CHARACTERIZATION OF A C.I. ENGINE OPERATED USING RETROFIT MONOGAS FUELLING CONCEPT

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A thesis submitted in
fulfilment of the requirement for the award of the
Doctor of Philosophy

Faculty of Mechanical and Manufacturing Engineering
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SEPTEMBER 2014

ABSTRACT

Recently, logistics and haulage companies are considering using CNG for their existing compression ignition (C.I.) engines. In an effort to address this challenge, a parametric study on a medium duty C.I. engine (naturally aspirated, 4.3L, 4-cylinder) operated using retrofitted Monogas concept is presented. Extensive simulation (GT-Power software) and experimental works using an engine test bed had been carried out to characterize the Monogas engine. Generally, successful retrofitting demands modifications in combustion chamber profiles, compression ratio, fuelling, ignition timing, intake, and exhaust systems. The optimum re-entrance (RE) and toroidal radius (TR) ratio for retrofitting must be between 0.16 and 0.60, for a compression ratio (CR) of 11:1. From the various combustion chamber profile designs, the design with lower central projection and RE to TR ratio of 0.16 was considered as the optimum combustion chamber geometry profile. Using this design, the 4.3L C.I. engine was successfully converted and tested at steady state engine conditions and selected set-points driving cycle. The findings from the simulation showed that the tested Monogas engine exhibited lower brake torque (BT) and brake power (BP) in the range of 13% - 19%. It also produced lower CO_2 (59%), CO (85%) and NO_X (85%) emissions, with the penalties of HC emissions and brake specific fuel consumption (BSFC); increase of 85% and 13% respectively. Comparisons with experimental works using C.I. engine had concluded that the Monogas engine was operating with high BSFC with an improved volumetric efficiency (η_{VE}) in the range of 40% to 58%. It also released lower CO (68%) and HC (48%) emissions, and high CO_2 emissions, indicating high combustion efficiency. However, NO_X emissions were higher in both experimental settings, whereas HC emissions were observed to be higher during the driving cycle set-point tests. Therefore, the methodology developed offers a successful C.I. engine converted to Monogas engine system via retrofit technology and an opening for future development and characterization into comprehensive support for implementation of energy efficient and environmental friendly vehicles.

ABSTRAK

Baru-baru ini, syarikat-syarikat logistik dan pengangkutan sedang mempertimbangkan menggunakan CNG untuk pencucuhan mampatan (C.I.) bagi enjin mereka yang sedia ada. Dalam usaha untuk menangani cabaran ini, satu kajian parametrik pada CI tugas sederhana enjin (beraspirasi semulajadi, 4.3L, 4-silinder) yang dikendalikan menggunakan konsep monogas telah dibentangkan. Simulasi ekstensif (perisian GT-Power) dan kerja-kerja eksperimen dengan menggunakan enjin dynamometer telah dijalankan untuk mencirikan enjin Monogas. Secara umumnya, kejayaan meretrofit memerlukan perubahan profil bagi kebuk pembakaran, nisbah mampatan, sistem minyak, masa nyalaan, masukkan and ekzos. Nilai optimum masukan (RE) dan nisbah jejari toroidal (TR) untuk retrofitting mesti di antara 0.16 dan 0.60, bagi nisbah mampatan (CR) 11:1. Daripada pelbagai reka bentuk profil kebuk pembakaran, reka bentuk dengan unjuran yang lebih rendah dan nisbah pusat RE/TR 0.16 dianggap sebagai kebuk pembakaran profil geometri yang optimum. Dengan menggunakan reka bentuk ini, 4.3L enjin C.I. telah berjaya diubahsuai dan diuji pada keadaan enjin mantap dan pemilihan nilai tetap bagi kitaran memandu. Hasil daripada simulasi menunjukkan enjin monogas yang diuji mempamerkan tork brek (BT) dan kuasa brek (BP) lebih rendah dalam lingkungan 13% - 19%. Ia juga menghasilkan perlepasan CO_2 (59%), CO (85%) dan NO_X (85%) yang lebih rendah, dan penalti terhadap perlepasan HC dan penggunaan bahan api brek (BSFC); peningkatan sebanyak 85% dan 13%. Perbandingan dengan kerja-kerja eksperimen menggunakan enjin C.I. dapat disimpulkan bahawa enjin monogas yang beroperasi dengan BSFC tinggi dengan kecekapan isipadu yang lebih baik (η_{VE}) dalam lingkungan 40% hingga 58%. Ia juga mengeluarkan perlepasan CO yang lebih rendah (68%) dan HC (48%) lebih rendah, tetapi pelepasan CO2 yang tinggi, menunjukkan kecekapan pembakaran yang tinggi. Walau bagaimanapun, pelepasan NO_X adalah lebih tinggi dalam kedua-dua eksperimen, manakala perlepasan HC dilihat lebih tinggi semasa ujian kitaran memandu. Oleh itu, kaedah yang dibangunkan ini telah berjaya menukarkan enjin C.I. kepada sistem enjin Monogas melalui teknologi retrofit dan membuka peluang pembangunan dan penciriannya secara menyeluruh untuk masa akan datang di dalam menyokong pelaksanaan kenderaan cekap tenaga dan mesra alam sekitar.

