ONE-DIMENSIONAL SIMULATION OF A RETROFITTED MEDIUM DUTY ENGINE RUNNING USING COMPRESSED NATURAL GAS

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ABSTRACT

Environmental improvement and energy issues are recently becoming one of the worldwide concerns due to the increasing demand for petroleum usage especially from the automotive sector. This situation had lead to encounter for a new technology and reliable alternative fuel. A potential alternative fuel for compression ignition (C.I.) engine is the compressed natural gas (CNG). For C.I. engines to operate using CNG, or to be converted as a retrofitted CNG engine, further modifications are required. Previous works reported loss in brake power (BP) and increase in hydrocarbon (HC) emission for C.I. engine retrofitted with CNG fuelling. Analysis of performance and exhaust emissions characteristics for CNG retrofitted engine through experimental analysis requires high cost and very time consuming. Thus, a One –Dimensional simulation software, was introduced in this study to reduce the experimental process and setup. In this study a medium duty 4.3L, 4-cylinder, 4-stroke retrofitted compression ignition engine (RE) model were used in this simulation work over various operational conditions at low engine speed. At the beginning of this study, the model was first compared with a medium duty 4.3L, 4-cylinder, 4-stroke C.I. engine (DE) in order to predict the engine model capabilities running with different fuel types at low speed condition. The most significant finding in this simulation configuration is the RE model was able to reduce the fuel consumption (BSFC) and experience lower; brake power (BP), brake torque (BT) and brake thermal efficiency (BTE) by 18.1%, 30.3%, 30.7%, and 14.6% respectively. For emissions results the model generated higher unburned hydrocarbon emissions (HC) and lower; oxides of nitrogen (NO_x), carbon dioxides (CO_2) and carbon monoxides (CO) by 99%, 60.2%, 56.4% and 36.1% respectively. The model also had been tested at various air-fuel ratio (AFR) condition varies from 15 (rich), 17.2 (stoichiometric) and 19 (lean) condition. Finally the comparison between the simulation model and experimental engine results for performance and emissions characteristics at low engine speed are presented, and it is confirmed that the result in this study able to produce a roughly similar trend.

ABSTRAK

Penambahbaikan alam sekitar dan isu-isu tenaga telah menjadi salah satu kebimbangan kepada dunia yang disebabkan oleh peningkatan permintaan terhadap pengunaan petroleum terutama daripada sektor automotif. Situasi ini membawa kepada pencarian teknologi baru dan sumber bahan api alternatif. Salah satu bahan api yang berpotensi untuk enjin mampatan pencucuh (C.I.) adalah gas asli termampat (CNG). Bagi sebuah C.I. enjin untuk beroperasi mengunakan CNG, atau ditukar menjadi retrofit CNG enjin, beberapa perngubahsuaian diperlukan. Beberapa kajian sebelum ini melaporkan kehilangan kuasa brek (BP) dan peningkatan pelepasan hidrokarbon (HC) bagi C.I. enjin yang dipasang dengan CNG. Analisis bagi ciri-ciri prestasi dan ekzos pelepasan untuk retrofit CNG enjin melalui eksperimen memerlukan kos yang tinggi dan memakan masa. Oleh itu, satu perisian Satu–Dimensi, telah diperkenalkan untuk mengurangkan proses uji kaji dan penyelengaraan. Dalam kajian ini enjin model bersaiz sederhana 4-silinder, 4-stroke retrofit C.I. (RE) telah digunakan dalam kerja simulasi dalam pelbagai operasi pada kelajuan enjin yang rendah. Pada awal kajian ini model itu telah dibandingkan dengan enjin model bersaiz sederhana 4-silinder, 4-stroke C.I (DE) bagi meramalkan keupayaan enjin berjalan dengan mengunakan bahan api yang berbeza pada kelajuan enjin yang rendah. Penemuan yang paling penting dalam konfigurasi simulasi ini adalah model RE itu mampu mengurangkan penggunaan bahan api tertentu (BSFC) dan mengalami pengurangan; BP , tork brek (BT) dan kecekapan terma brek (BTE) masing-masing sebanyak 18.1 %, 30.3 %, 30.7 %, dan 14.6 %. Bagi jenis pelepasan keputusan yang dihasilkan oleh enjin model adalah peningkatan HC dan pengurangan; nitrogen oksida (NO_x), karbon dioksida (CO_2), dan karbon monoksida (CO) dengan 99%, 60.2%, 56.4% dan 36.1%. Model ini juga telah diuji pada pelbagai nisbah udara bahan api (AFR) dengan keadaan berbeza daripada 15 (campuran-kaya), 17.2 (stoikiometrik) dan 19 (campuran-kurang). Akhirnya perbandingan antara model simulasi dan keputusan eksperimen untuk prestasi dan ekzos pelepasan pada kelajuan enjin rendah dibentangkan, dan ia mengesahkan bahawa keputusan dalam kajian ini mampu menghasilkan trend lebih kurang sama.

CONTENTS

LIST OF SYMBOLS

A	Flow area
A_s	Heat transfer surface area
(A/F)	Air-fuel ratio
$(AF)_{stochiometric}$	Stoichiometric air-fuel ratio
$(AF)_{actual}$	Actual air-fuel ratio
B	Bore
C_f	Skin friction coefficient
CO	Carbon monoxides
CO_2	Carbon dioxides
C_p	Pressure loss coefficient
D	Equivalent diameter
D_x	Length of mass element in the flow direction
dp	Pressure differential acting across dx
E	Total internal energy (internal energy + kinetic energy)/mass
H	Total enthalpy
$H_{blended}$	LHV for blended fuel
H_g	LHV for gasoline
H_b	LHV for butanol
HC	Unburned hydrocarbon
h	Heat transfer coefficient
h_c	Heat transfer coefficient
m	Mass of the volume
$\dot{m}_a$	Air flow rate
$\dot{m}_f$	Fuel flow rate
N	Engine speed

N_c	Number of cylinder
NO_x	Oxides of Nitrogen
ø	Equivalence ratio
p	Cylinder pressure
ρ	Density
ρ_h	Butanol density
ρ_g	Gasoline denstity
$\rho u A_{eff}$	Boundary mass flux into volume, $\rho u A_{eff} = m_{flux}$
S	Stroke
T	Gas temperature
T_{fluid}	Fluid temperature
T_{wall}	Wall temperature
u	Velocity at the boundary
T	Torque
V	Volume
V_c	Clearance volume (combustion chamber)
V_d	Displacement volume
V_h	Volume fraction of butanol
V_g	Volume fraction of gasoline
w	Cylinder gas velocity

LIST OF ABBREVIATIONS

AFR	Air-fuel ratio
BDC	Bottom dead centre
BP	Brake power
BSFC	Brake specific fuel consumption
BT	Brake torque
bTDC	Before top dead centre
BTE	Brake thermal efficiency
CA	Crank angle
CNG	Compressed natural gas
CNG-BI	4-cylinder, 4-stroke retrofitted petrol engine
CNG-DI	4-cylinder, 4-stroke CNG direct injection engine
DE	Medium duty 4-cylinder, 4-stroke C.I. engine
GHG	Greenhouse gasses
LHV	Lower heating value
LNG	Liquid natural gas
MPI	Multiport injection
NGV	Natural gas vehicle
PG	Pure gasoline
RCM	Rapid compression machine
RE	4-cylinder, 4-stroke retrofitted compression ignition engine
RPM	Revolution per minute
TDC	Top dead centre

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“For him who embarks on the path of seeking knowledge,

Allah will ease for him the way to paradise”.

