, et al. [54, 55] investigated engine characteristics and emissions with using hydrogen in CNG spark ignition engine. They were expected that small amount of hydrogen addition into the CNG supply can increase the burning velocity and the combustion will be faster even when the mixing is poor in the low engine speed. Their results have demonstrated that engine torque increased in low speed but decreased in high speed of 4000 rpm. The brake thermal efficiency was also increased with additional hydrogen in the CNG supply to the engine. As well as improvements in performance of the engine, their results also show that emissions were also improved as well.

Suryawanshi and Nitnaware [21] investigated HCNG in the spark ignited engine and summarized many benefits of using HCNG as a better choice of alternative fuel. Their arguments pointed out that using CNG alone will result in engine wear out, damage inlet valve and engine parts as compared to conventional fuel gasoline. Because using CNG alone in gasoline engine will slow down burning velocity, thus leading to poorer combustion stability. Furthermore, using CNG alone in gasoline engine will reduce torque and power of the engine comparing to using gasoline. Therefore, based on their findings; using HCNG will be a better choice for gasoline engine comparing to the original fuel supply from using CNG. Their report further examines properties of adding hydrogen to natural gas. Many benefits of using blending hydrogen with natural gas were investigated thoroughly in their report. These results are hydrogen mass specific lower heating value, LHV of 120 MJ/kg is nearly three times that of methane and gasoline, an approximate seven fold of increasing burning speed over pure methane and gasoline, less heat transfer from a hydrogen flame compared to either methane and gasoline flames and quenching distance of 0.064cm is approximately 1/3rd of pure methane and gasoline.

For HCNG, technical adaptation to the actual engine is the most significant in getting better performance and emission results. Many researchers have found difficulties in balancing expected performance results and satisfied decreasing results of emission levels. Ceper, et al. [56] evaluated a blended of varies percentage of hydrogen from 0% to 30% and found that at the rich mixtures of hydrogen content went up to 30%, CO2 emission level also increased as the percentage of hydrogen content had increased at the same time. Ma, et al. [57] also found the same problem with increasing percentage of hydrogen in the spark-ignition engine but in different results of emission concerns. Ma, et al. found that nitrogen oxides (NO_x) increased as the percentage of hydrogen has increased during the experiment. On the other hand, Ortenzi, et al. [58] conducted experimental study of using 10% and 15% hydrogen addition to the CNG spark-ignition engine and found HC emissions increased at the low load when applying hydrogen addition. Huang, et al. [59] found similar characteristic of hydrogen addition when comparing to pure CNG operation alone. They found that at the normal operation, running the engine with CNG gave higher values of peak cylinder pressure and better heat release rate. Only in the case of stoichiometric mixture combustion, then hydrogen addition gave the highest values of peak cylinder pressure and maximum heat release rate. Park, et al. [60] conducted an experimental study of using HCNG in spark-ignition engine and found greater performance but also found that CH_4 emission was higher than normal CNG and did not meet the standard of EURO VI requirement.

In summary from reviewing all of the literatures, there are still many problems of using alternative fuels with internal combustion engine either in finding optimization point to balance in between gaining better performance and better emission levels or finding effective and reliable technology to maximize the use of alternative fuels. Thus, it is rational to explore the potential of using reliable, affordable and emission friendly technology to achieve greater performance and lower emission levels from the advantages and disadvantages of many alternative fuels for diesel dual fuel engines. In addition to that, HCNG has the highest feasibility to the normal CNG supply to the diesel dual fuel engines. Therefore, this experiment will be choosing HCNG as the main source of normal diesel substitution.

CHAPTER III

RESEARCH METHODOLOGY

The research methodology in this project involves selection of correct materials, choosing correct testing equipment, data collection and data analysis. The complete overview of the system and wiring diagram as well as ECU connection diagram are shown in figure 24, figure 25, figure 26 and figure 27 in the appendix section of this dissertation. The complete processes of possible results are coming from many insight thoughts and lessons learned from the literature reviews.

Materials for the experiment

Correct materials on this research project included many major equipment and many minor parts to comply with the design of HCNG DDF system (figure 25) that could possibly provide positive satisfy results. Below is the list of materials for this experiment and their technical specification details are shown in the table next to them.

1. Common-rail direct injection vehicle

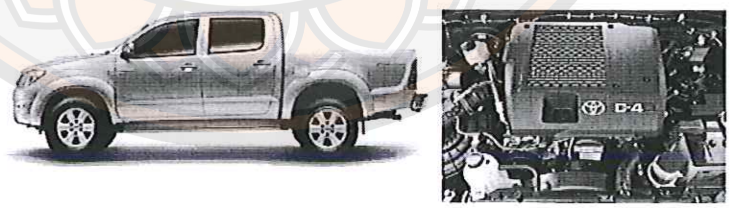

Figure 3 Vehicle with Commonrail D4D engine for this experiment

Table 5 Specification of the vehicle for this experiment

Manufacture	Toyota
Vehicle Model	2.5 J (VNT)
Outside Dimension	5135 x 1750 x 1560
(Length x Width x Height) mm.	
Height above ground mm	151
Inside Dimension	1340 x 1475 x 1190
(Length x Width x Height) mm.	
Weight	1460

2. CNG Automotive cylinder

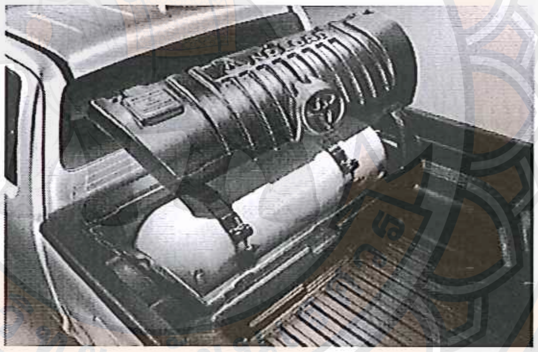

Figure 4 CNG cylinder ISO11439 standard for CNG storage

Table 6 Specification of CNG automotive cylinder

Manufacture	Zhejiang Jindun Pressure Vessel Co., Ltd.
Size	100 Liters
Material	Steel 34CrMo4
Model Number	ISO 11439
Outside Diameter	406mm
Standard	ISO11439-2000

3. CNG filling valve NGV1 profile

Figure 5 CNG filling valve with NGV1 profile

Table 7 Technical specifications of CNG filling valve

Manufacture	OMB
Model	APUS 1
Maximum working pressure	260 Bar
Maximum working temperature	-40 C - 120 C
Supply System	CNG
Standard	ISO 15500
	ECE R110
Power Supply	12 Volt
In Connection	M12 x 1

4. CNG Reducer

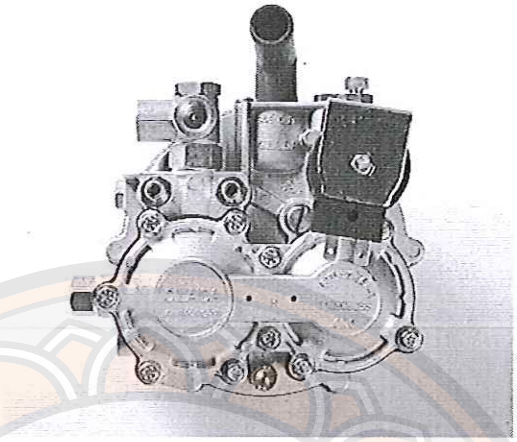

Figure 6 Three stages CNG reducer for this project

Table 8 Technical specification for CNG reducer

Manufacture	Tomasetto Achille
Model number	AT04
Dimension	154.5 x 190 x 110 mm
Material	Die-cast aluminium body, CNC machined
Type of product	CNG traditional reducer
Max. inlet pressure	26 Mpa
Coil voltage	12 V DC
Coil Power	15 W
Inlet Connection	OD 6mm M12x1
Outlet Connection	Swivel plastic pipe OD 19mm

5. CNG pressure sensor

Figure 7 CNG pressure sensor

Table 9 Technical specifications of CNG pressure sensor

Manufacture	AEB
Model	806
Maximum Pressure	250 Bar
Standard	UN ECE R110
	ISO 15500
Power Supply	+12 Volts

6. CNG LED indicator

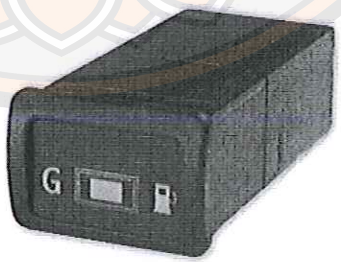

Figure 8 CNG LED level indicator in the CNG cylinder

Table 10 Technical specification of the CNG LED indicator

Manufacture	AEB
Model	706
Operating Power	DC 12V
Standard	UN ECE R110
	ISO 15500

7. CNG high pressure tube

Figure 9 CNG high pressure tube for this experiment

Table 11 CNG high pressure tube technical specifications

Manufacture	OMB
Maximum working pressure	260 Bar
Maximum working temperature	-40 C - 120 C
Supply System	CNG
Standard	ISO 15500
	ECE R110
In Connection	M12 x 1

8. CNG stepping motor

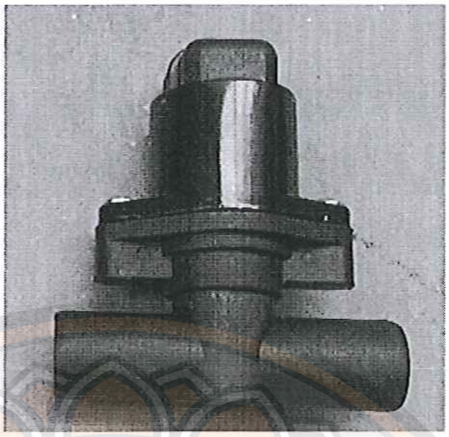

Figure 10 CNG stepping motor

Table 12 CNG stepping motor technical details

Manufacture	LAE
Model	D2
Maximum Pressure	3 Bar
Standard	UN ECE R110
	ISO 15500
Power Supply	+12 Volts

9. Electronic controlled unit for this project

Figure 11 Electronic controlled unit for this project

Table 13 Technical details of the electronic controlled unit

Manufacture	ECOMAX
Engine Configuration	4-6 Cylinder Diesel Engine
Fueling Adjustment	Up to 440 Zone table with configurable load and RPM, TPS, MAP, MAF and options
Limits	Vehicle speed limit, Engine Temp. Limit System Voltage Limit
Processing	40 MHz Automotive Processor Ignition Control to 0.1 degree, Fuel to 0.01 ms, 32 Bit Calculation, Max 6000 RPM 10 Bit ADC Resolution
Inputs / Outputs	2 High current injector drives 4 ignition channels, 2 + 5 Volts 8 Fuel Reduction output, 8 sensor inputs
Communication	On Board USB (Tuning Port), Serial, CAN BUS
Analog Inputs	Display LCD, Wideband O2 Voltage Signal (0-5)
Idle Control	Closed Loop System Solenoid and Stepper Motor Electronic Valve

10. Electrolyzer for H2 generation and its accessories

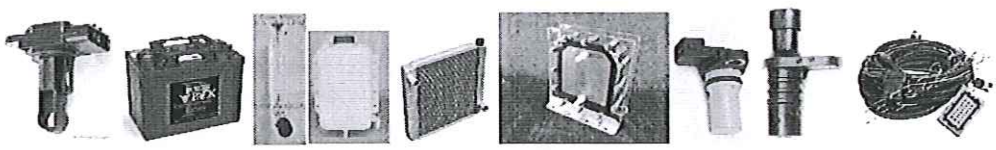

Figure 12 Various parts and sensor for the hydrogen generator for this project

Table 14 Electrolyzer and its accessories details

Manufacture	Custom made only for this project
Materials	SS 316L
Capacity	at least 0.5 liter per minute
Cooling Method	Incinerator and water membrane
Weight	5 Kg
Dimension	4 inches x 4 inches
Working sensor	Camshaft for RPM
	TPS sensor
	Acceleration Sensor
Battery	12 Volts DC
Flow rate	Measure up to 2.5 liter per minute

Testing Equipment

Testing Equipment has been chosen to meet the desire expected results in this experiment with accuracy and repeatability of at least three tests at each time. Pre-selected destination on each test are chosen to meet the require results.