CONTENTS

LIST OF TABLE

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVISTIONS

1-D	-	One Dimensional
3-D	-	3-Dimensional
B	-	Bore
L	-	Stroke
N	-	Engine Speed (rpm)
T	-	Torque
V_d	-	Engine Displacement
$\dot{m}_f$	-	Fuel Mass Flow Rate
μ_R	-	Number of Crank Revolutions
AFR	-	Air Fuel Ratio
ANG	-	Absorbed Natural Gas
ANGVA	-	Asian Natural Vehicle Association
ATF	-	Aviation Turbine Fuel
AV gas	-	Aviation Gasoline
BP	-	Brake Power
BDC	-	Bottom Dead Centre
BBDC	-	Before Bottom Dead Centre
BTDC	-	Before Top Dead Centre
BMEP	-	Brake Mean Effective Pressure
BSFC	-	Brake Specific Fuel Consumption
cc	-	Cubic Centimeter
CA	-	Crank Angle
CI	-	Compressed Ignition
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide

CNG	-	Compressed Natural Gas
DI	-	Direct Injection
EI	-	Emission Index
ECU	-	Electronic Control Unit
EGR	-	Exhaust Gas Recirculation
GHG	-	Green House Gas
HC	-	Hydrocarbon
HD	-	Heavy Duty
H_2O	-	Water
HCCI	-	Homogeneous Charge Compression Ignition
IC	-	Internal combustion
ICE	-	Internal Combustion Engine
IDI	-	Indirect Injection
Ktoe	-	Thousand Tonnes of Oil Equivalent
LNG	-	Liquefied Natural Gas
LPG	-	Liquefied Petroleum Gas
MD	-	Medium Duty
MPI	-	Multipoint Port Fuel Injection
Mtoe	-	Million Tonnes of Oil Equivalent
NA	-	Natural Aspirated
NG	-	Natural Gas
NO_X	-	Nitrogen Oxide
NGV	-	Natural Gas Vehicle
NGVA	-	Natural and Biogas Vehicle Association (Europe)
O_2	-	Oxygen
OEM	-	Original Equipment Manufacturing
PM	-	Particulate Matter
PPM,ppm	-	Part Per Millions
RON	-	Research Octane Number
RE	-	Re-entrance
RPM,rpm	-	Revolution-per-minute
SI	-	Spark Ignition
SO_x	-	Sulphur Oxides
SOF	-	Soluble Organic Fraction

SOHC	-	Single Overhead Camshaft
SUV	-	Sport Utility Vehicle
TBI	-	Throttle Body Fuel Injection
TDC	-	Top Dead Centre
THC	-	Total Hydrocarbon
TKE	-	Turbulent Kinetic Energy
TR	-	Toroidal radius
USD	-	United State Dollar
WOT	-	Wide Open Throttle
VOC	-	Volatile Organic Compound

LIST OF APPENDIX

CHAPTER 1

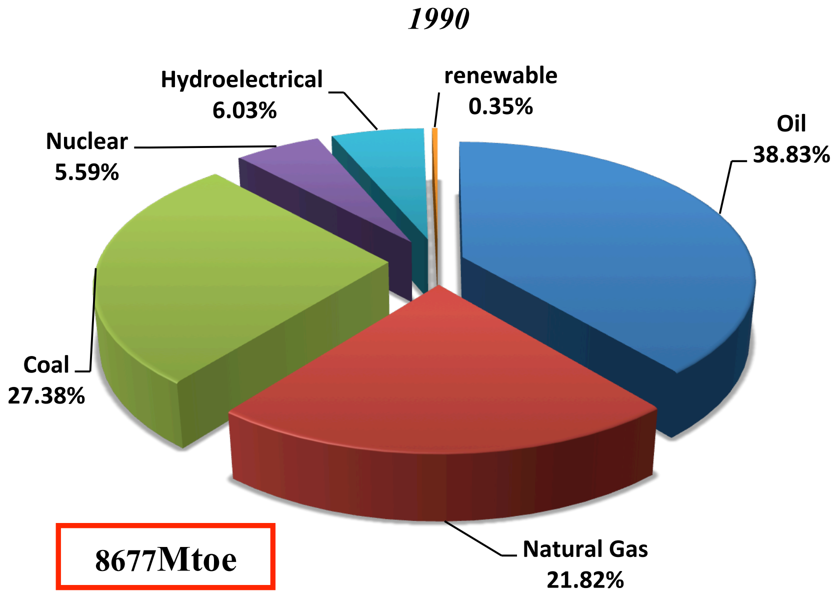
INTRODUCTION

1.1 Background

Currently, fossil fuel reserves all over the world are diminishing at an alarming rate and a shortage of crude oil is expected due to unbalance ratio between production and demand rates (Semin *et. al,* 2009). According to The U.S. Energy Information Administration & Energy, 2013, the final energy consumption was projected to increase about 2.8% annually. The growth in demand are expected to be high due to the expending countries development activity as economies grow and improving the quality of life, where the energy demand and consumption are discussed in next sub-chapter as below.

1.1.1 Energy consumptions

The global energy consumption is likely to grow faster than the increase in population. Proven global reserves of crude oil and natural gas are estimated to last for 41.8 and 60.3 years respectively based on the current global production rates. According to the BP Statistical Review of World Energy, June 2013 (British Petroleum, 2013), primary global energy consumption grew by 12,476.6 million tons of oil equivalents (Mtoe) in 2012, well above the energy consumption for the last 22 years by 8677 Mtoe with 30% increments, as shown in Figure 1.1. In 2012, the demand for fossil fuel was recorded at 86.93% of the energy consumption, where 33.1% consisted for crude oil, 29.89% coal and 23.94% natural gas. This demand is expected to remain resilient and will continue to be the anchor for growth attributed to the international economic environment.