\- Prophet Muhammad (PBUH) -

(Related by Muslim)

CHAPTER 1

INTRODUCTION

In 1997 an international summit was held at Kyoto, Japan to discuss on environmental issues. The main card is to stabilize the atmospheric concentration of Greenhouse gases (GHG) which causes global warming. One of the main factor is the combustion of hydrocarbon from crude oil (Clémençon, 2008; Prins & Rayner, 2008; Vlachou & Konstantinidis, 2010). The current emission pollution has focused the world attention to develop alternative fuel and reduce dependency on fossil fuel. An approach have been made which seen the usage of natural gas appears to be suitable candidate in order to overcome emission problem caused by internal combustion engine.

Natural gas is a fossil fuel primary consists of methane and is one of the cleanest burning alternative fuels (Cascetta *et al.*, 2008). It can be used in the form of compressed natural gas (CNG) and liquefied natural gas (LNG) to fuel car and truck. According to the Cascetta *et al.*, (2008) use of natural gas as in a CNG engine propose several advantages; high octane number thus allowing high compression ratio in otto-cycle; promoting clean burning; negligible sulphur/toxic content and less CO_2 unit of energy than gasoline or diesel.

The CNG engine are first been used as a substitute to gasoline fuel during mid-1930 in Italy. After the energy crisis in mid-1970's most of the developing countries start to promote CNG to reduce dependency on foreign oil (Yeh, 2007). In Malaysia, the used of CNG engine was started for the use of taxi cab and airport limousine during the end of 1990's. The Increased of retrofit CNG engine user was during 2008 as the fuel subsidies were removed which seen an increase price of diesel and petrol fuel.

1.1 Background of the study

For the past 20 years, Malaysia crude oil production is at the stage of low output production since reaching the highest peak of 755 thousand barrels/day in 2004. The downside of Malaysia production in crude oil began at 2005, however at that year Malaysia still manage to produce excess crude oil production up to 40 thousand barrels/day. However, starting from 2008 until 2011, Malaysia unfortunately has consumed excess crude oil at least 8 thousand barrels/days and forecasted consumed more crude oil until a new discovery of petroleum (Malaysia Crude Oil Production and Consumption by Year, 2013). This scenario based on Figure 1.1 indicates that Malaysia is now facing higher energy demand.

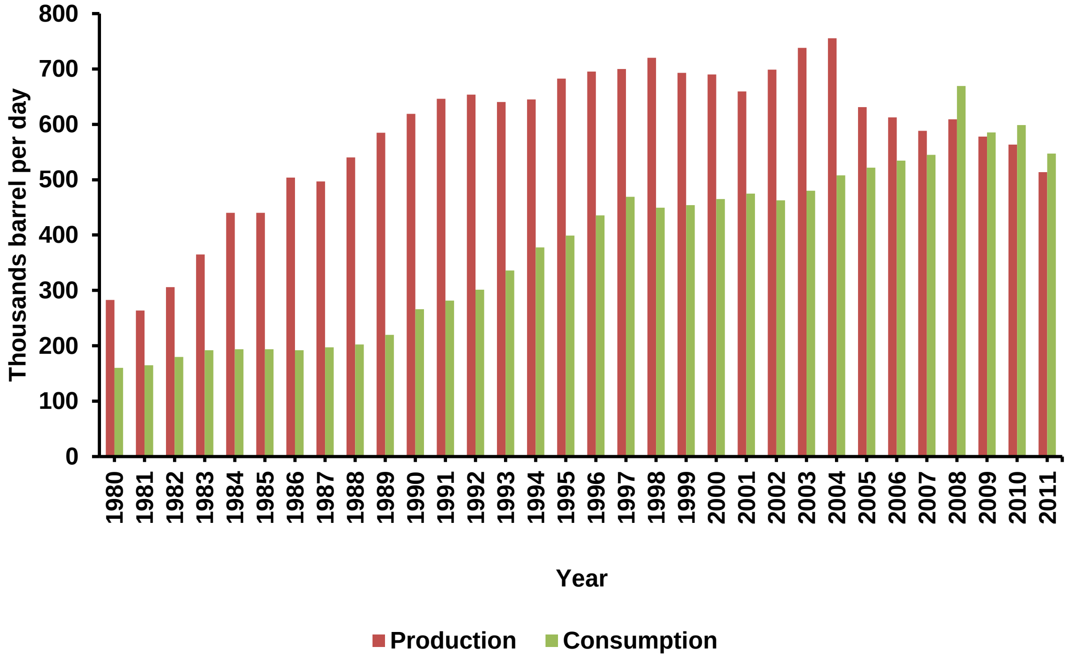

Figure 1.1: Malaysia crude oil production and consumption by year (Malaysia Crude Oil Production and Consumption by Year, 2013)

One of the solution to reduce the energy demand is by utilising the natural gas as an alternative fuel. Malaysia is regarded as one of the luckiest country in this world due to the abundance of natural gas reserves. Based on Figure 1.2, the proven natural gas reserves stand on 83 trillion cubic feet at 2013 and expected to rise by years. In Asia-Pacific region, Malaysia is the fourth natural gas reserves holder after Australia, China and Indonesia (Malaysia Natural Gas Reserves, 2013). Most of the natural gas resources were found in the region of east Malaysia which is Sabah and Sarawak.

Based on the study from Rahim & Liwan (2012), the production and consumption of natural gas in Malaysia is approximately directly proportional with, production exceeding consumption and the difference is widening through years as shown in Table 1.1. This indicates that if the trend continues the export of natural gas will be increased. At the current production rate even though there were no new discoveries of natural gas field, current reserve are still sufficient for 24 years until 2036, however if the slower rate of development in natural gas consumption continues Malaysia's natural gas reserve can last until 2053.

Table 1.1: Natural gas production and consumption (Rahim & Liwan, 2012)

Year	Production (billion cu m) (Bcm)	Consumption (billion cu m) (Bcm)
2012	2,431	1,201
2013	2,508	1,240
2014	2,585	1,279
2015	2,662	1,315
2020	3,046	1,504
2025	3,431	1,693
2030	3,815	1,882

1.1.1 Prospect of natural gas

The Association of South East Asian Nation (ASEAN) was established on August 8th, 1967 with one of the task to promote a single product that can raise economic growth to all ASEAN members. Ever since, ASEAN was regarded as one of the most abundant natural gas, ASEAN had been moving forward to build an integrated natural gas pipeline to supply the gas across the border. In January 15th 2007, a "Cebu Declaration on East Asian Energy Security" was held at Cebu, Philippines with the agenda to support a multibillion dollar project Trans-Asia Gas Pipeline (TAGP). Figure 1.2 illustrates the mega project connection involving the ASEAN country.

According to Sovacool (2009) ASEAN had already invested $14.2 billion for 3452 km gas pipeline to supply 3095 million cubic feet (mcf) of gas per day. Two operational cross border projects that currently involving Malaysia are Trans-Thailand-Malaysia (TTM) and PETRONAS-Keppel which connects Gulf of Thailand to Changlun, Malaysia and Peninsular Gas Utilisation Johor, Malaysia to Jurong Island, Singapore that cost USD 2.42 billion and USD 4 million respectively.