1. Chassis Dynamometer

Figure 13 Chassis dynamometer

Table 15 Chassis dynamometer specifications

Manufacture	MAHA
Model	LPS 3000
Measurement Program	Display of Speed RPM, and oil Temperature Project of engine power
Standard	DIN 70020, EEC 80/1269 ISO 1585, JIS D 1001 SAE J 1349
Load Simulation	Constant RPM, Speed Tractive Force
Evaluation	Visual Display of limit value deviation Selection of measurement units (Kw/Ps/ Brake Horse power/Torque)
Printout	Clear Color printout (graphics printout) Performance diagrams of continuous and discrete measurements printable in tabular form, maximum values highlighted, selection of tabular values
Database	Storage and loading of performance diagrams Data import and Export Freely programmable load simulation profiles Determination of data according to vehicle type

2. Smoke meter

Figure 14 Smoke detector and the measuring equipment

Table 16 Technical specification of the smoke meter unit

Manufacture	MAHA
Model	MGT 5
Weight	24 kg
Test Method	Light extinction detection
Standard	SAE J 1667

3. Gas Analyzer

Figure 15 Gas analyzer stationary unit for this experiment

Table 17 Stationary automotive gas analyzer for this experiment

Manufacture	Naptune
Model	HG 540
Measuring item	HC, CO, CO2, O2, Nox
Measuring Method	HC, CO, CO2,Nox (non-disersive infrared)
	O2 (Electro Chemical)
HC	0-10000 ppm
CO	0.000-9.999%
CO_2	0-20%
O2	0-25%
NO_x	0-10000 ppm
Repeatability	Less than +/- 2% FS
Response Time	Within 10 Seconds
Warming Up time	about 5-10 Minutes

Table 17 (Cont.)

Flow Rate	2-4 L / Min
Power Supply	AC 110 / 220V, 50/60Hz
Operating Temperature	-10 Celsius to 40 Celsius
Dimension	270 (W) x 340 (D) x 165 (H) mm
Weight	5 Kg
Printer Type	Built-in Thermal Printer
Basic Accessories	Probe, Probe hose, spare fuse, Leak test cap, Dust Filter carbon filter, Operation Manual, Power cord, Printer Paper
PRM / OIL TEMP	Measurable with HRT-300

Testing Procedures

After gathering all of the chosen equipment and arrange the testing devices for data logging and measurement following the connection diagram in figure 26, the experiment would be following the procedures below under each different testing standards require in each testing programs which are the minimum requirement by the ministry of transportation in Thailand. The procedures are separated into three different parts.

Part 1 Performance test

Under this performance test, the purpose is to investigate the horsepower, fuel consumption, flow rate, torques and thermal efficiency of the engine during normal operation and HCNG operation following the connection diagram in figure 26.

The first set up is to test from idle normal diesel operation alone and speed up to the maximum rpm of the engine (approximately from 1400 rpm to 4500 rpm according to the chassis dynamometer standard) which will provide desired details for the calculation of final expected performance parameters. The expected result will provide accurate data of fuel consumption, horsepower, and torque, flow rate of diesel, brake power, air-fuel ratio and thermal efficiency of the vehicle.

The second procedure starts with running in HCNG operation with minimum pilot diesel injection in the engine controlled by the software of the electronic controlled unit by turning on the HCNG mode. The speed on the chassis dynamometer would start the test from running at the idle speed up to the maximum rpm or from 1400 rpm to 4500 rpm during the test. Once the vehicle has been accelerated, the chassis dynamometer computer system will print out both normal diesel operation and HCNG operation for future references. The test will be repeated three consecutive times for more accurate results.

Part 2 Emission Test

The emission test aims to examine the emission level from operating the vehicle under normal diesel operation and HCNG diesel dual fuel operation. The first procedure under this part is to test the vehicle with normal factory standard or under EURO IV standard which advices details require for new vehicle under category M that the chosen experimental vehicle has been classified with particular values in each emission category. The test begins with starting the vehicle under normal operation and speed the engine from idle rpm to the maximum rpm or from 800 rpm to 4,500 rpm. Once the test is done with accuracy, the computerized system will print out the results of both normal diesel operation and HCNG operation for further evaluation. The test will be repeated for 3 consecutive times for more accuracy on the expected results.

Part 3 Real road testing for fuel saving

The procedure starts from filling up full tank of normal diesel into the vehicle and drive at least 20 kilometer in distance with constant speed of 80 kilometer per hour. The purpose of this test is to determine real mass fuel consumption of the diesel engine with the chosen vehicle and compare the result with HCNG operational mode. Data recording starts with recording total kilometer, total diesel in full diesel tank and actual distance of travelling per trip in three consecutive times. And afterward, during HCNG mode; the vehicle will be filled up with CNG and H_2 will be generated while minimum pilot diesel injection will be used to start the engine. Expected results will be recorded in terms of how much diesel and CNG were consumed per trip and the data will be compared against the data from operating diesel alone.

Data collection

1. Performance parameters

The data collection of this experiment consists of 3 main parts. The first part is the performance testing which will incorporate collecting data for further analysis of the engine performance. Performance parameters such as brake horsepower, brake torque, fuel consumption, original diesel substitution, sensor values and brake thermal efficiency were designed to be measured in the most accurate manner and collect all related data for further mechanical analysis on MAHA LPS 3000 chassis dynamometer.

The fuel consumption flow rates are measuring accordingly from two flow meters and also from the chassis dynamometer in advance mode. Brake specific thermal efficiency could be calculated from fuel consumption, times, power input and power output of different fuels for further mechanical analysis of the real engine performance parameter. For the performance test, the experiment begins with mainly double checking on safety practices of both diesel operation and HCNG DDF operation ensuring no leakages of any sort of hazard and dangerous fuels were leaking during the test and afterward. Then run only in diesel mode on chassis dynamometer to collect initial data for diesel operation three consecutive times. Horsepower, torque, fuel consumption and etc. were measured in three consecutive events on pure diesel operation to ensure accuracy of correct results in this experiment. The computerize system of chassis dynamometer will print out reports on each desire performance parameter against different RPM from the lowest to the highest possible for review and references. Afterward, the vehicle will be entered into HCNG diesel dual fuel mode and will run on the same test three consecutive times while performance data were collecting for further analysis of performance between pure diesel operation and HCNG diesel dual fuel operation. The printed reports of HCNG DDF operation were collected after three consecutive tests had been done with accuracy.

2. Emission parameters

The emission test for this experiment was separated into two parts. The first part was tested with gas analyzer, Naptune HG 540, to collect all of important data of the automotive emission according to the requirement under EURO IV standard, and to examine the vehicle appropriateness for this experiment. The computerize gas analyzer will print out reports of each emission after each test. Emission of pure diesel operation was tested three consecutive times starting from running at the lowest rpm (idle), approximately 800 rpm to the highest rpm of 4000 rpm. Printed out of the results were collected after each test had been done with accuracy. After that, emission of HCNG Diesel dual fuel operation was also tested three consecutive times from the same conditions which starting from at the lowest rpm to the highest rpm. Printed out results were collected after the all three tests had been conducted with gas analyzer with accuracy.

The second part of the emission test was smoke opacity test. Three tests were conducted with pure diesel operation and data of how much smoke in each test were recorded. Following with three more tests conducted through a smoke opacity computerized system, results of both pure diesel and HCNG diesel dual fuel were recorded and printed out for further data analysis.

3. Fuel saving parameters

Fuel saving is the key area in this research study. Accurate data collection was designed to ensure positive results and high accuracy. Data collecting started from running the vehicle with constant speed of 80 kilometer per hour on the road while collecting real mass fuel consumption during the test. Distance and actual mass fuel consumptions were measured and collected with printed out receipts from the filling stations of both diesel and CNG, while for the electrolyzer; purified water was added only 600 ml. at the beginning and it lasted until the end of the test.

The test began with running the chosen vehicle on pure diesel operation in three different distances and measured real mass diesel consumption in each diesel filling station for further data analysis on fuel saving. Afterward, with double checking on the HCNG diesel dual fuel operation; the same tests were done three consecutive times. Mass fuel consumptions were collected again at both filling stations for diesel and CNG real mass consumption for further fuel saving analysis. Once the results were satisfied and assured of accuracy, the fuel savings would then be ended with highest accuracy and great results for further analysis.

Data Analysis

The data analysis of this experiment consists of three parts. The first part is analyzing performance characteristics of using HCNG in diesel engine or turning normal diesel engine into HCNG diesel dual fuel. The second part is analyzing HCNG effects on emission level whether it will be within the require standard of EURO IV or it will produce undesirable results to the environment. The third part is the on-road experiment which was conducted in real situation with actual results that could later be developed into a newer version of fuel at the filling stations or new development in aftermarket devices option which could then be an option for automobile owners to operate their vehicle in the most affordable fuel saving manner in the near future.

The first part is to analyze data of the performance tests in both diesel and HCNG diesel dual fuel against the tested chassis dynamometer RPM. The printed out reports from the computerized chassis dynamometer were examined to provide indicators on the performance aspects of this experiment. Measurements of horsepower, torque, diesel substitution, sensor values and brake thermal efficiency were used to analyze the results. The average result will be an indicator which can be summarized into performance indicator for further suggestions, recommendation and conclusion.

The second part is to analyze emission levels and smoke opacity. Printed reports from gas analyzer and smoke opacity meter provided values of emission levels. These values showed emission levels accurately because both tests were conducted in three consecutive times. An average of all three tests was concluded in each emission parameters for further suggestion, review and recommendation.

Lastly, fuel saving analysis shows exactly the values of how much mass fuel consumption in each three tests was used during the test. It could be a real indicator whether HCNG diesel dual fuel would be appropriated for the new generation of dual fuel system for diesel engine. Results recorded from the test would show exactly the distance travelled by the vehicle and how much diesel had been consumed in each given time frame at the same speed, loads and distances.

CHAPTER IV

RESULTS

The results of this experimental study explain many characteristics in performance and emission of using pilot diesel injection and HCNG as a secondary source of fuel in dual fuel engine. It explains why there is better fuel saving when using HCNG in diesel HCNG dual fuel mode as comparing to the normal diesel operation. Three different sections are separated to explain this experimental study results.

Performance Characteristics

Performance characteristics of the engine are shown in figure 16, 17 and table 18, 19, 20, 21, and 41. Figure 16 shows the engine horsepower versus the speed (RPM) of diesel engine operating in pure diesel operation and diesel with HCNG diesel dual fuel operation. It can be seen that engine operating in diesel with HCNG DDF mode provided more horsepower of the average of 30% to the engine as comparing against the pure diesel operation. The reason for that is because the combustion speed is higher than that of diesel operation alone. Using HCNG together with pilot diesel injection in diesel engine also provides higher torques of 30% comparing to the pure diesel operation as shown in figure 17. This was due to the more complete combustion of fuels in the internal combustion engine.