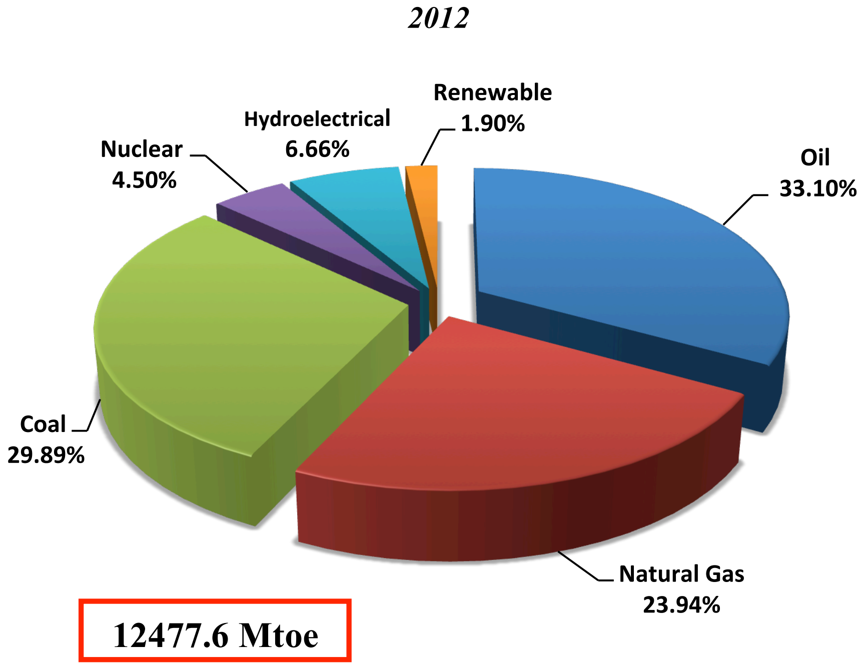


Figure 1.1:Total world energy consumption by fuels (reproduced from British Petroleum, 2013)

In Malaysia's energy scenario, the economic growth has improved due to the stronger domestic demand. With a positive and strong economic growth, Malaysia's energy supply and demand also rose in tandem. According to the Malaysian Energy Commission (2010, 2011), total primary energy supply and final energy demand recorded a growth of 3.2% and 4.8% respectively when compared with that of the previous year. All major petroleum products showed an upward trend due to the local demand. (Energy Commission, 2010)

The total final energy demand by fuel type shows that Petroleum products constituted about 44.29% of the total energy demand, followed by Electricity at 24.59%, Natural Gas at 22.67%, Coal and Coke at 4.67% and Non-Energy type at 3.14%, as shown in Figure 1.2. With future energy demand expected to grow at an annual growth rate of 5-7.5% for the next 20 years, energy security is becoming a serious issue as fossil fuels are a non-renewable energy and will be depleted eventually in near future. Faced with the possibility of a prolonged energy crisis, a diversification of energy resources was implemented to reduce the dependency on crude oil by introducing alternative fuels for the largest energy consuming sector, which is the transportation sector (Ong *et al.*, 2011).

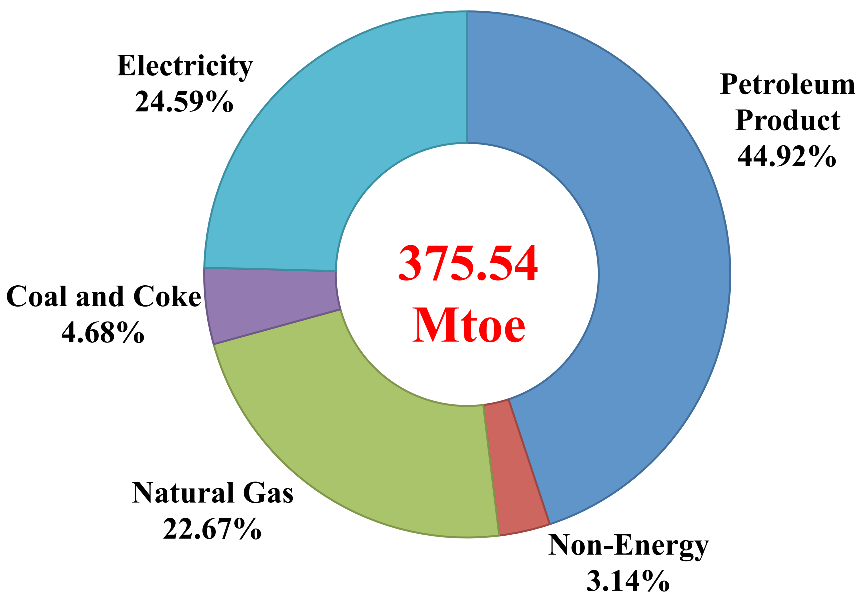


Figure 1.2: Final energy consumption by fuel type in Malaysia (Energy Information Administration, 2013)

1.1.2 Energy demands by the road transportation sector

The transportation sector has experienced steady growth in the past 30 years, whereby this sector is the one of the major components of globalization and makes a vital contribution to the economy. Besides, it plays a curial role in daily activities around the world. According to 'The Outlook for Energy: A View to 2040' (ExxonMobil, 2013) , the total transportation energy demand will increase by more than 40% from 2010 to 2040, with growth coming almost entirely from commercial transportation, where heavy-duty vehicles are expected to grow about 65% by 2040. In contrast to the growth in commercial transportation, the energy demand for personal vehicles; cars, sports utility vehicles (SUVs) and small pickup trucks will be plateaus fairly soon and begin a gradual decline as consumers turn to smaller, lighter vehicles while technologies improve fuel efficiency, as shown in Figure 1.3.