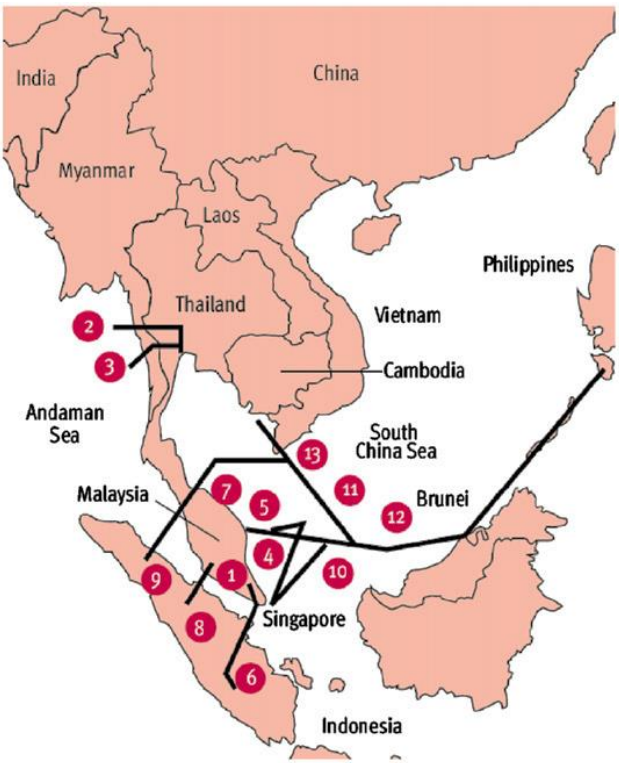

Figure 1.2: TAGP project connection (Sovacool, 2009)

1.1.1.1 Properties of natural gas

Fossil fuels occur in three fundamental of states: in solid form as coal, in liquid form as oil, and in gaseous form as natural gas. Natural gas is a non-renewable fuel and similar to other fossil fuel. The formation of natural gas occurs when the buried plants and animal were exposed to the heat for thousands of years. The composition of Natural gas is made up primarily of methane ethane, propane, nitrogen, helium, carbon dioxide, hydrogen sulphide, and water vapor with normally 95% of natural gas composition is methane. The physical chemical properties taken from (Ibrahim, 2006) described natural gas as; colourless, and odourless; lighter than air with a specific gravity about 0.6 – 0.8; inflamed during range 5 – 15% by volume of gas in air; self-ignition temperature is 537 – 540°C; lower environmental impact compare to other fuel; octane number of 130.

1.1.1.2 Advantages and disadvantages of Natural gas

The advantages of natural gas over other fuels include the following; it has fewer impurities, it is less chemically complex, and its combustion generally results in less pollution. In most application, using natural gas produces less of the following substances than oil or coal. Table 1.2 shows the advantages and disadvantages of using natural gas engine based on report from Agee *et al*., (2009).

Table 1.2: Advantages and disadvantages of natural gas engine (Agee *et al*., 2009)

Advantages		Disadvantages	
(i)	60 – 90% less smog pollutants	(i).	Require large space for fuel storing tank
(ii)	30 – 40% less greenhouse gas emissions	(ii).	Lack of infrastructure leading for fuelling station
(iii)	Less expensive than gasoline and diesel	(iii).	Fewer driving kilometer
(iv)	Good for engine, as cylinder and oil contamination is reduce.	(iv).	Issues around the spare part and maintenance centre

1.1.2 An overview of the medium and heavy duty engine

Medium and heavy duty engine are typically used for haul goods over long distances. The engine has been using diesel fuel burned in compression-ignition engines. These types of engine comprises of high fuel consumption and GHG emissions thus restricted to stringent emissions legislation. This relatively has long dominated the medium and heavy duty engine sector because it provides essential attributes to the manufacturers and their main commercial customers. Despite these strong attributes of diesel engine, it burns large volumes of diesel fuel and emit high levels of two harmful air pollutants which is particulate matter, (PM) and oxides of nitrogen, (NO_x). In term of noise pollution, the engine yield considerably higher sound levels at all speeds compared to typical cars. Continuous sounds are also contributed from tires rolling on the roadway, compressor and braking system (Sandberg, 2001). Table 1.3 depicts the description based on vehicle class. Medium-duty vehicles are those vehicles with a gross vehicle weight of 4,537 to 11,793 Kg. The largest of this group (Class 6 trucks) are also referred to as medium heavy-duty trucks. Heavy-duty vehicles have a gross vehicle weight over 11,794 Kg.

Table 1.3: Description of vehicle class (Ramachandran *et al*., 2012)

Size Class	Weight (Kg)	Characteristics	
1 and 2	Less than 4,536	Light duty vehicle	Pickups, small vans, SUVs
3	4,537 – 6,350	Medium duty vehicle	Delivery trucks, conventional van, small buses
4	6,351 – 7,258		
5	7,259 – 8845		
6	8,846 – 11,793		
7	11,794 – 14,969	Heavy duty vehicle	Tractor trailers and transit buses
8	14,970 – 36,287		

1.1.3 Retrofitting technology

The retrofit engine term represent the engines that undergo several modifications from the older system. Retrofit is a system that usually applies to any type of vehicle in order to improve the engine durability and reliability. Normally implementing retrofit system to an engine required added component as well as some mechanical changes. Retrofit engine also often related to reduction of performance and low emissions production. The current technology existed for retrofitting natural gas engine is based on Figure 1.3.

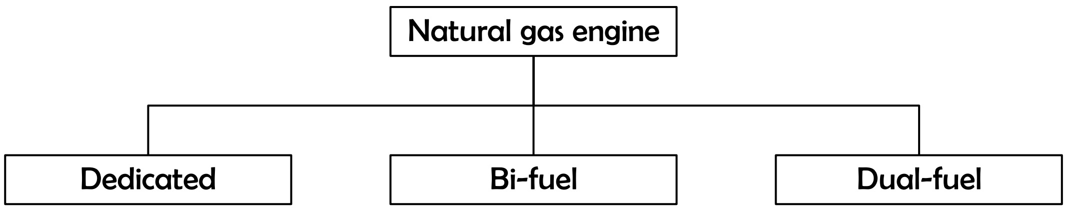

Figure 1.3: Natural gas engine classifications

A dedicated engine uses natural gas as its only fuel source. The engine has the advantage of being optimised to operate on natural gas, thus ensuring maximum efficiency and optimum emissions results. Diesel engines converted to natural gas engine are considered as dedicated engine due to removal of direct injection system thus the engine only capable to running single fuel type. For a spark ignition engine to work by bi-fuel mode required no major changes because the combustion cycle (otto cycle) remains the same. Most of the engine will be equipped with gas carburettor or gas injection system to be ignited with the air mixture. The engine can be running in switchable mode either by main fuel (gasoline) or gas (Jahirul *et al.*, 2010). In the dual fuel operation the cycle are based on compression ignition engine. The air-to-natural gas mixture from the intake processed is introduced into the cylinder, with a leaner air-to-fuel ratio. When the piston is closed to the end of the compression stroke, diesel fuel is injected, just as it would be in a traditional compression ignition engine. The diesel fuel ignites, and the diesel combustion causes the natural gas to burn (Bassi *et al*., 1993; Papagiannakis & Hountalas, 2003).

1.1.4 Potential of retrofitting CNG fuel for medium and heavy duty vehicle

The potential of retrofitting medium and heavy duty engine are no more questionable due to the various study successfully implemented the retrofitted technology for various size of engine. Previously (Pang *et al.,* 2013; Papagiannakis & Hountalas, 2003; Poompipatpong & Cheenkachorn, 2011; Wong, 2005) are among the researcher who successfully converted the engine from compression ignition engine to natural gas engine.

Today, more than 11.3 million of natural gas vehicles (NGV) are on the road and about 16.5 thousand of refuelling stations are in operation worldwide (Ong *et al.,* 2012). Medium and heavy duty vehicles is a small percentage of the vehicles on the road, however they consume large amount of petroleum. By using CNG fuel the vehicle was able to reduce the dependency on the conventional fuel. Malaysia government currently has ensured that CNG is priced at one-third the cost of petrol and diesel fuel. Presently the diesel fuel price stand at MYR 2.00 compared to the CNG fuel at MYR 0.62 (as of date 10th October 2013).

Although the process of converting the engine is expensive, but that is not been much of a bother considering the savings making in terms of fuel purchases. Moreover, reduction of taxation schemes price introduced by Malaysia government has helped the development and entrance into the market of the NGV technology for any type of engine capacity.