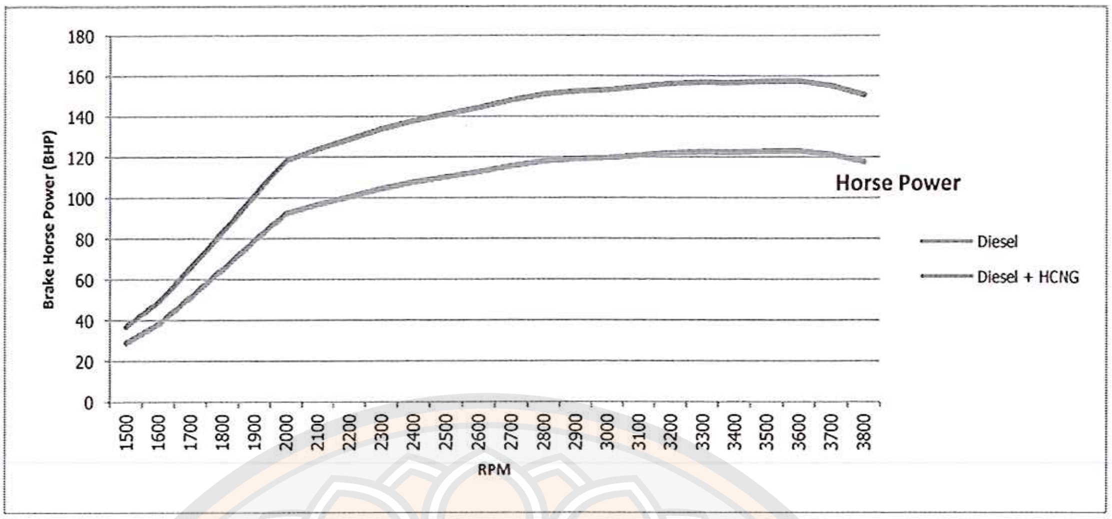

Figure 16 BHP comparison of Diesel Operation and Diesel with HCNG Operation

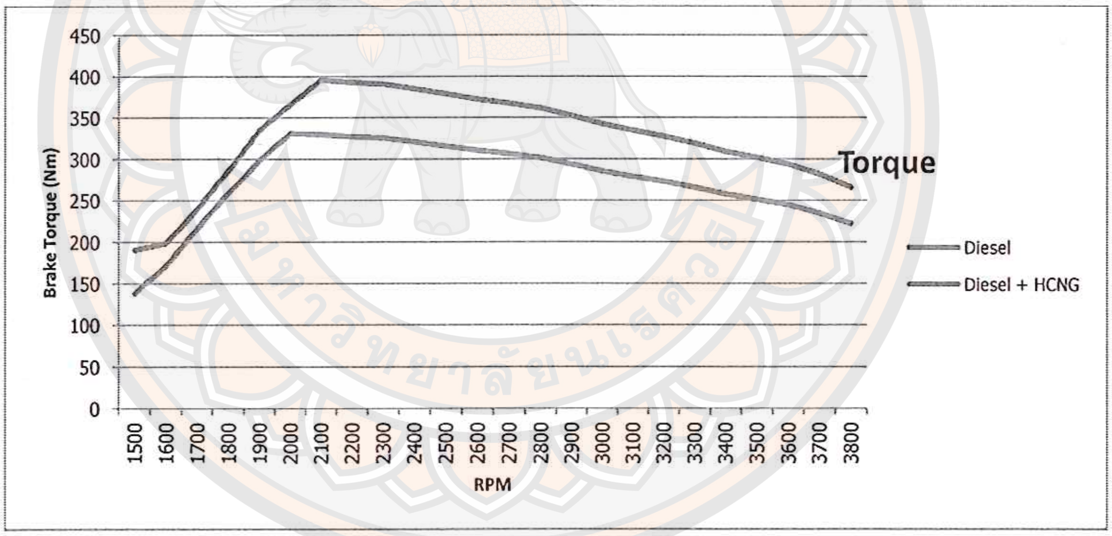

Figure 17 RPM versus Torques

Another important performance parameter is the thermal efficiency. Brake thermal efficiency has been calculated and averaged out of the three tests in table 41. The results in table 41 show BSTE of normal diesel operation and HCNG DDF operation. Thermal efficiency has increased with satisfactory results in HCNG DDF mode comparing to normal diesel mode because better combustion, perfect timing of injection each fuel into the cylinder and perfect controlled of the whole system.

Table 41 Brake thermal efficiency of original diesel operation and HCNG DDF operation

RPM	BSTE (Diesel Mode) %	BSTE (HCNG DDF mode) %
1500	20	23.32
1600	21.25	23.39
1700	22.36	25.21
1800	24.23	26.95
1900	25.46	28.24
2000	25.98	29.32
2100	26.78	29.98
2200	27.25	31.12
2300	29.41	32.82
2400	30.15	33.84
2500	31.25	35.05
2600	33.25	37
2700	33.45	38.25
2800	35.25	39.12
2900	35.89	40.12
3000	36.45	41.23
3100	34.26	38.75
3200	34.55	38.59
3300	33.25	37.56
3400	33.2	38.01
3500	31	36.89
3600	30	37.56
3700	29.2	33.98
3800	28.45	33.86

Emission Characteristics

Emissions of nitrogen oxides (NO_x), total hydrocarbon (HC), carbon monoxide (CO) and particulate matter (PM) are regulated for most vehicle types but the worldwide standards are under EURO standards. This section shows results of each different emission recorded between normal diesel operations against diesel with HCNG dual fuel operations from low RPM (800) to highest RPM of 4000. The expected emission results will be comparing against EURO IV standards as the vehicle was made under this standard.

1. **Carbon Monoxide (CO)**

Figure 18 shows comparison of carbon monoxide between pure diesel operation and diesel with HCNG operation. The results were clearly seen that average CO emission decreased by 12.97% within all speed of the engine (RPM) under diesel and HCNG dual fuel mode comparing against the pure original diesel operation, except at nearly no acceleration (800 rpm to 1200 rpm) on the engine; CO emission levels were nearly the same in both operations.

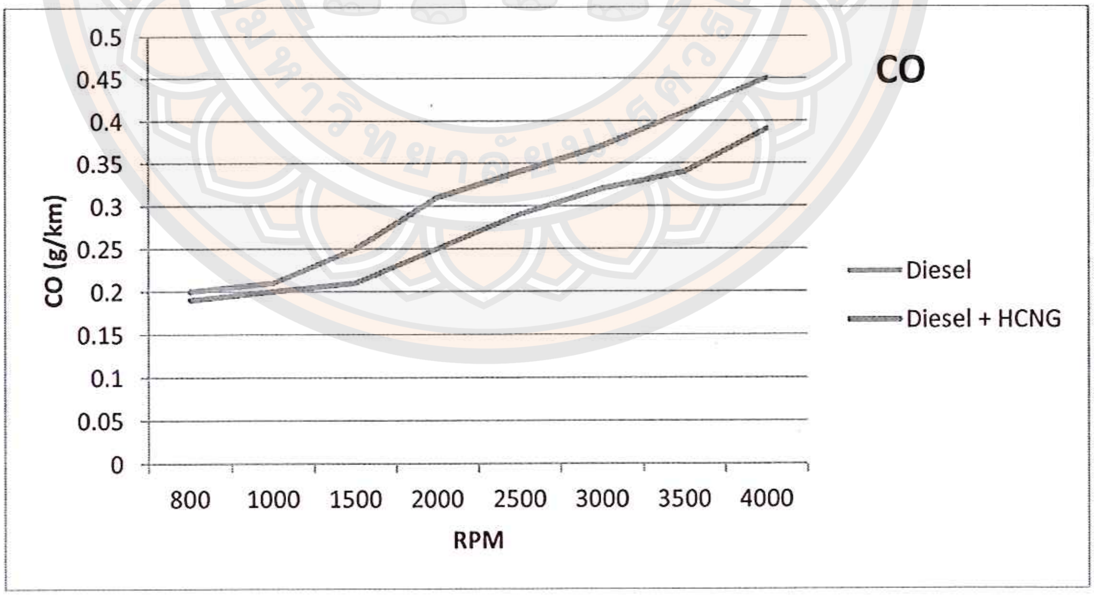

Figure 18 CO emission in comparison between diesel and diesel with HCNG

2. Hydro Carbon (HC)

Figure 19 shows comparison of hydro carbon between pure diesel operation and diesel with HCNG operation. The results demonstrated that the average HC emission decreased by 15.84% substantially with all speed of the engine (from 800 rpm to 4000 rpm) under diesel and HCNG dual fuel mode comparing against the pure original diesel operation.

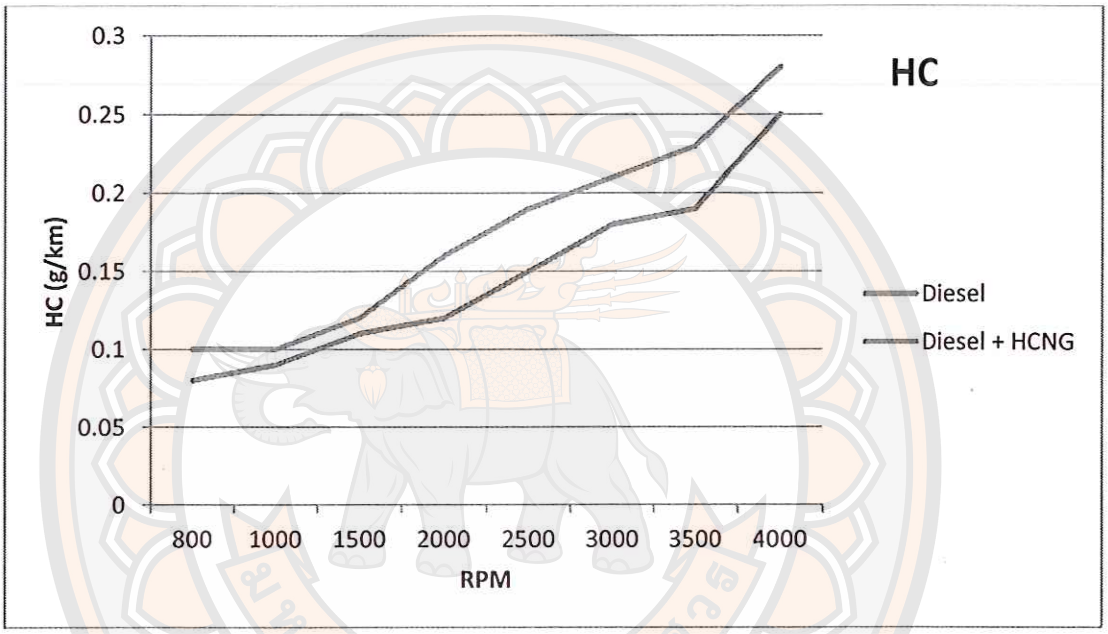

Figure 19 HC emission in comparison between diesel and diesel with HCNG

3. Nitrogen oxide (NO_x)

Figure 20 shows the comparison of nitrogen oxide between pure diesel operation and diesel with HCNG operation. The results demonstrated that the average NO_x emission level decreased by 1.16%. However, NO_x increased in low RPM (from 1000 rpm to 2500 rpm) under diesel and HCNG diesel dual fuel mode comparing against the pure original diesel operation. And NO_x decreased in higher RPM from 2600 up to 4000 RPM. This is due to the fact that in higher RPM, there is a faster rate of combustion which would leave small amount of nitric oxide as exhaust gaseous.

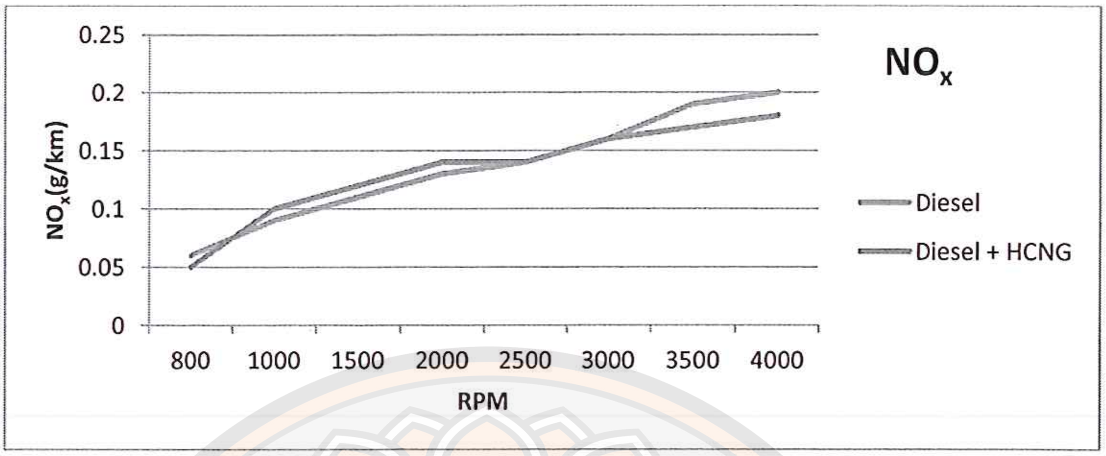

Figure 20 NO_x emission in comparison between diesel and diesel with HCNG

4. Particulate Matter (PM)

Figure 21 shows comparison of particulate matter due to incomplete combustion burning between pure diesel operation and diesel with HCNG operation. The results demonstrated that the average PM emission level decreased by 9.14% from in all speed (800 rpm to 4000 rpm) under diesel and HCNG dual fuel mode comparing against the pure original diesel operation.