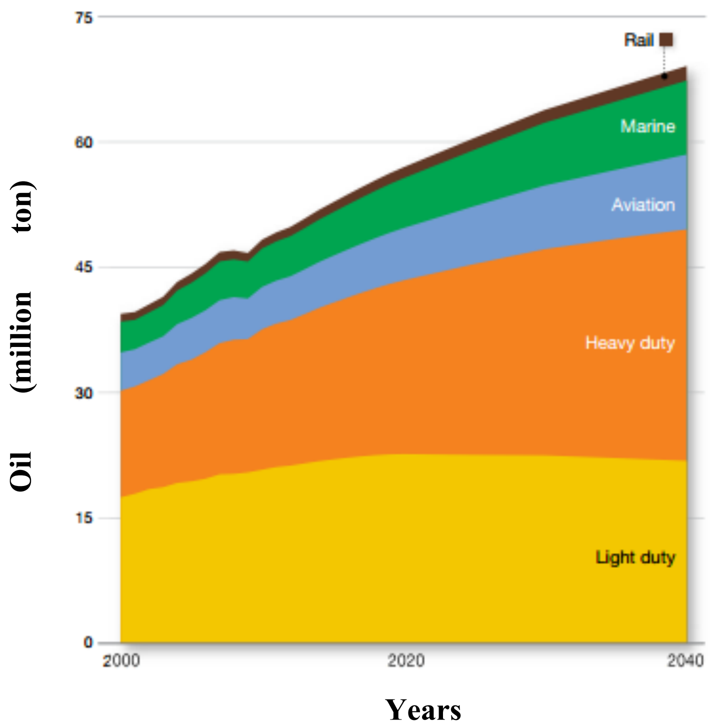


Figure 1.3: Transportation energy demands by sector (reproduced from ExxonMobil, 2013)

In Malaysia, total final energy demand according to sectors in 2011 had experienced an increase of 4.8% from the previous year to stand at 43,455 ktoe. Analysis by the National Energy Balance (NEB) (Energy Commission, 2011), shows that the transportation sector still remains the main energy consumer in the country with a share 39.44%, followed by industries at 38.04%, residential and commercial at 13.61%, non-energy at 8.06% and agriculture at 0.85%. The pattern of energy demand by the transportation sector is based on fuel types, as illustrated in Figure 1.4 and tabulated in Table 1.1. It shows that the main energy consumption is from fossil fuels with primary use is diesel, followed by petrol, aviation turbine fuel (ATF) and aviation gasoline (AV gas). The increase was attributed by the demand and growth in household income and number of vehicles.

Table 1.1:Malaysian energy consumption by the transportation sector (ktoe) (reproduced from Malaysia Energy Balance, 2011)

Years	Diesel	Petrol	Fuel Oil	ATF and AV gas	Natural Gas	Electricity	Total
2000	7,627	6,387	1,875	1,574	3,863	5,263	26,589
2001	8,116	6,827	1,497	1,762	4,621	5,594	28,417
2002	8,042	6,948	1,590	1,785	5,644	5,922	29,931
2003	8,539	7,360	1,256	1,852	5,886	6,313	31,206
2004	9,262	7,839	1,463	2,056	6,490	6,642	33,752
2005	8,672	8,211	1,954	2,010	6,981	6,943	34,771
2006	8,540	7,518	1,901	2,152	7,562	7,272	34,945
2007	9,512	8,600	2,203	2,155	7,708	7,683	37,861
2008	9,167	8,842	1,963	2,112	7,818	7,986	37,888
2009	8,634	8,766	1,291	2,120	6,800	8,286	35,897
2010	8,388	9,560	478	2,380	6,254	8,993	36,053
2011	8,712	8,155	414	2,553	8,515	9,235	37,584

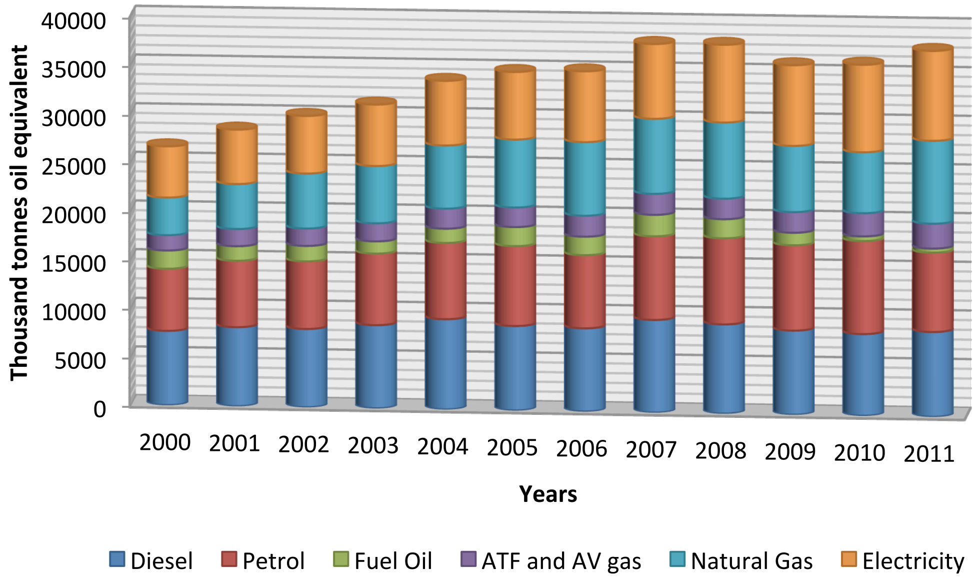


Figure 1.4:Energy pattern by the transportation sector in Malaysia (reproduced from Malaysia Energy Balance, 2011)

Faced with the challenge of energy security, energy shortage and high energy demand, the government had introduced fuel diversification as a new policy to sustain the energy supply by enhancing energy efficiency and increasing energy sufficiency to reduce the dependency on petroleum products, which would create an economic impact on shocking fuel prices (Ong *et al.*, 2012).

1.2 Malaysian fuel prices

Globally, the increasing energy demand in respect to energy supply has created an economic turmoil especially in petroleum products. The fluctuation of current oil prices is expected to grow as demand increases. Figure 1.5 shows the actual global trend and price fluctuations of petroleum products from February 2007 to April 2014. Overall, the average fuel price was recorded to stand at USD 3.67 and USD 3.93 per gallon for petrol and diesel respectively. The highest price for petrol and diesel was registered in July 2008 at USD 4.29 and USD 4.71 per gallon respectively. These are equivalent to USD 1.13 per litre petrol and USD 1.24 per litre diesel.