For higher growth of retrofitted CNG engine Malaysian government should promote NGV, for example personal tax rebates on purchase, fuel price advantages, infrastructure grants and more stringent national and local emission standards thus more natural gas vehicle will be used by considering its benefits.

1.1.5 The need of simulation for automotive study

Perhaps simulation methodology is still new in the Malaysian automotive industry. Currently, there are no such an intensive research done by our car manufacturer e.g. Proton, Perodua, and DRB-Hicom. However, major international automotive industry e.g. Mercedes, Volvo, Mitsubishi, and Toyota has been widely use the simulation tool at various operating conditions with respect to the simulation capabilities. This proves that simulation analysis is equally important as the experimental approaches.

In this research study, the application of one of the leading automotive engineering One-Dimensional simulation software will be extensively used to predict the capabilities of the retrofitted medium duty engine. A key and unique element in One-Dimensional software is the ability it offers users to build integrated models of systems, including integration across sub-systems being modelled, physical domains and modelling levels.

By using the software a large amount of saving is possible by considering the modification of the engine. Furthermore simulation took less time to run the case study compared to the experimental and also can be done repeatedly without considering the fuel needed for the actual engine. The model is also was able to analyse the engine condition based on the actual measured experimental analysis; in-cylinder pressure, valve lift, swirl, turbulence and squish effects (Meyer, 2007; Morrissey, 2008; Said, 2006). This is applicable to any engine sizes, from smallest utility engine to largest marine application.

1.2 Problem statement

Presently natural gas engine offer numerous of advantages over conventional fuel e.g. petrol and diesel especially in term of economic and environmental perspectives. However in Malaysia, the use of natural gas fuel are mostly limited to spark ignition and light duty vehicles with less attention paid to the medium duty engine. It is therefore a medium duty 4.3L engine capacity, 4-cylinder, 4-stroke retrofitted C.I. engine was modelled using One-Dimensional simulation software in order to predict the performance and emissions characteristics capability of the engine fuelled with CNG. This study also intended to investigate the influential parameters; in-cylinder pressure, engine geometry and fuel injection that able to improve the reliability and accuracy of the One-Dimensional simulation software. Nowadays computational modelling methodology offers; reduction in time, repeatable analysis, not dependent to fuel constraint, and capable of running various operating conditions simultaneously; compared to the experimental approach. Thus by considering the advantages of natural gas and simulation capabilities, it will be a very fruitful endeavour to be explored.

1.3 Scope of the study

This study will focus on the following below

(i) 4-cylinder, 4-stroke medium duty engine with capacity of 4.3L.

(ii) Engine operating at steady state varied from engine speed 850, 1000, 1150, 1300, 1500 and 1650 RPM.

(iii) Various AFR operations varied from rich (AFR = 15), stoichiometric (AFR = 17.2) and lean (AFR = 19).

(iv) The engine performance and emissions; brake power (BP), brake torque (BT), brake specific consumption (BSFC), brake thermal efficiency (BTE) oxides of nitrogen (NO_x), carbon monoxides (CO), carbon dioxides (CO_2) and hydrocarbons (HC).

1.4 The objectives of the study

The main objectives of the study are to:

(i) Produce a One-Dimensional model for 4.3L, 4-cylinder, 4-stroke retrofitted compression ignition engine fuelled with CNG.

(ii) Investigate the performance and emissions characteristics between RE (medium duty 4-cylinder, 4-stroke retrofitted C.I. engine fuelled with CNG) and DE (medium duty 4-cylinder, 4-stroke direct injection diesel engine) model at low engine speed condition.

(iii) Investigate the effects of various AFR to the RE model at low engine speed condition.

(iv) Study the reliability and accuracy of the One-Dimensional simulation software in predicting the engine performance and emissions characteristics.

1.5 Significance of the study

The One-Dimensional model designed is based on actual engine where as far as the author concern the engine model has not been applied before. In fact the methodology used could help further understanding in term of engine modelling. This method might certainly represent a step forward as it would enable reduction of experimental approach as the engine testing was operated by the computational model. Furthermore the simulation results have wide implications particularly on; engine performance and emissions characteristics and analysis of air fuel ratio from lean to rich condition.

CHAPTER 2

LITERATURE REVIEW

This chapter presents the literature reviews related to engine parameters that affected the engine performance and emissions, and existing type of retrofitted CNG engine. The methodology used for previous researcher in modelling One-Dimensional simulation software were also been discussed in term of; fuel properties, engine layout design, and modelling accuracy achieved by the researcher.

2.1 Spark ignition engine

The actions in the spark-ignition engine can be divided into four parts. Each part consists of a piston stroke. This is the movement of the piston from bottom dead centre (BDC) to top dead centre (TDC), or from TDC to BDC. The complete cycle of events in the engine cylinder requires four piston strokes. These are intake, compression, power and exhaust. The crankshaft makes two complete revolutions to complete the four piston strokes. This makes the engine a four-stroke-cycle engine.

During the intake stroke of a spark ignition engine, the piston is moving down. The intake valve is open. Air-fuel mixture flows through the intake port and into the cylinder. After that the mixture is compress during the compression stroke. Both valves are closed. The upward moving piston compresses the air-fuel mixture into a smaller space, between the top of the piston and the cylinder head. At the end of the compression stroke, an electric spark jumps the gap at the spark plug. The heat from the spark ignites the compressed air-fuel mixture. The air-fuel mixed then burns rapidly. These high temperatures cause very high pressure which pushes down the piston. on the power stroke, the exhaust valve opens. After passing through BDC, the piston moves up again. The burned gases escape through the open exhaust port (Heywood, 1988; Salazar, 1998; Pulkrabek, 2004).

2.2 Compression ignition engine

Compression ignition engine concept is difference from spark ignition engine in a variety of ways but the most obvious one being the way in which the air and fuel mixture is ignited. In a compression ignition engine there is no spark to create the flame but rather high temperatures and pressures in the combustion chamber cause a flame to initiate at different sites of the combustion chamber.

The intake stroke in a diesel engine is used to draw in a new volume of charge air into the cylinder by moving the piston from TDC to BDC. The compression stroke begins as the inlet valve closes and the piston is driven upwards in the cylinder bore by the momentum of the crankshaft and flywheel. The purpose of the compression stroke in a diesel engine is to raise the temperature of the charge air to the point where fuel injected into the cylinder spontaneously ignites. Ignition takes place when the fuel from the high pressure fuel injector spontaneously ignites in the cylinder, thus moving the piston from TDC to BDC. As the rapidly burning mixture attempts to expand within the cylinder walls, it generates a high pressure which forces the piston down. Finally the exhaust stroke occur during the gases formed during combustion are ejected from the cylinder (Heywood, 1988; Salazar, 1998; Pulkrabek, 2004).

2.3 Engine emission types

A complete combustion of diesel and gasoline in the engine, produce only water (H_2O), CO_2 and unaffected nitrogen emissions in the exhaust. However, there is no 100% of efficiency for any mechanical being, therefore resulting to incomplete combustion. The typical type of pollutant in the exhaust emissions are CO, CO_2, uHC, NO_x and PM.