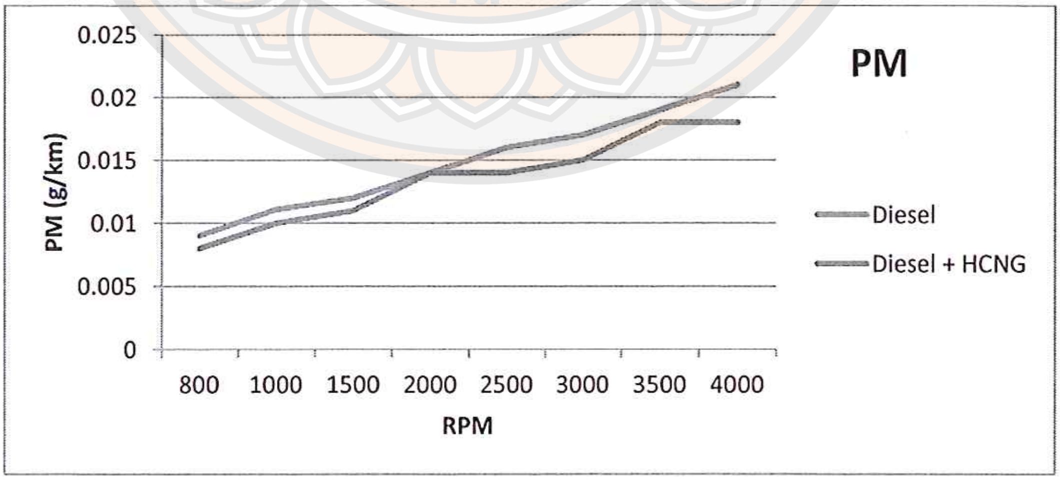

Figure 21 PM emission in comparison between diesel and diesel with HCNG

5. Smoke Density

Smoke opacity measurement has been measured and shown in figure 22 and figure 23. Figure 22 shows smoke density of both diesel mode and diesel with HCNG DDF mode. The results of three trials on each operation were clearly seen that using HCNG DDF with pilot diesel injection lower smoke density on average of 10% comparing to pure diesel operation. Figure 23 shows smoke opacity in both diesel mode and diesel with HCNG DDF mode. The reason for lower smoke is due to the fact that HCNG DDF increases higher performance and lower the engine temperature, thus resulting in more complete combustion stability of the engine. Therefore, the smoke emission is lesser than pure diesel operation.

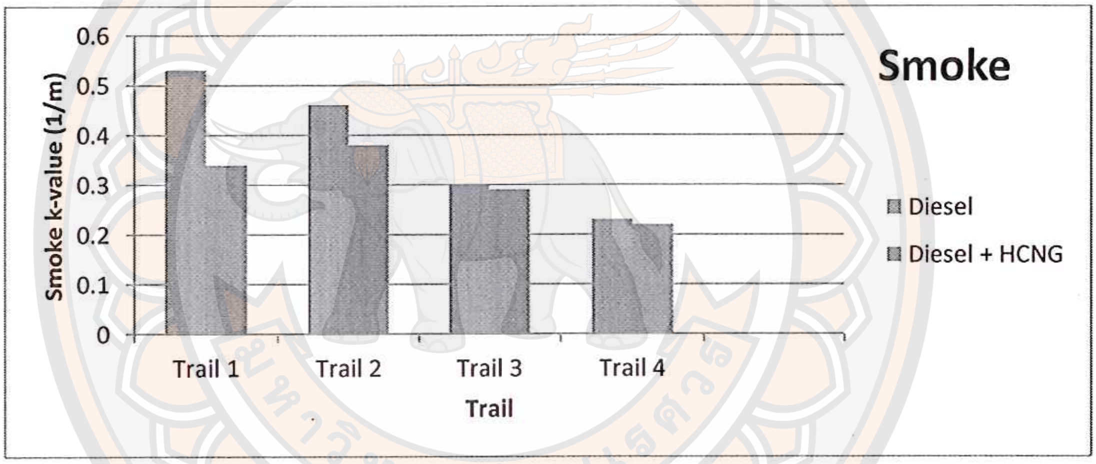

Figure 22 Smoke density

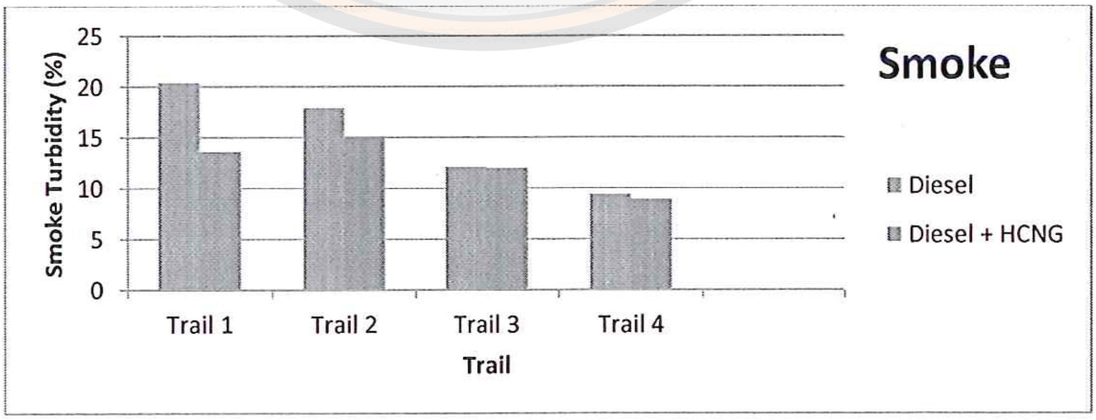

Figure 23 Smoke turbidity

Fuel Economy

Fuel Economy of an automobile is the relationship between distance travelled and the amount of fuel consumed by the vehicle. Fuel consumption of vehicles is a great factor of air pollution; therefore vehicles with the least fuel economy will greatly reduce air pollution. Figure 24 shows a comparison of fuel economy between driving with pure diesel operation and driving with diesel plus HCNG DDF on the road with a constant speed of 80 kilometer per hour. It certainly shows that HCNG DDF mode provides longer distance with the same amount of diesel per one liter. The average improvement of fuel economy is 177% in HCNG DDF mode comparing to the normal diesel mode.

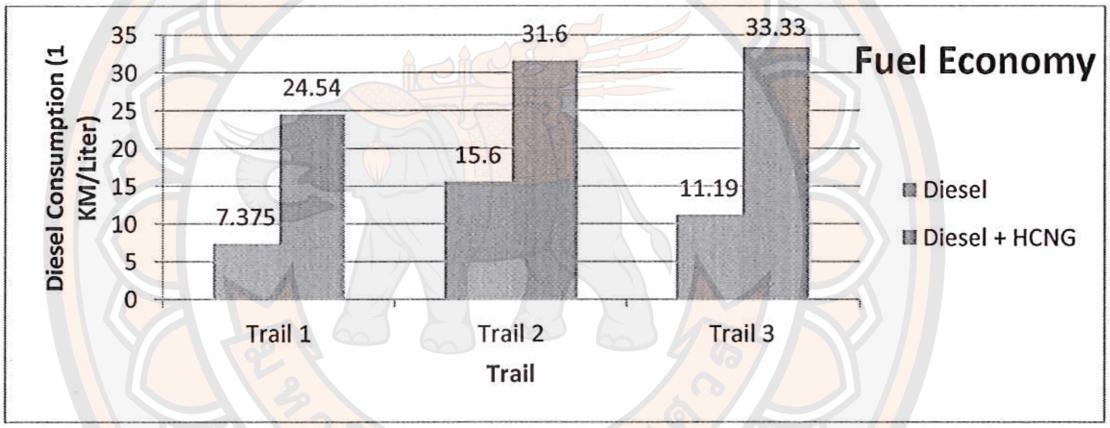

Figure 24 Fuel economy of pilot diesel in 1 liter per a kilometer

In summary, by creating initial optimum point between great performance and better emission levels; this experiment leads up to overall improved version of dual fuel engine. It advises that using HCNG diesel dual fuel system in the common rail diesel vehicle reduce emission lower than the EURO IV standard requirement from the automobile manufacturer and provide greater performance with eventually reduce the normal expenses when comparing to the original diesel operation alone.

CHAPTER V

CONCLUSION

With using a proper HCNG blended as a secondary source of engine with the minimum pilot diesel in the internal combustion engine, performances of the internal combustion engine can be increased. Furthermore using HCNG blended with pilot diesel injection in the internal combustion engine through a lean burned strategy with special designed diesel and CNG dual fuel system and additional hydrogen generation system; burning velocity, complete perfect combustion, increased of horsepower and increased of engine torque all lead to better engine performances. A significant engine horsepower and engine torque increased on average by 30% with using HCNG blended with the pilot diesel engine comparing to the pure diesel operation. Along with improvement in engine performances, smoke is also reduced substantially on average by 10% under normal EURO IV standard requirement from the OEM standards. From the results of the experiment on fuel economy, the travelling distance under HCNG DDF on average increased by 177% in distance per 1 liter of diesel as comparing to normal diesel operation.

This study indicates that HCNG is safe to use for the diesel engine with chosen engine and proper designed of HCNG diesel dual fuel system. Further researches of using HCNG as a secondary source in the pilot diesel engine can be done with many other different strategies. In addition to that, future research must also keep the optimum balance of higher performances along with keeping the lowest emission levels while maintaining higher fuel economic in all different type of strategies in making HCNG diesel dual fuel system for the internal combustion engine.

With using a proper HCNG blended as a secondary source of engine with the minimum pilot diesel in the internal combustion engine, emission levels can be substantially decreased. This study indicates that HCNG is safe to use for the diesel engine with chosen experimental engine and proper designed of HCNG diesel dual fuel system. From the experimental results, it is clearly seen that using HCNG diesel dual fuel system in diesel engine can reduce emission levels below the EURO IV emission requirements as well as normal diesel operation. The results indicated that the average CO emission decreased by 12.97%, HC emission decreased by 15.84%, NO_x emission decreased by 1.16% and PM emission decreased by 9.14% with the diesel HCNG dual fuel mode from low RPM (800) to highest RPM (4000).

Recommendation

Further researches of using HCNG as a secondary source in the pilot diesel engine to reduce emission levels can be done with many other different strategies with the need of making sure the correct injection of different fuel are properly injected into the engine at the perfect timing.

Some useful recommendations are listed below.

1. The injection of the HCNG needs stronger injector that can accommodate instant injection when needed

2. Pilot diesel injection cut off can be most improved with connecting cut off point with eight different variable signal from available cut off signal of the vehicle

3. Installation of the catalytic control with oxygen sensor preferably prior and after exhaust of the engine

4. For better results in fuel economy, overall design of the complete vehicle needs new design to make sure there is no unnessarily weigh and ensuring aerodynamic of the vehicle

5. A strong complete electronic controlled need to be redesigned to ensure long lasting performance

6. A driving pattern of the driver needed to be properly trained to maximize the benefit of the overall system

Lastly, future research must also keep the optimum balance of higher performances along with keeping the lowest emission levels while maintaining highest possible fuel economy in all different type of approaches in developing any alternative source of fuels for diesel engine.

REFERENCES

REFERENCES

[1] Stone, R. (2012). **Introduction to internal combustion engines** (4^{th} ed.). U.S.A: SAE International and Macmillan Press.

[2] Makartchouk, A. (2002). **Diesel engine engineering thermodynamics, dynamics, design, and control**. Switzerland: Marcel Dekker AG.

[3] Chai D Lai, M. and Dingle, P.J. (2005). **Diesel common rail and advanced fuel injection systems.** U.S.A: SAE International.

[4] Kumaran, D., Rajendran, M., Jeeva, P.A. and Karthikeyan, S. (2013). Formulation of novel bio based tri fuel for I.C. Engines. **International Journal of ChemTech Research,** 5(4), 1797-1801.

[5] Leelanoi, P., Suksangpanomrung, A. and Asadamongkon, P. (October 17-19, 2007). **The performance study of a diesel engine using Buthanol base Diesohol fuel.** Chonburi: Department of Mechanical Engineering, Faculty of Engineering, Srinakharinvirot University and Department of Engineering, Chulajomklao Loyal Military Academy Jointed Graduate Program.

[6] Das, D.K., Dash, S.P. and Ghosal, M.K. (2011). Performance study of a diesel engine by using producer gas from selected agricultural residues on dual-fuel mode of diesel-cum-producer gas. **World Renewable Energy Congress,** 13(006), 3541-3548.

[7] Wannatong, K., Siengsanorh, S. and Akarapanyavit, N. (March 28, 2011 –April 1, 2011). **DF-PCCI: Concept development of new diesel dual fuel technology for diesel common-rail light duty pickup truck.** Challenger, Impact, Maung Thong Thani, Bangkok, Thailand: The 7^{th} International Conference on Automotive Engineering (ICAE-7).