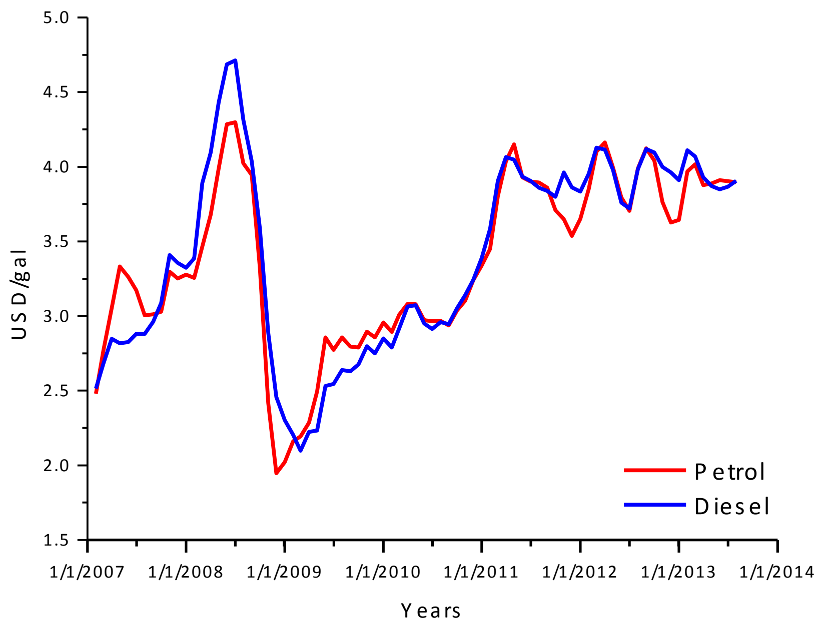
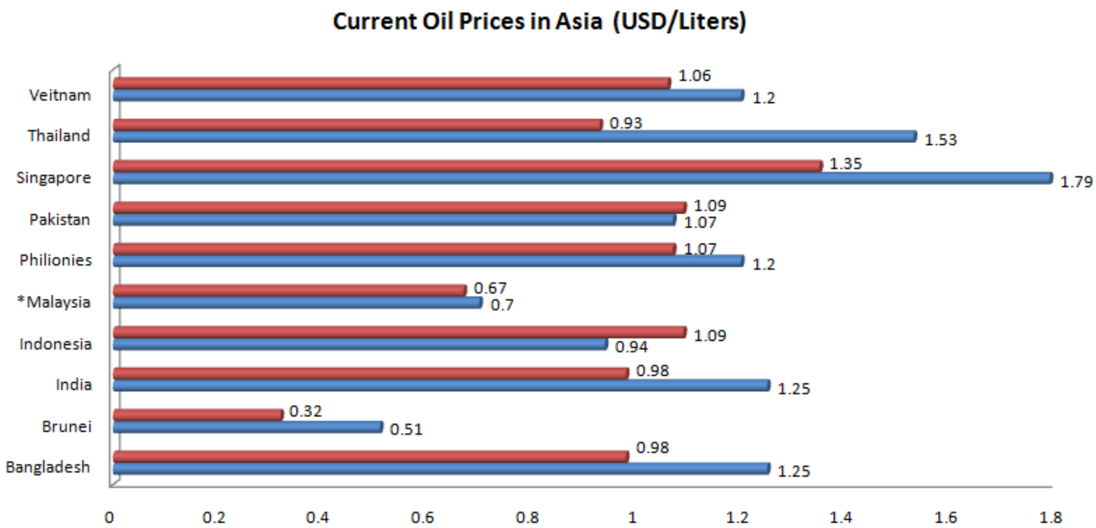


Figure 1.5:Global energy prices for petroleum products from February 2007 to August 2013 (reproduced from US Energy InformationAdministration, 2013)

Meanwhile, current energy prices in Asia are also affected by the volatility of world oil prices, especially in Malaysia. Until September 3, 2013, the oil price was traded at USD 0.70 per litre for petrol and USD 0.67 per litre for diesel as depicted in Figure 1.6. These prices are slightly lower compared to other countries due to the government’s subvention. This subvention, however, is not valid for commercial and industrial sectors. Hence, this has created a negative impact on economic developments especially for the transportation sector, where companies had to bear higher operating expenses due to the fluctuations in fuel prices. Therefore, fuel diversification strategies by using alternative fuels, such as hydrogen, natural gas and dual fuels with very low and stable prices will help to overcome the fluctuation and uncertainty of fuel prices and fuel supply. This will benefit the end-user or companies by reducing their expenses and overhead cost for transportation fuel.



	Bangladesh	Brunei	India	Indonesia	*Malaysia	Philionies	Pakistan	Singapore	Thailand	Veitnam
Diesel	0.98	0.32	0.98	1.09	0.67	1.07	1.09	1.35	0.93	1.06
Petrol	1.25	0.51	1.25	0.94	0.7	1.2	1.07	1.79	1.53	1.2

* Price updated May 12, 2014

Figure 1.6:Current oil prices in Asia(reproduced from MyTravelCost, 2014)

1.3 Emissions from vehicles in the road transport sector

Until 30th June 2013, the total number of registered road vehicles in Malaysia has been growing at an average rate of 3% to 4% annually. Figure 1.7 shows the total number of vehicles by type, registered in Malaysia from 2009 until 2013. The figure was edited from the Road Transport Department of Malaysia (2013).