Complete combustion:

ΔFuel + Air (Oxygen + Nitrogen) $\rightarrow$ Carbon dioxide (CO_2) + Water (H_2O) + unaffected nitrogen (United States Environmental Protection Agency, 2009)

Typical engine combustion:

ΔFuel + Air (Oxygen + Nitrogen) $\rightarrow$ Unburned hydrocarbon (uHC) + Nitrogen oxides (NO_x) + Carbon monoxide (CO) + Carbon dioxide (CO_2) + Water (H_2O) (United States Environmental Protection Agency, 2009)

2.3.1 Carbon monoxides

Carbon monoxide is colourless, odourless, and tasteless gas that is lighter than air. It is released when a carbon containing fuel such as gas, coal, coke, gasoline and diesel incompletely combust due to lack of air. The compound consists of one carbon and oxygen atom which is bad for human health, when encountered in higher concentrations. Carbon monoxide is harmful when breathed because it ruins oxygen flow in the blood thus deprives the heart, brain, and other vital organs that consume oxygen. Large amounts of CO can overcome human antibody in minutes without warning causing the person to lose consciousness and suffocate. (Industrial Accident Prevention Association, 2008; Martinez *et al.*, 2011).

2.3.2 Carbon dioxides

Carbon dioxides is the most anthropogenic GHG. About three-quarters of CO_2 emitted to the atmosphere during the past 20 years due to fossil fuel burning. The rest is predominantly due to land-use change, especially deforestation (Fong *et al.*, 2007). Since the starting of the industrial revolution in 1850, the average atmospheric concentration of CO_2 trapped are in between 280 ppm to 370 ppm resulted to the average global temperature between 0.6℃ and 1℃. The International Panel on Climate Change (IPCC) expect that, by the year 2100, the atmosphere will comprised of 570 ppm CO_2, causing arise in the mean global temperature up to 1.9℃ (Liu *et al.*, 2013). Continuous increments in CO_2 emissions lead to the increases of sea level and species extinction due to temperature rise.

2.3.3 Oxides of nitrogen

Oxides of nitrogen (NO_x) commonly consists of nitrogen oxide (NO) and nitrogen dioxide (NO_2) which is formed from combination of oxygen (O_2) and nitrogen (N_2) in the air at high temperature when the fuel is burned. Almost half of the NO_x emissions are produced from automotive sector followed by industrial boilers, incinerators, gas turbines, cement manufacturer, petroleum refineries and nitric acid manufacture (United States Environmental Protection Agency, 1999). These various sources leading to different type of chain chemical reaction involving the NO_x emissions. The NO_2 emissions are able to react with the atmosphere surrounding to form ozone (O_3) and acid rain. It is vital to reduce the amount of ozone formation since it is freely moving in tropospheric (lowest ground of atmosphere). Ozone can cause adverse effects such as damage to lung tissue and reduction in lung function mostly in children, elderly, and asthmatics patients (United States Environmental Protection Agency, 1999).

2.3.4 Unburned hydrocarbon

Hydrocarbon emissions result from elements of the air-fuel mixture that have not completely burn at the time the exhaust valve opens. Hydrocarbon emissions are Composed of unburned fuel and products of partial combustion, such as ethylene and formaldehyde. Hydrocarbon sources include crevice volumes, such as the space between the piston and cylinder wall above the piston ring, and the quenched layer next to the combustion chamber walls. Unburned mixture is forced into these crevices during compression and combustion, and emerges late in the expansion and during the exhaust stroke. In lean mixtures, flame speeds may be too low for combustion to be completed during the power stroke, or combustion may not occur. These conditions also cause high hydrocarbon emissions. This is the major source of hydro-carbon emissions from four-stroke engine (Damrongkijkosol, 2006; Ogawa *et al.*, 2014).

2.4 Conversion characteristics related to natural gas engines

The characteristics of the CNG engine is determine by the feasibility of the conversion process. A defective conversion resulted to; higher exhaust emissions, losses of unacceptable brake power, increase of fuel consumption and maintenance cost. In order to avoid such drawbacks, natural gas engine have to essentially consider two main characteristics which is combustion system and compression ratio.

2.4.1 Combustion system

Substituting the conventional fuel to natural gas in an engine system can be achieved by converting the engine. In order to convert the engine, the following options are possible (United States Environmental Protection Agency, 2009; York, 1993):

(i) Modification of a gasoline (otto cycle) engine to CNG combustion (so called conversion to a dedicated fuel;

(ii) Modification of gasoline engine to either CNG or gasoline (bi-fuel combustion);

(iii) Conversion of diesel engine to dedicated CNG (spark ignition) combustion; and

(iv) Conversion of a diesel engine to dual fuel (gas and diesel mixture) combustion

For diesel engine options (iii) and (iv) can be selected, depending on the engine characteristics and the operating conditions. In that case, the diesel engine needs to be modified (converted) to a spark ignition engine in order to burn 100 per cent natural gas instead of diesel. The major modification required is reduction of the compression ratio down which is achieved by removal of material from the piston bowl or the exchange of pistons and/or cylinder head. Diesel injectors need to be replaced with spark plugs and a gas carburettor (mixer) has to be fixed. The diesel fuel pump also needs to be removed and a distributor (or an electronic spark ignition system) added.

In the dual fuel system (option iv) the quantity of diesel is reduced to a pilot injection to initiate the combustion. Dual fuel engines remain diesel, i.e. self-ignition, engines for which the energy deficit, caused by reduced diesel injection, is at any given throttle setting compensated for by natural gas mixed with the induction air. Constructional changes are minor: the injection system has to be modified to reduce diesel flow, supplemented by a gas mixer in the induction tract to supply the balancing quantity of gas to the engine (Korakianitis *et al.*, (2011); Zheng *et al.*, (2009).

A brief description of the advantages and disadvantages of the two diesel engine conversion concepts is given in the following overview:

Table 2.1: Diesel conversion concept (Reproduced from York, 1993)

	Advantages	Disadvantages
Dedicated CNG	100% substitution of diesel by CNG	Lack of qualified expertise in conversion and maintenance area
Dual fuel operation	High reliability and durability	Reduced substitution of diesel fuel; minor reduction of exhaust emissions except for black smoke

2.4.2 Compression ratio

Compression ratio (CR) is the ratio of the total volume of the combustion chamber when the piston is at the BDC to the total volume of the combustion chamber when piston is at the TDC. The formula expressing the definition of compression ratio is based on equation 2.1 and 2.2

Equation 2.1: Compression ratio (Pulkrabek, 2004)

$$r_c = \frac{V_c + V_d}{V_c}$$

Equation 2.2: Displacement volume (Pulkrabek, 2004)

$$V_d = N_c \left(\frac{\pi}{4} \right) B^2 S$$

B = Bore

S = Stroke

N_c = Number of cylinder

V_c = Clearance volume (combustion chamber)

V_d = Displacement volume

r_c = Compression ratio

Generally, increasing the CR of an engine can improve the overall efficiency of the engine hence producing more power output. However if the compression ratio approaches the limit of maximum allowable CR the engine will suffer a knocking phenomenon (Saidur *et al.*, 2007; Wong, 2005). Thus it is important for the engine to obtain the optimum CR. Kim *et al.*, (1996) study the effect of using CNG under different CR. They discover that, although the engine achieve approximately equal power under both CRs, however at higher CRs the total exhaust emissions for HC and NO_x increases.

Damrongkijkosol (2006) investigate the effect of CR on the performance and emissions in a CNG dedicated engine. The result indicates that increasing the CR gave more power output. The NO_x emissions showed a trend of increasing and decreasing which is unstable. The overall HC emissions are higher as the increase of CR and reflected to lower CO emissions.

Based on study by Zheng *et al.,* (2009) the increase of CR resulted to higher BTE. For exhaust emissions, CO decreases while NO_x increases with increase of CR. The HC concentration shows a decreasing trend and then an increasing trend with increasing compression ratio.

Different case studied by Poompipatpong & Cheenkachorn (2011) investigated the effect of converted indirect diesel engine to CNG engine at increasing CR 9.0 : 1, 9.5 : 1, 10.0 : 1 and 10.5 : 1 for 4-cylinder, 4-stroke 2197cc engine capacity. In order to operate the engine with CNG fuel, the engine must undergo several modifications by reducing the engine initial condition from CR 22: 1 to 9.0: 1, 9.5: 1, 10.0: 1 and 10.5: 1, substitute the fuel injector to spark plug and new piston geometry. Throughout the testing, CNG engine was able to improve the engine BP approximately from 5.7% to 13%. He also observes that increasing the compression ratio lead to higher generation of NO_x emissions.