[8] Mahalingam, S., Kumar, P.S.M. and Pranesh, R.V. (July 2013). **Experimental study of performance and emission characteristics of a bio dual fuel blends in diesel engine for variation of injection pressures.** London, U.K.: The World Congress on Engineering (WCE).

[9] Cozzarini, C. and Lenz, H.P. (1999). **Emissions and air quality.** U.S.A: SAE International.

[10] Lim, H. (2002). **Study of exhaust emissions from idling heavy-duty diesel trucks and commercially available idle-reducing devices.** Washington, D.C.: U.S. Environmental Protection Agency.

[11] NRC (National Research Council). (2011). **Assessment of fuel economy technologies for light-duty vehicles.** Washington, D.C.: The National Academic Press.

[12] Leelanoi, P., Suksangpanomrung, A. and Asadamongkon, P. (October 2007). **The performance study of a diesel engine using Buthanol base Diesohol fuel.** Chonburi: Department of Mechanical Engineering, Faculty of Engineering, Srinakharinvirot University and Department of Engineering, Chulajomklao Loyal Military Academy Jointed Graduate Program.

[13] Das, D.K., Dash, S.P. and Ghosal, M.K. (2011). Performance study of a diesel engine by using producer gas from selected agricultural residues on dual-fuel mode of diesel-cum-producer gas. **World Renewable Energy Congress,** 13(006), 3541-3548.

[14] Lata, D.B. and Misra, A. (2012). Experimental investigations on the performance of a dual fuel diesel engine with Hydrogen and LPG as secondary fuels. In **International Conference on Future Electrical Power and Energy Systems.** Department of Mechanical Engineering, Birta Institute of Technology, Mesra, Ranchi, India: India.

[15] Fontaras, G., Martini, G., Manfredi, U., Marotta, A., Krasenbrink, A., Maffioletti, F., et al. (2012). Assessment of on-road emissions of four EURO V diesel and CNG waste collection trucks for supporting air-quality improvement initiatives in the city of Milan. **Science of the Total Environment,** 426, 65-72.

[16] Verhelst, S. and Wallner, T. (2009). Hydrogen-fueled internal combustion engines. **Progress in Energy and Combustion Science,** 35, 490-527.

[17] Amrouche, F., Benzaoui, A., Erickson, P., Mahmah, B., Herouadi, F. and Belhamel, M. (2010). Toward hydrogen enriched natural gas "HCNG" fuel on the Algerian road. **International Journal of Hydrogen Energy,** 36, 4094-4102.

[18] Morrison, G.M., Kumar R., Chugh, S., Puri, S.K., Tuli, D.K. and Malhotra, R.K. (2011). Hydrogen transportation in Delhi? Investigating the hydrogen-compressed natural gas (HCNG) option. **International Journal of Hydrogen Energy,** 37, 644-654.

[19] Nanthagopal, K., Subbarao, R., Elango, T., Baskar P. and Annamalai, K. (2011). Hydrogen Enriched compressed natural gas – a futuristic fuel for internal combustion engines. **Thermal Science,** 15(4), 1145-1154.

[20] Patil, K.R., Khanwalkar, P.M., Thipse, S.S., Kavathekar, K.P. and Rairikar, S.D. (2010). Development of HCNG blended fuel engine with control of NOx emissions. **International Journal of Computer Information Systems and Industrial Management Application,** 2, 087-095.

[21] Suryawanshi, J.G. and Nitnaware, P.T. (2011). An investigation on S.I engine using hydrogen and CNG blends. **International Journal of Research and Reviews in Applied Sciences,** 7(3), 295-303.

[22] Lata, D.B., Misra, A. and Medhekar, S. (2012). Effect of hydrogen and LPG addition on the efficiency and emissions of a dual fuel diesel engine. **International Journal of Hydrogen Energy,** 37, 6084-6096.

[23] Acharya, S.K. and Jens, S.P. (2013). Performance and emission analysis of a CI engine in dual mode with LPG and Karanja oil methyl ester. **ISRN Renewable Energy,** 2(13), 1-7.

[24] Poonia, M.P., Bhardwaj, A., Jethoo, A.S. and Pandel, U. (2011). Experimental investigations on engine performance and exhaust emissions in an LPG diesel dual fuel engine. **International Journal of Environmental Science and Development,** 2(6), 418-422.

[25] Saleh, H.E. (2008). Effect of variation in LPG composition on emissions and performance in a dual fuel diesel engine. **Fuel,** 87, 3031-3039.

[26] Egusquiza, J.C., Braga, S.L. and Braga, C.V.M. (2009). Performance and gaseous emissions characteristics of a natural gas and diesel dual fuel turbocharged and aftercooled engine. **Journal of the Brazilian Society of Mechanical Sciences and Engineering,** 31(2), 1-8.

[27] Liu, J., Yang, F., Wang, H., Ouyang, M. and Hao, S. (2013). Effects of pilot fuel quantity on the emissions characteristics of a CNG and diesel dual fuel engine with optimized pilot injection timing. **Applied Energy,** 110, 201-206.

[28] Ryu, K. (2013). Effects of pilot injection timing on the combustion and emissions characteristics in a diesel engine using biodiesel-CNG dual fuel. **Applied Energy,** 111, 721-730.

[29] Ryu, K. (2013). Effects of pilot injection pressure on the combustion and emissions characteristics in a diesel engine using biodiesel-CNG dual fuel. **Energy Conversion and Management,** 76, 506-516.

[30] Paul, A., Bose, P.K., Panua, R.S. and Banerjee, R. (2013). An experimental investigation of performance-emission trade off of a CI engine fueled by diesel-compressed natural gas (CNG) combination and diesel-ethanol blends with CNG enrichment. **Energy,** 55, 787-802.

[31] Carlucci, A.P., Laforgia, D., Saracino, R. and Toto, G. (2011). Combustion and emissions control in diesel-methane dual fuel engines: the effects of methane supply method combined with variable in-cylinder charge bulk motion. **Energy Conversion and Management,** 52, 3004-3017.

[32] Ehsan, M. and Bhuiyan, S. (2009). Dual fuel performance of a small diesel engine for applications with less frequent load variations. **International Journal of Mechanical and Mechatronics Engineering,** 9(10), 19-28.

[33] Papagiannakis, R.G., Rakopoulos, C.D., Hountalas, D.T. and Rakopoulos, D.C. (2010). Emission characteristics of high speed, dual fuel, compression ignition engine operating in a wide range of natural gas and diesel fuel proportions. **Fuel,** 89, 1397-1406.

[34] Venkatesan, M. (2011). Performance and emission characteristics of Jatropa biodiesel in dual fuel mode with CNG in a single cylinder four stroke diesel engine. **International Journal of Applied Engineering Research,** 1(4), 813-823.

[35] Wannatong, K., Akarapanyavit, N., Siengsanorh, S. and Chanchaona, S. (2007). Combustion and knock characteristics of natural gas diesel dual fuel engine. **Society of Automotive Engineers of Japan,** 2007(1), 1-6.

[36] Debnath, B.K., Saha, U. K. and Sahoo, N. (2012). Effect of hydrogen-diesel quantity variation on brake thermal efficiency of a dual fuelled diesel engine. **Journal of Power Technologies,** 92(1), 55-67.

[37] Bose, P.K. and Maji, D. (2009). An experimental investigation on engine performance and emissions of a single cylinder diesel engine using hydrogen as inducted fuel and diesel as injected fuel with exhaust gas recirculation. **International Journal of Hydrogen Energy,** 34, 4847-4854.

[38] Boretti, A. (2011). Advantages of the direct injection of both diesel and hydrogen in dual fuel H_2ICE. **International Journal of Hydrogen Energy,** 36, 9312-9317.

[39] Kose, H. and Ciniviz, M. (2013). An experimental investigation of effect on diesel engine performance and exhaust emissions of addition at dual fuel mode of hydrogen. **Fuel Processing Technology,** 114, 26-34.

[40] Zhunqing, H. and Xin, Z. (2012). Experimental study on performance and emissions of engine fueled with lower heat value gas and hydrogen mixtures. **International Journal of Hydrogen Energy,** 37, 1080-1083.

[41] Chaisermtawan, P., Jarungthammachote, S., Chuepeng, S. and Kiatiwat, T. (2012). Gaseous emissions and combustion efficiency analysis of hydrogen-diesel dual fuel engine under fuel-lean condition. **American Journal of Applied Sciences,** 9(11), 1813-1817.

[42] Santoso, W.B., Bakar, R.A. and Nur, A. (2013). Combustion characteristics of diesel-hydrogen dual fuel engine at low load. **Energy Procedia,** 32, 3-10.

[43] Saravanan, N., Nagarajan, G., Sanjay, G., Dhanasekaran, C. and Kalaiselvan, K.M. (2008). Combustion analysis on a DI diesel engine with hydrogen in dual fuel mode. **Fuel,** 87, 3591-3599.

[44] Szwaja, S. and Grab-Rogalinski, K. (2009). Hydrogen combustion in a compression ignition diesel engine. **International Journal of Hydrogen Energy,** 34, 4413-4421.

[45] SinghYadav, V., Soni, S.L. and Sharma, D. (2012). Performance and emission studies of direct injection C.I. engine in dual fuel mode (hydrogen-diesel) with EGR. **International Journal of Hydrogen Energy,** 37, 3807-3817.

[46] Escalante Soberanis, M.A. and Fernandez, A.M. (2010). A review on the technical adaptations for internal combustion engines to operate with gas and hydrogen mixtures. **International Journal of Hydrogen Energy,** 35, 12134-12140.

[47] Christodoulou, F. and Megaritis, A. (2013). Experimental investigation of the effects of separate hydrogen and nitrogen addition on the emissions and combustion of a diesel engine. **International Journal of Hydrogen Energy,** 2013, 1-15.

[48] Arat, H.T., Aydin, K., Baltacioglu, E., Yasar, E., Baltacioglu, M.K., Conker, C., et al. (2013). A review of hydrogen-enriched compressed natural gas (HCNG) – fuel in diesel engines. **The Journal of Macro Trends in Energy and Sustainability,** 1(1), 115-122.

[49] Lata, D.B. and Misra, A. (2010). Theoretical and experimental investigations on the performance of dual fuel diesel engine with hydrogen and LPG as secondary fuels. **International Journal of Hydrogen Energy,** 35, 11918-11931.

[50] Ma, F., Wang, M., Jiang, L., Chen, R., Deng, J., Naeve, N., et al. (2010). Performance and emission characteristics of a turbocharged CNG engine fueled by hydrogen-enriched compressed natural gas with high hydrogen ratio. **International Journal of Hydrogen Energy,** 35, 6438-6447.

[51] Ma, F., Wang, Y., Ding, S. and Jiang, L. (2009). Twenty percent hydrogen-enriched natural gas transient performance research. **International Journal of Hydrogen Energy,** 34, 6523-6531.

[52] Ma, F. and Wang, Y. (2008). Study on the extension of lean operation limit through hydrogen enrichment in a natural gas spark-ignition engine. **International Journal of Hydrogen Energy,** 33, 1416-1424.

[53] Ma, F., Wang, Y., Liu, H., Li, Y., Wang, J. and Ding, S. (2008). Effects of hydrogen addition on cycle-by-cycle variations in a lean burn natural gas spark-ignition engine. **International Journal of Hydrogen Energy,** 33, 823-831.

[54] Mohammed, S.E., Baharom, M.B., Aziz and A.R.A., Firmansyah. (2011). The effects of fuel-injection timing at medium injection pressure on the engine characteristics and emissions of a CNG-DI engine fueled by a small amount of hydrogen in CNG. **International Journal of Hydrogen Energy,** 36, 11997-12006.

[55] Mohammed, S.E., Baharom, M.B. and Aziz, A.R.A. (2011). Analysis of engine characteristics and emissions fueled by in-situ mixing of small amount of hydrogen in CNG. **International Journal of Hydrogen Energy,** 36, 4029-4037.

[56] Ceper, B.A., Akansu, S.O. and Kahraman, N. (2009). Investigation of cylinder pressure for H2/CH4 mixtures at different loads. **International Journal of Hydrogen Energy,** 34, 4855-4861.