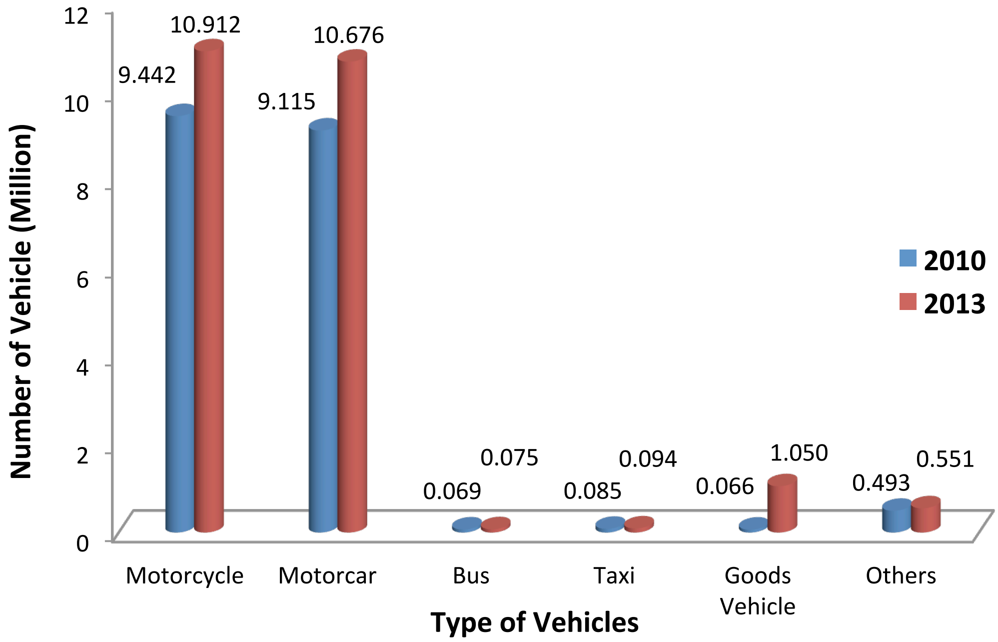


Figure 1.7:Total vehicles registered in Malaysia from 2010 to 2013 according to type (reproduced from Road Transport Department of Malaysia, 2013)

According to the Annual Report of the Road Transport Department of Malaysia, the number of registered road vehicles had increased from more than 9.4 million in 2010 to more than 10.91 million in the second quarter of 2013. Motorcycles accounted for the largest share of the motor vehicle fleet in the country, closely followed by cars and goods vehicles. The increasing number of vehicles on the road, especially in the urban areas, has contributed to environmental deterioration. It is therefore also one of the highest contributors to overall carbon dioxide (CO_2) emissions. Figure 1.8 shows Malaysia's total CO_2 emissions from consumption of fossil fuel.

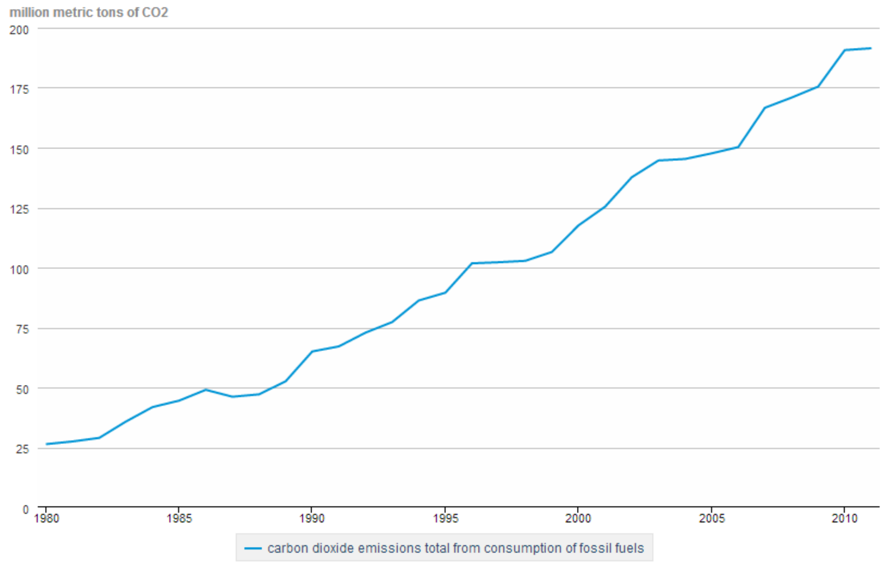


Figure 1.8: Malaysia's total CO_2 emissions from consumption of fossil fuel (reproduced from US Energy Information Administration, 2013)

From the figure, Malaysian CO_2 emissions had rapidly increased to 190.67 million metric tons in 2010 to 191.44 million metric tons. The increase of CO_2 emissions are expected to continue due to the increasing population ratio as well as improvements in the quality of social-life. As reported by the CAI-Asia Secretariat (2006), the major source of air pollutant emissions were motor vehicles, contributing at least 70% to 75% of the total air pollutants. A study on Malaysia's air pollutants by the Department of Environment, (2013), showed that motor vehicles contributed 80% of the air pollutants.

Recent estimates of emissions in Malaysia are shown in Figure 1.9.Carbon monoxide (CO) emission is the highest air pollutant emitted by the transportation sector, followed closely by hydrocarbon (HC), nitrogen oxide (NO_X) and particulate matter (PM). The root cause of these emissions was attributed to motor vehicles and the effect of these emissions on human health is discussed in chapter 2.