2.5 CNG engine characteristics

The characteristics of the CNG engine are highly depending on the engine setup; air fuel ratio and ignition timing. Thus in this section the mentioned characteristics is discussed briefly.

2.5.1 Air-fuel ratio

Air-to-fuel (A/F) ratio is the mass ratio of the A/F mixture trapped inside a cylinder before combustion begins, and it affects engine emissions, fuel economy, and other performances (Diesel, 2011; Pace & Zhu, 2013). The formula expressing the definition of compression ratio is based on equation 2.3, 2.4 and 2.5.

Equation 2.3: Air/fuel ratio (Pulkrabek, 2004)

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

Equation 2.4: Fuel/air ratio (Pulkrabek, 2004)

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

Equation 2.5: Equivalence ratio (Pulkrabek, 2004)

$$\phi = \frac{(AF)_{Stoichiometric}}{(AF)_{Actual}}$$

The purpose of AFR control is to maintain stoichiometry between the mass of air and fuel entering the combustion chamber. This is important because if stoichiometry is not achieved, the engine will not be able to oxidize or reduce harmful exhaust emissions. For natural gas fuel, the stoichiometric air/fuel mixture is approximately 17.2 (Heywood, 1988) equal to the mass of air to fuel. Any mixture less than 17.2 to 1 is considered to be a rich mixture, and any more than 17.2 is a lean mixture.

Saidur *et al.,* (2007) study the variation of brake power (BP) with air fuel ratio for diesel engine running by natural gas fuel. Based on the analysis that BP decrease as air fuel ratio increases. The BP increase is caused by increased fuel supply. At lower AFR, air-fuel mixture is rich that facilitates more burning and therefore engine power (kW) is higher at lower AFR. BP gradually decreases with increasing AFR, because at higher AFR lean mixture causes reduced burning.

A reviewed done by Korakianitis *et al.,* (2011) conclude that the combustion of a lean-fuel mixture of natural gas engine $(\phi \leq 1)$ result in low NO_x emissions this also can result to reduction of power output. Meanwhile running the engine on fuel-rich $(\phi \geq 1)$ is also undesirable. However if the NO_x is high during lean condition the engine are currently experience high exhaust temperature due to lack of oxygen.

A study conducted by Pang *et al.*, (2013) the effect of excess air ratio on turbocharged lean burned 6 cylinder retrofitted diesel engine running with CNG fuel. The output torque of each condition decreases slightly with the increase of the λ from 1.25, 1.35, 1.45, 1.55 and 1.6. When the excess air ratio exceeds 1.5, HC emissions increased dramatically up to 3000 ppm. NO_X emissions of lean burn CNG engine are significantly reduced with the increase of λ.

2.5.2 Ignition timing

Fuel injection timing is the process of setting the ignition to occur in the combustion chamber during the compression stroke relatively to the piston and crankshaft position.

If the fuel injection timing take place earlier (advance), the initial air temperature and pressure are inferior thus increasing the time for ignition delay. Meanwhile if the injection timing starts later (retard) the temperature and pressure are superior but reducing in ignition delay period. In a study done by Ali *et al.*, (2005) for CNG direct injection type observe that advance injection shows a slower burn in the initial stage and a faster burn in the late stage. In contrast to this, the late injection showed a faster burn in the initial stage and a slower burn in the late stage. Faster burn at the initial stage is caused by moderately strong turbulence and faster burn at the late stage is caused by moderately proceeding mixture formation.

An experimental work to investigate the natural gas combustion characteristics under various fuel injection timings was done by Huang *et al.*, (2003) using Rapid Compression Machine (RCM). The RCM showed that natural gas result in fast combustion due to the shortening of time interval. The NO_x emissions remain high but the CO level decrease of a wide range. By using natural gas better combustion efficiency can achieve due to the gaseous state of natural gas.

The aim of the injection timing is to ignite the fuel at precisely the right time so that the expanding combustion can achieve the maximum amount of work.

2.6 One-Dimensional engine simulation modelling software

One-Dimensional Engine modelling software is a widely subject of configuration that involve variation of pressure measurement, flow and volume that takes place during the engine process (Said, 2006). The engine simulation software was developed from the Gamma Technologies, Inc and can be integrated with other simulation software packages including Computational Fluid Dynamic, Matlab, and Fortran (Bos, 2007). One-dimensional simulation software that embodies the flow in the component (object) of the engine model. These entire components are linked together to produce a whole system of the engine with the properties of the object that were defined by the user. One–Dimensional simulation software will be analyse by the pre-processor and all the calculation of involve during the analysis will be shown in the post processing result. The attribute related in the One–Dimensional simulation software are involving several equation and correlation in order to perform the analysis for the engine cycle starting from intake, compression, expansion and exhaust process. For the next section the basic equation use in the simulation activity are presented to indicate the solution method in One–dimensional simulation software.

References

Abianeh, O. S., Mirsalim, M., & Ommi, F. (2009). Combustion Development of a BI-Fuel Engine. *International Journal of Automotive Technology*, *10*(1), 17–25. doi:10.1007/s12239

Agee, S. C., Dasgupta, S., & Caron, A. (2009). Natural Gas Vehicles : A Feasibility Study. In *Economic Research and Policy Institute* (pp. 1 – 16). Oklahama City University.

Aina, T., Folayan, C. O., & Pam, G. Y. (2012). Influence of Compression Ratio on the Performance Characteristics of a Spark Ignition Engine. *Advances in Applied Science Research*, *3*(4), 1915–1922.

Ali, Y., Muhammad, Z., & I-khamas, M. (2005). Valve Timing and Ignition Issues in Fuel System for Compressed Natural Gas, Direct Injection (CNGDI). In *The Asia Pacific Natural Gas Vehicles Association (ANGVA) 1st Conference & Exhibition (ANGVA2005)* (pp. 1–5).

Bakar, R. A., Kadirgama, K., Rahman, M. M., & Sharma, K. V. (2007). Application of Natural Gas for Internal Combustion Engines. *Advances in Natural Gas Technology*, *5*(5), 1–27. doi:ISBN 978-953-51-0507-7

Bassi, A., Srl, S. A., & Bodoni, G. B. (1993). Natural Gas Vehicle for a Clean Environment An Overview and the Trends for the Future. In *Clean Combustion Technologies: Proceedings of the Second International Conference, Part B (Energy, Combustion and the Environment Series , Vol 2)* (pp. 739–749). Milan: Gordon and Breach Science Publishers.

Bos, M. (2007). *Validation Gt-Power Model Cyclops Heavy Duty Diesel Engine, Master Thesis*. Technical University of Eindhoven.

Cascetta, F., Rotondo, G., & Musto, M. (2008). Measuring of Compressed Natural Gas in Automotive Application: A Comparative Analysis of Mass Versus Volumetric Metering Methods. *Flow Measurement and Instrumentation*, *19*(6), 338–341. doi:10.1016/j.flowmeasinst.2008.05.003

Clémençon, R. (2008). The Bali Road Map A First Step on the Difficult Journey to a Post-Kyoto Protocol Agreement. *The Journal of Environment & Development*, *17*(1), 70–95. doi:10.1177/1070496508314223

Damrongkijkosol, C. (2006). *An Experiment Study on Influence of Compression Ratio for Performance and Emissions of Natural Gas Retrofit Engine Master Thesis*. Skindhorn International Thai-German Graduate School of Engineering (TGGS) Graduate College King Mongkut's Institute of Technology North Bangkok.