[57] Ma, F., Wang, Y., Liu, H., Li, Y., Wang, J. and Zhao, S. (2007). Experimental study on thermal efficiency and emission characteristics of a lean burn hydrogen enriched natural gas engine. **International Journal of Hydrogen Energy,** 32, 5067-5075.

[58] Ortenzi, F., Chiesa, M., Scarcelli, R. and Pede, G. (2008). Experimental tests of blends of hydrogen and natural gas in light-duty vehicles. **International Journal of Hydrogen Energy,** 33, 3225-3229.

[59] Huang, Z., Liu, B., Zeng, K., Huang, Y., Jiang, D., Wang, X., et al. (2007). Combustion characteristics and heat release analysis of a spark-ignited engine fueled with natural gas and hydrogen blends. **Energy and Fuels,** 21, 2594-2599.

[60] Park, C., Kim, C., Choi, Y. and Lee, J. (2013). Operating strategy for exhaust gas reduction and performance improvement in a heavy-duty hydrogen-natural gas blend engine. **Energy,** 50, 262-269.

APPENDIX

APPENDIX

Table 18 The results of the first performance test on the chassis dynamometer for this research project

	Diesel Mode			HCNG DDF Mode		
n	v	P	M	v	P	M
RPM	km/h	BHP	Nm	km/h	BHP	Nm
1400	47.9	22.8	116.80	61.31	29.18	149.50
1500	51.3	28.90	138.10	65.66	36.99	176.77
1600	54.7	38.20	170.80	70.02	48.90	218.62
1700	58.2	51.40	216.40	74.50	65.79	276.99
1800	61.6	65.00	258.60	78.85	83.20	331.01
1900	65	79.20	298.40	83.20	101.38	381.95
2000	68.4	92.40	330.90	87.55	118.27	423.55
2100	71.9	96.70	329.90	92.03	123.78	422.27
2200	75.3	100.50	327.30	96.38	128.64	418.94
2300	78.7	104.50	325.60	100.74	133.76	416.77
2400	82.1	107.60	321.00	105.09	137.73	410.88
2500	85.5	110.20	315.70	109.44	141.06	404.10
2600	89	112.70	310.50	113.92	144.26	397.44
2700	92.4	115.50	306.30	118.27	147.84	392.06
2800	95.8	117.90	301.50	122.62	150.91	385.92
2900	99.2	119.00	293.80	126.98	152.32	376.06
3000	102.7	119.50	285.30	131.46	152.96	365.18
3100	106.1	120.80	279.00	135.81	154.62	357.12
3200	109.5	122.00	273.00	140.16	156.16	349.44
3300	112.9	122.50	265.80	144.51	156.80	340.22
3400	116.3	122.40	257.70	148.86	156.67	329.86
3500	119.8	122.90	251.40	153.34	157.31	321.79
3600	123.2	123.00	244.80	157.70	157.44	313.34
3700	126.6	121.30	234.80	162.05	155.26	300.54
3800	130	117.60	221.60	166.40	150.53	283.65

Date : 19 September 2013

Time : 16:30

Place : LTestCar, 64/12 Srinakarin Road, Suanluang, Bangkok 10250 Thailand

Performance Test : First Test

Table 19 The results of the second performance test on the chassis dynamometer for this research project

	Diesel Mode			HCNG DDF Mode		
n	v	P	M	v	P	M
RPM	km/h	BHP	Nm	km/h	BHP	Nm
1400	49.34	23.48	120.30	63.15	30.06	144.36
1500	52.84	29.77	142.24	67.63	38.10	170.69
1600	56.34	39.35	175.92	72.12	50.36	211.11
1700	59.95	52.94	222.89	76.73	67.77	267.47
1800	63.45	66.95	266.36	81.21	85.70	319.63
1900	66.95	81.58	307.35	85.70	104.42	368.82
2000	70.45	95.17	340.83	90.18	121.82	408.99
2100	74.06	99.60	339.80	94.79	127.49	407.76
2200	77.56	103.52	337.12	99.28	132.50	404.54
2300	81.06	107.64	335.37	103.76	137.77	402.44
2400	84.56	110.83	330.63	108.24	141.86	396.76
2500	88.07	113.51	325.17	112.72	145.29	390.21
2600	91.67	116.08	319.82	117.34	148.58	383.78
2700	95.17	118.97	315.49	121.82	152.28	378.59
2800	98.67	121.44	310.55	126.30	155.44	372.65
2900	102.18	122.57	302.61	130.79	156.89	363.14
3000	105.78	123.09	293.86	135.40	157.55	352.63
3100	109.28	124.42	287.37	139.88	159.26	344.84
3200	112.79	125.66	281.19	144.36	160.84	337.43
3300	116.29	126.18	273.77	148.85	161.50	328.53
3400	119.79	126.07	265.43	153.33	161.37	318.52
3500	123.39	126.59	258.94	157.94	162.03	310.73
3600	126.90	126.69	252.14	162.43	162.16	302.57
3700	130.40	124.94	241.84	166.91	159.92	290.21
3800	133.90	121.13	228.25	171.39	155.04	273.90

Date : 19 September 2013

Time : 16:45

Place : LTestCar, 64/12 Srinakarin Road, Suanluang, Bangkok 10250 Thailand

Performance Test : Second Time

Table 20 The results of the Third performance test on the chassis dynamometer for this research project

	Diesel Mode			HCNG DDF Mode		
n	v	P	M	v	P	M
RPM	km/h	BHP	Nm	km/h	BHP	Nm
1400	49.82	23.71	121.47	65.68	31.26	145.77
1500	53.35	30.06	143.62	70.34	39.63	172.35
1600	56.89	39.73	177.63	75.00	52.38	213.16
1700	60.53	53.46	225.06	79.80	70.48	270.07
1800	64.06	67.60	268.94	84.46	89.12	322.73
1900	67.60	82.37	310.34	89.12	108.59	372.40
2000	71.14	96.10	344.14	93.79	126.69	412.96
2100	74.78	100.57	343.10	98.58	132.59	411.72
2200	78.31	104.52	340.39	103.25	137.80	408.47
2300	81.85	108.68	338.62	107.91	143.28	406.35
2400	85.38	111.90	333.84	112.57	147.53	400.61
2500	88.92	114.61	328.33	117.23	151.10	393.99
2600	92.56	117.21	322.92	122.03	154.53	387.50
2700	96.10	120.12	318.55	126.69	158.37	382.26
2800	99.63	122.62	313.56	131.35	161.66	376.27
2900	103.17	123.76	305.55	136.02	163.17	366.66
3000	106.81	124.28	296.71	140.82	163.85	356.05
3100	110.34	125.63	290.16	145.48	165.63	348.19
3200	113.88	126.88	283.92	150.14	167.28	340.70
3300	117.42	127.40	276.43	154.80	167.96	331.72
3400	120.95	127.30	268.01	159.46	167.83	321.61
3500	124.59	127.82	261.46	164.26	168.51	313.75
3600	128.13	127.92	254.59	168.92	168.65	305.51
3700	131.66	126.15	244.19	173.59	166.32	293.03
3800	135.20	122.30	230.46	178.25	161.25	276.56

Date : 19 September 2013

Time : 16:45

Place : LTestCar, 64/12 Srinakarin Road, Suanluang, Bangkok 10250 Thailand

Performance Test : Third Time

Table 21 The results of an average performance test on the chassis dynamometer for this research project

	Diesel Mode			HCNG DDF Mode		
n	v	P	M	v	P	M
RPM	km/h	BHP	Nm	km/h	BHP	Nm
1400	49.02	23.33	119.53	63.38	30.17	143.43
1500	52.50	29.57	141.32	67.88	38.24	169.59
1600	55.98	39.09	174.79	72.38	50.55	209.74
1700	59.56	52.60	221.45	77.01	68.01	265.74
1800	63.04	66.52	264.63	81.51	86.01	317.56
1900	66.52	81.05	305.36	86.01	104.80	366.44
2000	70.00	94.56	338.62	90.51	122.26	406.35
2100	73.58	98.96	337.60	95.14	127.95	405.12
2200	77.06	102.85	334.94	99.64	132.98	401.92
2300	80.54	106.94	333.20	104.13	138.27	399.84
2400	84.02	110.11	328.49	108.63	142.37	394.19
2500	87.50	112.77	323.07	113.13	145.81	387.68
2600	91.08	115.33	317.75	117.76	149.12	381.29
2700	94.56	118.20	313.45	122.26	152.83	376.14
2800	98.04	120.65	308.54	126.76	156.00	370.24
2900	101.51	121.78	300.66	131.26	157.46	360.79
3000	105.10	122.29	291.96	135.89	158.12	350.35
3100	108.58	123.62	285.51	140.39	159.84	342.61
3200	112.06	124.85	279.37	144.89	161.43	335.24
3300	115.53	125.36	272.00	149.39	162.09	326.40
3400	119.01	125.26	263.71	153.89	161.96	316.46
3500	122.60	125.77	257.27	158.52	162.62	308.72
3600	126.07	125.87	250.51	163.02	162.75	300.61
3700	129.55	124.13	240.28	167.51	160.50	288.33
3800	133.03	120.34	226.77	172.01	155.61	272.12

Date : 19 September 2013

Time : 16:45

Place : LTestCar, 64/12 Srinakarin Road, Suanluang, Bangkok 10250 Thailand

Performance Test : Overall average results on the performance test on this experiment

Table 22 An average sensor measurements in diesel mode for this research project

DIESEL OPERATION				
RPM	V (Km/H)	MAF (Volts)	TPS (Volts)	Diesel Ratio (%)
800	0	2.3	1.065	100
1000	30	2.5	1.074	100
1500	51.3	2.8	1.12	100
1600	54.7	2.9	1.131	100
1700	58.2	3	1.15	100
1800	61.6	3.1	1.19	100
1900	65	3.2	1.21	100
2000	68.4	3.3	1.23	100
2100	71.9	3.35	1.25	100
2200	75.3	3.4	1.27	100
2300	78.7	3.5	1.3	100
2400	82.1	3.6	1.32	100
2500	85.5	3.65	1.35	100
2600	89	3.69	1.39	100
2700	92.4	3.75	1.42	100
2800	95.8	3.8	1.48	100
2900	99.2	3.9	1.5	100
3000	102.7	3.931	1.56	100
3100	106.1	3.945	1.575	100
3200	109.5	3.96	1.61	100
3300	112.9	3.98	1.64	100
3400	116.3	4	1.67	100
3500	119.8	4.15	1.7	100
3600	123.2	4.3	1.75	100
3700	126.6	4.5	1.82	100
3800	130	4.7	1.98	100

Table 23 An average sensor measurements with HCNG DDF mode turned on for this research project and normal diesel substitution for this research project

HCNG Diesel Dual Fuel Operation (HCNG Fraction Data)					
n (RPM) HCNG DDF	v (KM/H) HCNG DDF	MAP - HCNG DDF (Volts)	TPS - HCNG DDF (Volts)	Diesel Ratio (%)	HCNG Substitution Ratio (%)
800	0	2.1	0.80	91.30	8.70
1000	35	2.3	0.81	92.00	8.00
1500	53	1.9	0.84	67.86	32.14
1600	58	1.95	0.85	67.24	32.76
1700	65	1.95	0.86	65.00	35.00
1800	69	1.95	0.89	62.90	37.10
1900	72	1.95	0.91	60.94	39.06
2000	75	1.99	0.92	60.30	39.70
2100	78	1.99	0.94	59.40	40.60
2200	80	2	0.95	58.82	41.18
2300	82	2.1	0.98	60.00	40.00
2400	86	2.13	0.99	59.17	40.83
2500	90	2.17	1.01	59.45	40.55
2600	92	2.21	1.04	59.89	40.11
2700	96	2.25	1.07	60.00	40.00
2800	98	2.28	1.11	60.00	40.00
2900	101	2.34	1.13	60.00	40.00
3000	105	2.35	1.17	59.78	40.22
3100	110	3.2	1.18	81.12	18.88
3200	113	3.3	1.21	83.33	16.67
3300	119	3.4	1.23	85.43	14.57
3400	125	3.5	1.25	87.50	12.50
3500	130	3.7	1.28	89.16	10.84
3600	134	4.3	1.31	100.00	0.00
3700	137	4.5	1.37	100.00	0.00
3800	142	4.7	1.49	100.00	0.00

Table 24 The results of CO emission level during the first test on this research project