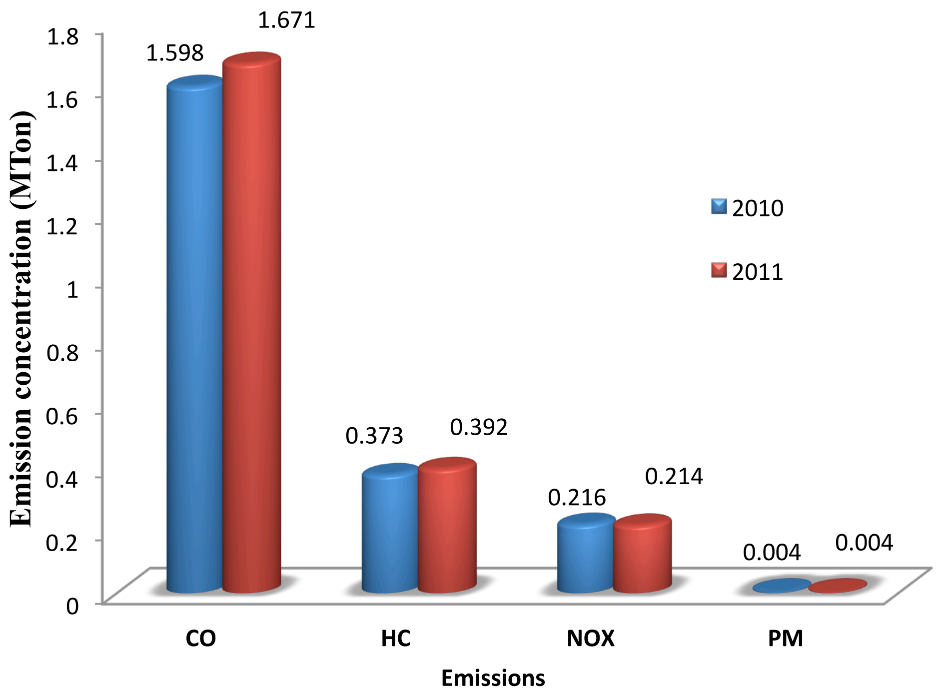


Figure 1.9**:** Malaysian air pollutant emissions caused by the transportation sector from 2010 to 2011 (reproduced from Department of Environment, Malaysia 2013)

The deterioration of environmental quality had been caused by the extensive use of conventional fuels and this had encouraged the government to execute the national energy policies. The main thrust of energy policies is the importance of ensuring adequate, secure and reliable supply of energy at affordable costs in addition to promoting efficient utilisation of energy. Efforts to reduce dependency on petroleum products and environmental considerations are major objectives. In order to support this, promoting public interest and awareness of clean energy vehicles that utilize an alternative fuel, namely Compressed Natural Gas (CNG) has been introduced. CNG has become the best candidate for replacing diesel fuel due to its lower price, less pollutant emitted and an abundance of resources compared to conventional fuels.

1.4 Problem statement

In Malaysia, the use of CNG has been dominated by the spark ignition (S.I.) engine via the retrofit system, while retrofitted compression ignition (C.I.) engines are still limited and has tremendous potential of filling the gap in research. However, there are still barriers of implementation such as:

i. Diversification of C.I. to S.I engine operations
ii. The controlling parameters that involved during the conversion process
iii. Methodologies of conversion process towards a Monogas engine system
iv. The unknown characteristics of Monogas engine in terms of engine performance and exhaust gas emissions.

Therefore, it is desired to have a C.I. engine converted to Monogas engine system via retrofit as a promising technology as well as a solution to current issues, which offers all the advantages over the conventional fuel engine.

1.5 Objectives of research

This study embarks on the following objectives:-

a. To identify the influencing parameters of a retrofitted Monogas engine.
b. To diversify the existing C.I. engine to be retrofitted with Monogas engine system
c. To investigate the performance and emissions characteristics of the retrofitted Monogas engine

1.6 Scope of research

This study covers the following scopes:-

a. The research focused on the medium-duty direct C.I. engine with a capacity of 4.3 litres.

b. The simulation works are focused on:

    i. To identify the optimum combustion chamber geometry profiles for a retrofitted Monogas engine using CFD simulation

    ii. To determine the engine performance and emissions characteristics for retrofitting Monogas engine using 1-dimensional software.

c. The experimental works are conducted at two different test conditions via engine dynamometer:

    i. Steady-state condition with specific dynamometer loads (27Nm, 54Nm and 81Nm)

    ii. Road load conditions with selected 7 points driving cycle set-point tests.

d. A dedicated gas mixer system has been selected in this research.

e. The test engine equipped with the retrofitted Monogas engine system is only applied to the stoichiometric value of 17.2 with a compression ratio 11:1.

1.7 Thesis outline

The present thesis comprises of five chapters. Chapter One is the introduction in which the problem statement, objectives and scope of research, contribution to the knowledge in research work are presented. The literature review is presented in Chapter Two and covers topics from the basic of retrofitted Monogas CNG system, the performances and emission characteristics of converting engines and related information on techniques of engine diversification. In Chapter Three, detail description of the experimental setup, procedures and techniques, the conversion processes; design and development of retrofitting the Monogas engine system into medium-duty direct injection C.I. engine towards a fully functioning engine employed in the research are presented. All experimental results are presented and discussed with evidence to support them are presented in Chapter Four. Finally, in Chapter Five a set of conclusions drawn from the research work conducted are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of the literature on the efforts relating to the retrofitting of a Monogas system into a compression ignition (C.I.) engine. It is an attempt to establish the parameters, modifications, and technologies etc., which are required for making this conversion successful. It begins with the concept of an internal combustion engine followed by the automotive trends and demand in implementing the CNG as an alternative fuel. In addition, the state of art CNG engine technology and engine diversifications that affect the exhaust gas emissions and engine performances are presented.