Das, a, & Watson, H. C. (1997). Development of a Natural Gas Spark Ignition Engine for Optimum Performance. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, *211*(5), 361–378. doi:10.1243/0954407971526506

Deng, B., Yang, J., Zhang, D., Feng, R., Fu, J., Liu, J., … Liu, X. (2013). The challenges and strategies of butanol application in conventional engines: The sensitivity study of ignition and valve timing. *Applied Energy*, *108*, 248–260. doi:10.1016/j.apenergy.2013.03.018

Diesel, B. (2011). Diesel Tuning and Air-Fuel Ratios. Old Huma Hwy, Nsw 2577: Industry Corner.

Fong, W.-K., Matsumoto, H., Ho, C.-S., & Lun, Y.-F. (2007). Energy Consumption and Carbon Dioxide Emissions Considerations in the Urban Planning Process in Malaysia. Skudai Johor Baharu.

Gamma Technologies, I. (2009a). GT-SUITE: Flow Theory Manual. 601 Oakmont Lane,Suite 220 Westmont.IL 60559 USA.

Gamma Technologies, I. (2009b). GT-SUITE: Engine Performance Tutorials. 601 Oakmont Lane,Suite 220 Westmont.IL 60559 USA.

Gamma Technologies, I. (2009c). GT-SUITE. 601 Oakmont Lane,Suite 220 Westmont.IL 60559 USA: Gamma Technologies.

Gamma Technologies, I. (2009d). GT- Suite Engine Performance Application Manual Version 7.0. 601 Oakmont Lane,Suite 220 Westmont.IL 60559 USA.

Gatts, T., Liu, S., Liew, C., Ralston, B., Bell, C., & Li, H. (2012). An experimental investigation of incomplete combustion of gaseous fuels of a heavy-duty diesel engine supplemented with hydrogen and natural gas. *International Journal of Hydrogen Energy*, *37*(9), 7848–7859. doi:10.1016/j.ijhydene.2012.01.088

Geok, H. H. (2009). Experimental Investigation of Performance and Emission of a Sequential Port Injection Natural Gas Engine. *International Journal of Engineering and Innovative Technology*, *30*(2), 204–214. doi:ISSN: 2277-3754

Hammill, D. (2002). *How to Choose Camshafts and Time Them for Maximum Power* (1st Editio., pp. 1 – 53). London: Veloce Publishing.

Heywood, J. B. (1988). *Internal Combustion Engine Fundamentals* (McGraw Hil.). New York: McGraw-Hill International Edition.

Huang, Z., Shiga, S., Ueda, T., Jingu, N., Nakamura, H., & Ishima, T. (2003). A Basic Behavior of Machine, NG DI Combustion in a Spark-Ignited Rapid Compression. *JSME International Journal Series B*, *45*, 891–900.

Hushim, M. F., Alimin, A. J., Selamat, H., & Muslim, M. T. (2013). PFI System for Retrofitting Small 4-Stroke Gasoline Engines. *International Journal of*

Environmental Science and Development, *4*(4), 375–378. doi:10.7763/IJESD.2013.V4.374

Ibrahim, N. K. (2006). 4th Year/Petroleum Refinery Engineering Branch.

Industrial Accident Prevention Association. (2008). Carbon Monoxide in The Workplace. United State of America.

Ismail, M. Y., Alimin, A. J., & Osman, S. A. (2012). Mono-Gas Fuelled Engine Performance and Emissions Simulation using GT-Power. In *4th International Conference on Mechanical and Manufacturing Engineering* (pp. 125 – 129). doi:10.4028/www.scientific.net/AMM.465-466.125

Jahirul, M. I., Masjuki, H. H., Saidur, R., Kalam, M. A., Jayed, M. H., & Wazed, M. A. (2010). Comparative engine performance and emission analysis of CNG and gasoline in a retrofitted car engine. *Applied Thermal Engineering*, *30*(14-15), 2219–2226. doi:10.1016/j.applthermaleng.2010.05.037

Kalam, M A, Masjuki, H. H., Maleque, M. A., Amalina, M. A., Abdesselam, H., Mahlia, T. M. I., … Varman, M. (2009). Power Improvement of a Modified Natural Gas Engine.

Kalam, M.A., & Masjuki, H. H. (2011). An Experimental Investigation of High Performance Natural Gas Engine with Direct Injection. In *Energy* (Vol. 36, pp. 3563–3571). Elsevier Ltd. doi:10.1016/j.energy.2011.03.066

Korakianitis, T., Namasivayam, a. M., & Crookes, R. J. (2011). Natural-gas fueled spark-ignition (SI) and compression-ignition (CI) engine performance and emissions. *Progress in Energy and Combustion Science*, *37*(1), 89–112. doi:10.1016/j.pecs.2010.04.002

Liu, H., Werst, M., Strank, S., Osara, J., & Hebner, R. (2010a). Combustion Emissions Modeling Testing of Conventional Diesel Fuel. In *ASME 2010 4th International Conference of Energy Sustainability* (pp. 1–10). Austin, Texas, USA.

Liu, H., Werst, M., Strank, S., Osara, J., & Hebner, R. (2010b). Combustion Emissions Modeling And Testing of Neat Biodiesel Fuels. In *ASME 2010 4th International Conference of Energy Sustainability* (pp. 1–10). Austin, Texas, USA.

Liu, J. Y., Zhang, X. F., Zhang, J. F., Liu, H., & Li, F. Q. (2013). Development Status and Energy Penalty of Carbon Dioxide Capture Technologies. In *Advanced Materials Research* (Vol. 864–867, pp. 1598–1601). doi:10.4028/www.scientific.net/AMR.864-867.1598

Liu, Y. F., Pei, P. C., Yang, J. W., & Zhu, A. H. (2012). Study on EGR Control Strategy for Vehicle Diesel Engine Based on Experiment. *Advanced Materials Research*, *490-495*, 1491–1495. doi:10.4028/www.scientific.net/AMR.490-495.1491

Maji, S., Sharma, P. B., & Babu, M. k G. (2005). Experimental Investigation on Performance and Emissions Characteristics in a Spark Ignition Engine. In *SAE Technical Paper NO. 2005-26-344* (pp. 1–6).

Malaysia Crude Oil Production and Consumption by Year. (2013). *United States Energy Information Administration, Retrieved on 09 Disember 2013, http://www.indexmundi.com/energy.aspx?country=my*.

Malaysia Natural Gas Reserves. (2013). *EIA Administration Independent Statistic & Analysis U.S. Energy Information , retrieved on 08 Disember 2013, from http://www.eia.gov/countries/country-data.cfm?fips*.

Martinez, P. a., Caba, F. M., Alvarado, S. a., & Caceres, D. D. (2011). Indoor and Personal Carbon Monoxide Exposure Risk Assessment in Sample of Apartment Buildings in Santiago, Chile. *Indoor and Built Environment*, *21*(3), 474–480. doi:10.1177/1420326X11411501

Meyer, J. (2007). *Engine Modeling of an Internal Combustion Engine Master Thesis*. The Ohio State University.

Morrissey, C. G. (2008). *Experimental Validation of an All Inclusive Small Engine Carburetor Model in One-Dimensional Engine Software, Master Thesis*. University of Wisconsin Madison.

Nerkar, A. (2013). Optimization and Validation for Injector Nozzle Hole Diameter of a Single Cylinder Diesel Engine using GT-Power Simulation Tool. *saefuel.saejournals.org*, *Volume 5*(Issue 3), 1372–1381. doi:10.4271/2012-01-2306

Numata, A., Nagae, Y., Kumagai, T., & Osafune, S. (2001). Increase of Thermal Efficiency and Reduction of NOx Emissions in DI Diesel Engines. *Mitsubishi Heavy Industries*, *38*(3), 136–140.