Date		19/9/2013
Time		10:00 AM
Diesel Density		0.8343 Kg/L
Electrolyzer		0.5 Liter / Minute
CO Emission Test #1 in Gram per KM (g/Km)		
RPM	Diesel Mode	HCNG DDF Mode
800	0.2	0.19
1000	0.21	0.2
1500	0.25	0.21
2000	0.31	0.25
2500	0.34	0.29
3000	0.37	0.32
3500	0.41	0.34
4000	0.45	0.39

Table 25 The results of CO emission level during the second test on this research project

Date		19/9/2013
Time		10:05 AM
Diesel Density		0.8343 Kg/L
Electrolyzer		0.5 Liter / Minute
CO Emission Test #2 in Gram per KM (g/Km)		
RPM	Diesel Mode	HCNG DDF Mode
800	0.24	0.21
1000	0.26	0.22
1500	0.29	0.25
2000	0.33	0.28
2500	0.36	0.31
3000	0.38	0.34
3500	0.43	0.38
4000	0.46	0.41

Table 26 The results of CO emission level during the third test on this research project

Date		19/9/2013
Time		10:10 AM
Diesel Density		0.8343 Kg/L
Electrolyzer		0.5 Liter / Minute
CO Emission Test #3 in Gram per KM (g/Km)		
RPM	Diesel Mode	HCNG DDF Mode
800	0.22	0.18
1000	0.24	0.23
1500	0.27	0.24
2000	0.31	0.25
2500	0.34	0.29
3000	0.36	0.31
3500	0.40	0.35
4000	0.43	0.39

Table 27 The results of CO emission level in average from all of the three tests on this research project

Date		19/9/2013
Time		10:15 AM
Diesel Density		0.8343 Kg/L
Electrolyzer		0.5 Liter / Minute
CO Emission Test Average Results in Gram per KM (g/Km)		
RPM	Diesel Mode	HCNG DDF Mode
800	0.22	0.193
1000	0.236	0.216
1500	0.27	0.233
2000	0.316	0.26
2500	0.346	0.296
3000	0.37	0.323
3500	0.413	0.356
4000	0.446	0.396

Table 28 The results of HC emission level during the first test on this research project

Date	**19/9/2013**
Time	**10:00 AM**
Diesel Density	**0.8343 Kg/L**
Electrolyzer	**0.5 Liter / Minute**

HC Emission Test #1 in Gram per KM (g/Km)

n (RPM)	Diesel	HCNG DDF
800	0.1	0.08
1000	0.1	0.09
1500	0.12	0.11
2000	0.16	0.12
2500	0.19	0.15
3000	0.21	0.18
3500	0.23	0.19
4000	0.28	0.25

Table 29 The results of HC emission level during the second test on this research project

Date	**19/9/2013**
Time	**10:05 AM**
Diesel Density	**0.8343 Kg/L**
Electrolyzer	**0.5 Liter / Minute**

HC Emission Test #2 in Gram per KM (g/Km)

n (RPM)	Diesel	HCNG DDF
800	0.11	0.088
1000	0.11	0.099
1500	0.132	0.121
2000	0.176	0.132
2500	0.209	0.165
3000	0.231	0.198
3500	0.253	0.209
4000	0.308	0.275

Table 30 The results of HC emission level during the third test on this research project

Date	19/9/2013
Time	10:10 AM
Diesel Density	0.8343 Kg/L
Electrolyzer	0.5 Liter / Minute

HC Emission Test #3 in Gram per KM (g/Km)

n (RPM)	Diesel	HCNG DDF
800	0.12	0.096
1000	0.12	0.108
1500	0.144	0.132
2000	0.192	0.144
2500	0.228	0.18
3000	0.252	0.216
3500	0.276	0.228
4000	0.336	0.3

Table 31 The results of HC emission level in average from all of the three tests on this research project

Date	**19/9/2013**
Time	**10:15 AM**
Diesel Density	**0.8343 Kg/L**
Electrolyzer	**0.5 Liter / Minute**

HC Emission Test Average Results in Gram per KM (g/Km)

n (RPM)	Diesel	HCNG DDF
800	0.11	0.088
1000	0.11	0.099
1500	0.132	0.121
2000	0.176	0.132
2500	0.209	0.165
3000	0.231	0.198
3500	0.253	0.209
4000	0.308	0.275

Table 32 The results of PM emission level during the first test on this research project

Date	**19/9/2013**
Time	**10:00 AM**
Diesel Density	**0.8343 Kg/L**
Electrolyzer	**0.5 Liter / Minute**

PM Emission Test #1 in Gram per KM (g/Km)

n (RPM)	Diesel	HCNG DDF
800	0.009	0.008
1000	0.0111	0.01
1500	0.012	0.011
2000	0.014	0.01
2500	0.016	0.01
3000	0.017	0.02
3500	0.019	0.02
4000	0.021	0.02

Table 33 The results of PM emission level during the second test on this research project

Date	**19/9/2013**
Time	**10:05 AM**
Diesel Density	**0.8343 Kg/L**
Electrolyzer	**0.5 Liter / Minute**

PM Emission Test #2 in Gram per KM (g/Km)

n (RPM)	Diesel	HCNG DDF
800	0.010	0.009
1000	0.012	0.011
1500	0.013	0.012
2000	0.015	0.015
2500	0.018	0.015
3000	0.019	0.017
3500	0.021	0.020
4000	0.023	0.020

Table 34 The results of PM emission level during the third test on this research project

Date	19/9/2013
Time	10:10 AM
Diesel Density	0.8343 Kg/L
Electrolyzer	0.5 Liter / Minute

PM Emission Test #3 in Gram per KM (g/Km)

n (RPM)	Diesel	HCNG DD
800	0.011	0.010
1000	0.014	0.013
1500	0.015	0.014
2000	0.018	0.018
2500	0.020	0.018
3000	0.021	0.019
3500	0.024	0.023
4000	0.026	0.023

Table 35 The results of PM emission level in average from all of the three tests on this research project

Date	**19/9/2013**
Time	**10:15 AM**
Diesel Density	**0.8343 Kg/L**
Electrolyzer	**0.5 Liter / Minute**

PM Emission Test Average Results in Gram per KM (g/Km)

n (RPM)	Diesel	HCNG DDF
800	0.010	0.009
1000	0.012	0.011
1500	0.013	0.012
2000	0.016	0.016
2500	0.018	0.016
3000	0.019	0.017
3500	0.021	0.020
4000	0.023	0.020

Table 36 The results of NO_x emission level during the first test on this research project

Date	**19/9/2013**
Time	**10:00 AM**
Diesel Density	**0.8343 Kg/L**
Electrolyzer	**0.5 Liter / Minute**

NO_x Emission Test #1 in Gram per KM (g/Km)

n (RPM)	Diesel	HCNG DDF
800	0.060	0.050
1000	0.090	0.100
1500	0.110	0.120
2000	0.130	0.140
2500	0.140	0.140
3000	0.160	0.160
3500	0.190	0.170
4000	0.200	0.180

Table 37 The results of NO_x emission level during the second test on this research project

Date	**19/9/2013**
Time	**10:05 AM**
Diesel Density	**0.8343 Kg/L**
Electrolyzer	**0.5 Liter / Minute**

NO_x Emission Test #2 in Gram per KM (g/Km)

n (RPM)	Diesel	Diesel + HCNG
800	0.069	0.058
1000	0.104	0.115
1500	0.127	0.138
2000	0.150	0.161
2500	0.161	0.161
3000	0.184	0.184
3500	0.219	0.196
4000	0.230	0.207

Table 38 The results of NO_x emission level during the third test on this research project

Date	**19/9/2013**
Time	**10:10 AM**
Diesel Density	**0.8343 Kg/L**
Electrolyzer	**0.5 Liter / Minute**

NO_x Emission Test #3 in Gram per KM (g/Km)

n (RPM)	Diesel	HCNG DDF
800	0.072	0.060
1000	0.108	0.120
1500	0.132	0.144
2000	0.156	0.168
2500	0.168	0.168
3000	0.192	0.192
3500	0.228	0.204
4000	0.240	0.216

Table 39 The results of NO_x emission level in average from all of the three tests on this research project

Date	**19/9/2013**
Time	**10:15 AM**
Diesel Density	**0.8343 Kg/L**
Electrolyzer	**0.5 Liter / Minute**

NO_x Emission Test Average Results in Gram per KM (g/Km)

n (RPM)	Diesel	HCNG DDF
800	0.067	0.056
1000	0.101	0.112
1500	0.123	0.134
2000	0.145	0.156
2500	0.156	0.156
3000	0.179	0.179
3500	0.212	0.190
4000	0.223	0.201

Table 40 A summary of fuel saving measurement

Fuel Source	Diesel 1	Diesel 2	Diesel 3	HCNG 1	HCNG 2	HCNG 3
Starting Kilometer	17896	17913	17940	17987.3	18044	18106
Ending Kilometer	17913	17940	17963.5	18044	18106	18156
Net Traveling Distance (Km) at constant speed of 80Km/Hour	17	27	23.5	56.7	57	50
Diesel Consumption (Liter)	2.305	1.73	2.10	2.31	1.8	1.50
Total cost at the filling point (Baht)	70	52.6	70	70	60	50
CNG Consumption (Kg.) (1kg/10.50B)	n/a	n/a	n/a	0.84	1.068	1.089
Total cost at the filling point (Baht)	n/a	n/a	n/a	8.9145	11.21	11.43
H_2 Flow Rate (Liter / Minute) no cost!	0.5	0.5	0.5	0.5	0.5	0.5
Overall Expenses (Diesel + HCNG)	n/a	n/a	n/a	78.9145	71.21	61.43
OEM Factory Data on Fuel Consumption (KM/L)	7.3	7.3	7.3	7.3	7.3	7.3
Total Fuel Consumption (KM/L) per Trail (Diesel Only) (80KM/H)	7.375	15.6	11.19	24.54	31.6	33.33
Net cost per Kilometer (1 KM/Baht)	4.117	1.94	2.978	2.31	1.24	1.228

(Note: @60Km Constant Speed – HCNG will result in 40+ Km / Liter of Diesel)

REMARK:

1. Approximately Fuel Saving is equal to about 58.36% as comparing to the Diesel Operation Mode
2. Cost of Diesel Depends on Each Filling Stations Not always the same and also depending on each day the price can go up and down
3. The test is purposely done with constant speed without traffic at the average constant speed of approximately 80KM/Hour

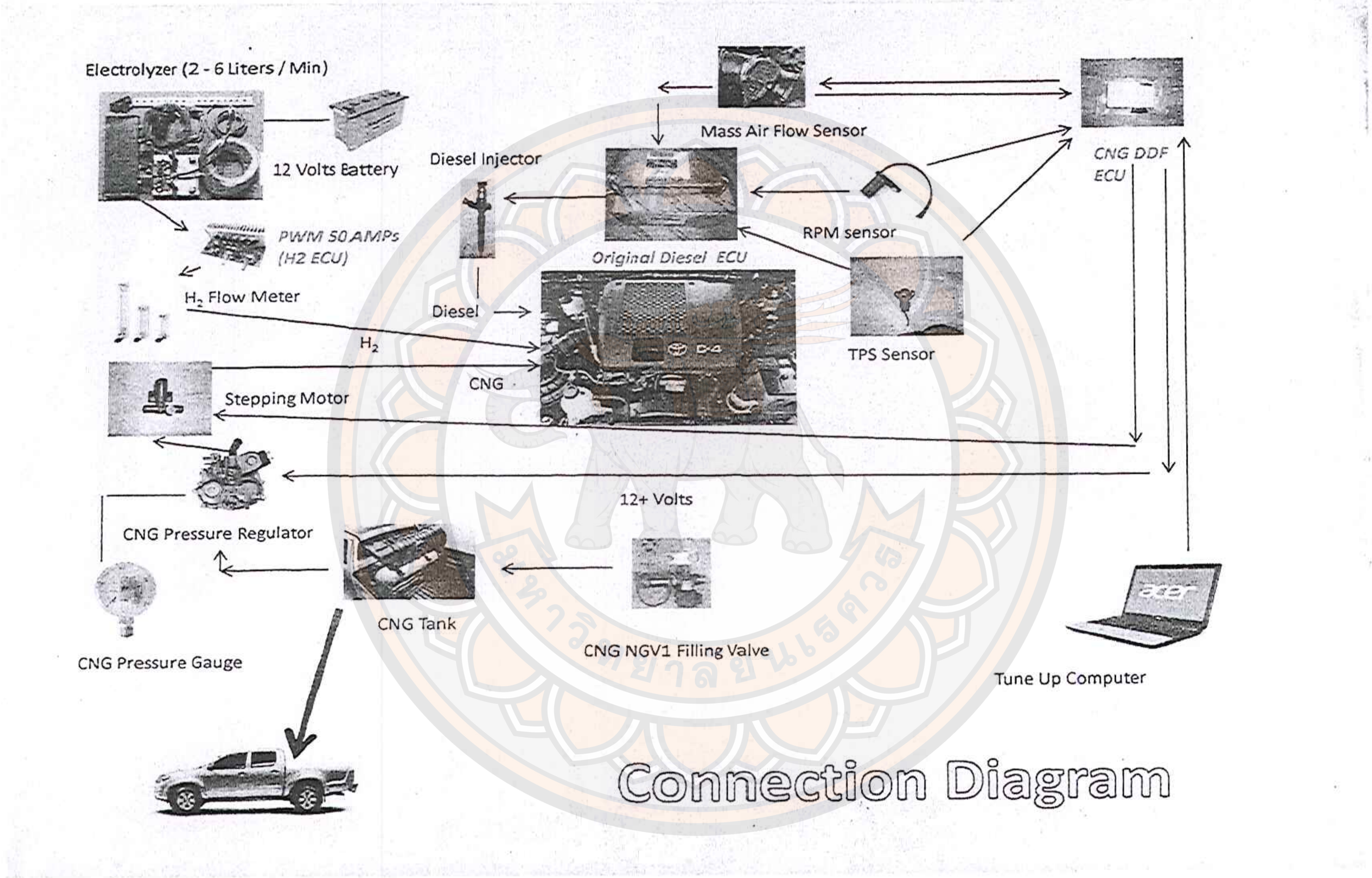

Figure 25 An overview of the connection diagram

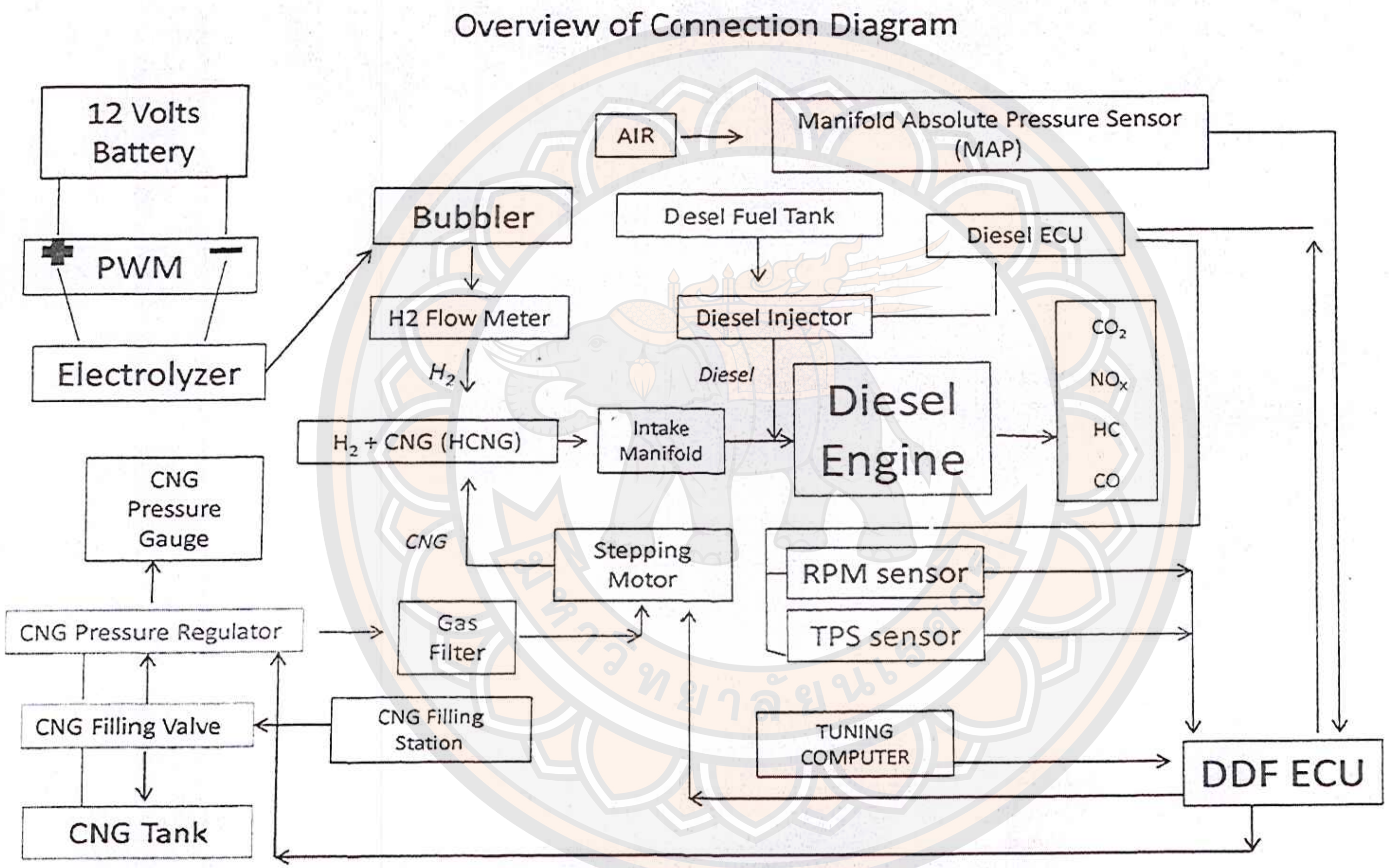

Figure 26 An overview of the complete designed HCNG DDF system

ผังตำแหน่งสายไฟ การวางสาย แบบเก่า

	8	7	6	5	4	3	2	1	
A	+12V	IGI	TPS	RPM	Gas Gauge	+5V Temp1	+5V Temp2	Main Gas	A
B	GND	In AD1	Out AD1	In AD2	Out AD2	Data Temp1	Data Temp2	Gas Valve	B
C	OT1	1A	2A	2B	1B	GND Temp1	GND Temp2	OT2	C

ตำแหน่ง	สี	ชนิดสาย	ความหมาย	ความยาว/M	หมายเหตุ
A8	แดง	AWG18	+12V	1.0	
A7	ส้ม	AWG24	IGI	1.0	
A6	น้ำตาล	AWG24	TPS	2.0	
A5	เขียว	AWG24	RPM	2.0	
A4	เหลือง	AWG24	Gas Gauge		
A3	แดง	Standard	+5V Temp 1		Temp 1
B3	ขาว	Standard	Data Temp 1	2.0	มีสัญญาณไฟ
C3	Shield	Shield	GND Temp 1		+5V นำไปใช้ได้
A2	แดง	Standard	+5V Temp 2		
B2	ขาว	Standard	Data Temp 2	1.5	Temp 2
C2	Shield	Shield	GND Temp 2		
A1	น้ำเงิน	AWG18	Main Gas	2.0	
B8		AWG18	GND	1.0	
B7		สายคู่	IN AD 1	2.0	ลดน้ำมัน IN 1
B6		AWG24	OUT AD 1		ลดน้ำมัน OUT 1
B5	แดง	สายคู่	IN AD 2	2.0	ลดน้ำมัน IN 2
B4		AWG24	OUT AD 2		ลดน้ำมัน OUT 2
B1	เขียว	AWG18 ·	Gas Vaive	2.0	
C7	แดง	AWG24	1A	1	
C6	เทา	AWG24	2A	1	Step Motor
C5	เขียว	AWG24	2B	1	
C4	ม่วง	AWG24	1B	1	
·C8	ขาว	AWG18	OT1	0.5	
C1	เหลือง	AWG18	OT2	0.5	

Figure 27 Wiring diagram for the controlled unit

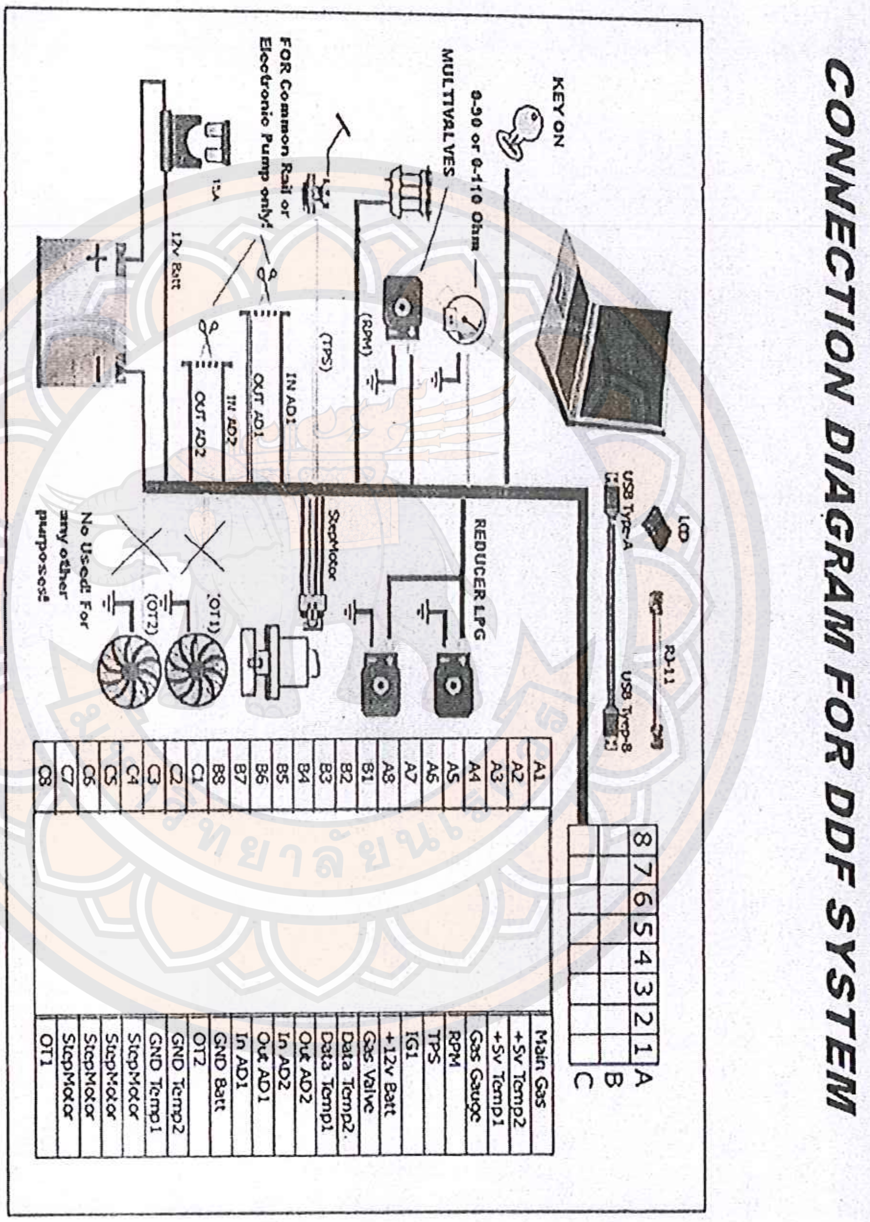

Figure 28 Diesel dual fuel (DDF) ECU connection diagram

Table 41 Brake thermal efficiency of original diesel operation and HCNG DDF operation

RPM	BSTE (Diesel Mode) %	BSTE (HCNG DDF mode) %
1500	20	23.32
1600	21.25	23.39
1700	22.36	25.21
1800	24.23	26.95
1900	25.46	28.24
2000	25.98	29.32
2100	26.78	29.98
2200	27.25	31.12
2300	29.41	32.82
2400	30.15	33.84
2500	31.25	35.05
2600	33.25	37
2700	33.45	38.25
2800	35.25	39.12
2900	35.89	40.12
3000	36.45	41.23
3100	34.26	38.75
3200	34.55	38.59
3300	33.25	37.56
3400	33.2	38.01
3500	31	36.89
3600	30	37.56
3700	29.2	33.98
3800	28.45	33.86