Ogawa, H., Miyamoto, N., Kawabe, T., & Tosaka, S. (2014). Characteristics of Unburned Hydrocarbon Emissions in a Low Compression Ratio DI Diesel Engine. In *SAE Technical Paper 2009-01-1526* (pp. 1 – 7).

Ong, H. C., Mahlia, T. M. I., & Masjuki, H. H. (2012). A review on energy pattern and policy for transportation sector in Malaysia. *Renewable and Sustainable Energy Reviews*, *16*(1), 532–542. doi:10.1016/j.rser.2011.08.019

Osman, S. A., Alimin, A. J., Ismail, M. Y., & Hui, K. W. (2013). Performance and Emission Characteristics of Direct Injection C.I Engine Retrofitted with Mono-CNG System. In *Applied Mechanics and Materials* (Vol. 446–447, pp. 443–447). doi:10.4028/www.scientific.net/AMM.446-447.443

Pace, S., & Zhu, G. G. (2013). Air-to-Fuel and Dual-Fuel Ratio Control of an Internal Combustion Engine. *SAE Technical Paper 2009-01-2749*, *2*(2), 245–253.

Pang, J. X., Qu, D. W., Lu, X., & Liu, G. Y. (2013). Experimental Research on the Effect of Excess Air Ratio on Turbocharged Lean-Burned CNG Engine. In *Advanced Materials Research* (Vol. 724–725, pp. 1422–1426). doi:10.4028/www.scientific.net/AMR.724-725.1422

Papagiannakis, R. G., & Hountalas, D. T. (2003). Experimental Investigation Concerning the Effect of Natural Gas Percentage on Performance and Emissions of a DI Dual Fuel Diesel Engine. In *Applied Thermal Engineering* (Vol. 23, pp. 353–365).

Poompipatpong, C., & Cheenkachorn, K. (2011). A modified diesel engine for natural gas operation: Performance and emission tests. *Energy*, *36*(12), 6862–6866. doi:10.1016/j.energy.2011.10.009

Prins, G., & Rayner, S. (2008). The Kyoto Protocol. In *Bulletin of the Atomic Scientists* (Vol. 64, pp. 45–58). doi:10.2968/064001011

Rahim, K. A., & Liwan, A. (2012). Oil and gas trends and implications in Malaysia. *Energy Policy*, *50*, 262–271. doi:10.1016/j.enpol.2012.07.013

Rahim, R., Mamat, R., Taib, M. Y., & Abdullah, A. A. (2012). Influence of Fuel Temperature on a Diesel Engine Performance Operating with Biodiesel Blended, *43*.

Rahman, M. M., Mohammed, M. K., & Bakar, R. A. (2008). Effect of Engine Speed on Performance of Four-Cylinder Direct Injection Hydrogen Fueled Engine. In *4th BSME-ASME International COnference on Thermail Engineering* (pp. 500–505).

Ramachandran, K., Suneetha, Kanchustambham, Wingerden, V., Ladipo, O., Aggarwal, S., & Rucker, A. (2012). *Road Transport: Unloacking Fuel Saving Technologies In trucking and Fleets* (pp. 1–28).

Said, M. F. M. (2006). *Performance and Emissions Tests of Biodiesel Fuels Using a Conventional Diesel Engine Master Thesis*. Universiti Teknologi Malaysia.

Saidur, R., Jahirul, M. I., Moutushi, T. Z., Imtiaz, H., & Masjuki, H. H. (2007). Effect of partial substitution of diesel fuel by natural gas on performance parameters of a four-cylinder diesel engine. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *221*(1), 1–10. doi:10.1243/09576509JPE182

Salazar, F. (1998). Internal combustion engines. Department of Aerospace and Mechanical Engineering.

Semin, Ismail, A. R., & Bakar, R. A. (2008). Investigation of CNG Engine Intake Port Gas Flow Temperature Based on Steady-State and Transient Simulation. *European Journal of Scientific Research*, *22*(3), 361–372.

Sovacool, B. K. (2009). Energy policy and Cooperation in Southeast Asia: The History, Challenges, and Implications of the Trans-ASEAN Gas Pipeline (TAGP) Network. *Energy Policy*, *37*(6), 2356–2367. doi:10.1016/j.enpol.2009.02.014

Suardi, M., Zahedi, G., & Belyamin, B. (2013). Modeling of Diesel Engine Emission Running on Biodiesel. *Proceeding of the International Conference on Process Systems Engineering (PSE ASIA)*, (June), 25–27.

Tony Sandberg. (2001). *Heavy Truck Modelling for Fuel Consumption Simulations and Measurements*. Linkoping University Sweden.

Tziourzioumis, D. (2010). *Simulation and Experimental Validation of Steady State Operation of a Turbocharged, Common Rail HDI Diesel Engine Runnging on Biodiesel Blends*. University of Thessaly.

United States Environmental Protection Agency. (1999). Technical Bulletin: Nitrogen Oxides (NOx), Why and How They Are Controlled. Research Triangle Park, North Carolina 27711: Information Transfer and Program Integration Division.

United States Environmental Protection Agency. (2009). Automobile Emissions : An Overview. Plymouth Road: EPA National Vehicle and Fuel Emissions Laboratory.

Vlachou, A., & Konstantinidis, C. (2010). Climate Change: The Political Economy of Kyoto Flexible Mechanisms. *Review of Radical Political Economics*, *42*(1), 32–49. doi:10.1177/0486613409357179

Vudumu, S. K., & Koylu, U. O. (2011). Computational Modeling, Validation, and Utilization for Predicting the Performance, Combustion and Emission Characteristics of Hydrogen IC engines. *Energy*, *36*(1), 647–655. doi:10.1016/j.energy.2010.09.051

W.Pulkrabek, W. (2004). *Engineering Fundamentals of the Internal Combustion Engine* (Second Edi., p. 478). Pearson Prentice-Hall.

Wang, X., & Stone, C. R. (2008). A Study of Combustion, Instantaneous Heat Transfer, and Emissions in a Spark Ignition Engine During Warm-Up. In *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* (Vol. 222, pp. 607–618). doi:10.1243/09544070JAUTO610

Wong, W. L. (2005). *Compressed Natural Gas as an Alternative Fuel in Diesel Engine*. Master Thesis, University of Southern Queensland.

Woschni, G. (1967). A Universally Applicable Equation for The Instantaneous Heat Transfer Coefficient in The Internal Combustion Engine. In *SAE International Journal of Engines* (pp. 3065 – 3083).

Xiao, Y., & Zhou, P. (2011). Investigation of Emission Characteristic of a Diesel Engine by Simulation. *Applied Mechanics and Materials*, *80-81*, 752–756. doi:10.4028/www.scientific.net/AMM.80-81.752

Xinguang, L., & Jianguo, Y. (2010). Research on NOx Emissions of the Engine Fueled with M15. *2010 International Conference on Intelligent Computation Technology and Automation*, 49–52. doi:10.1109/ICICTA.2010.729

Yeh, S. (2007). *An empirical analysis on the adoption of alternative fuel vehicles: The case of natural gas vehicles*. *Energy Policy* (Vol. 35, pp. 5865–5875). doi:10.1016/j.enpol.2007.06.012

York, U. N. N. (1993). *Guideline for Conversion of Diesel Busses to Compressed Natural Gas* (pp. 1–39).

Zheng, J. (2009). *Use of An Engine Cylcle Simulation to Study a Biodiesel Fueled Engine*. Texas A&M University.

Zheng, J.-J., Wang, J.-H., Wang, B., & Huang, Z.-H. (2009). Effect of the compression ratio on the performance and combustion of a natural-gas direct-injection engine. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, *223*(1), 85–98. doi:10.1243/09544070JAUTO976