2.2 The internal combustion engine

The internal combustion engine (ICE) has served the automotive industries for over a century. In detail, the development and tested engines in many different styles of ICEs started during the second half of 19^{th} century (Pulkrabek, 2004). For automotive powered vehicles, the standard ICEs can be classified in a number of different ways (Heywood, 1988; Pulkrabek, 2004):

a. Ignition types
   i. **Spark ignition (S.I.) -** engine requires the use of spark plugs as an igniter to initiate the combustion process.
   ii. **Compression ignition (C.I.) -** where the combustion starts when the appropriate air-fuel mixture self-ignites due to the high compression caused by the high temperature.

b. Engine cycles
   i. **Four stroke cycle -** where a complete cycle has four piston movements in two engine revolutions.
   ii. **Two stroke cycle -** where a complete cycle has two piston movements in a single engine revolution.

c. Method of fuel input for S.I. engine
   i. **Carbureted**
   ii. **Multipoint port fuel injection (MPI)**, where required one or more fuel injectors at each cylinder intake.
   iii. **Throttle body fuel injection (TBI)**, where the injectors are mounted upstream in the intake manifold.
   iv. **Gasoline direct injection**, where the injectors are in the combustion chambers with injections directly into the cylinders.

d. Method of fuel input for C.I. engine

   i. **Direct injection (DI)**, where the fuel injected directly into main combustion chamber.

   ii. **Indirect injection (IDI)**, where the fuel is injected into the secondary combustion chamber.

   iii. **Homogeneous charge compression ignition (HCCI)**, where some of the fuel is added during the intake stroke.

e. Air intake process

   i. **Naturally aspirated (NA)**, where no intake air pressure system.

   ii. **Supercharged**, where intake air pressure increases with the compressor driven by the engine's crankshaft.

   iii. **Turbocharger**, where intake air pressure increases with the turbine-compressor driven by the engines exhaust gases.

f. Types of cooling

   i. **Air-cooled**.

   ii. **Liquid or water-cooled**.

All of these classifications are important as they provide a basic understanding when selecting the engines to be retrofitted with a mono-CNG system. In this research, the medium duty direct injection C.I. engine with four stroke cycles and 4 inline cylinders that are naturally aspirated was considered, which would be described later in chapter 3.

Generally, the C.I. or diesel engine can be categorized into three basic engine groups based on power output; small, medium and large engines. The small engines normally have power output values of less than 188 kilowatts (kW) or 252-horse power (HP). These engines are used in automobiles, light trucks and small generators. An engine that is capable of producing power outputs between 188kW and 750 kW, and equivalent between 252 and 1,005 HP is considered a medium engine. These engines are usually used in heavy-duty trucks. Moreover, the large engines have power rating in an excess of 750 kW or 1,006 HP. These engines are normally used for prime movers, marine and locomotive engines (Armstrong, 2013; Heywood, 1988).

A complete combustion for four stroke cycles in internal combustion engines; both C.I. and S.I. requires four events, which are intake stroke, compression stroke, power stroke and exhaust stroke. Figure 2.1 shows the typical sequence of cycles for a complete combustion.

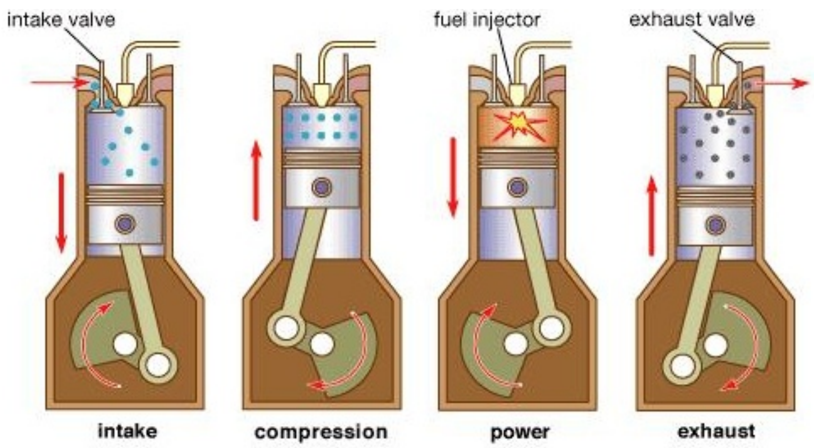


Figure 2.1:Four stroke cycles in an internal combustion engine (reproduced from Britannica, 2013)

During the intake stroke or also known as the suction stroke for C.I. engines, the intake valve is open and the exhaust valve is closed and the piston travels downward from Top Dead Centre (TDC) to Bottom Dead Centre (BDC). The traveling of the piston will create a pressure differential, which in turn creates a vacuum in the cylinder. Then, fresh air is drawn into the cylinder without any fuel added.

In the compression stroke, the piston travels upward from the BDC to the TDC with the intake and exhaust valves being closed. The compression by the intake air results in higher pressure and temperature in the cylinder. The injection of fuel directly into the combustion chamber at certain degrees Before Top Dead Centre (BTDC) and varied with very hot air will cause the fuel to evaporate and self-ignite, causing the combustion to begin.

The combustion will start to develop until the piston reaches the TDC and continues at about a constant pressure until fuel injection is complete. At this moment, the intake valve and exhaust valve remain closed. The energy from the combustion will force the piston to move downwards to the BDC as well as creating the rotary motion on the crankshaft. This is called a power stroke.

In the exhaust stroke, the burnt gas from the combustion is removed from the cylinder when the piston travels from a few degrees Before Bottom Dead Centre (BBDC) until it reaches the TDC. The movement of the piston will force out the exhaust gas and start the new operating cycle. In this situation, the intake valve remains closed, while the exhaust valve is opened.

The difference between C.I. engine and S.I engine cycles are: at the intake stroke, the air passes the intake system with the desired amount of added fuel required by the engine into the cylinder. For the compression stroke, it is similar to the C.I engine except that the compression of combustible mixtures (in the form of fresh air and fuel mixture) causes the increase of pressure and temperature in the cylinder. Hence, when nearing the end of the compression stroke, the spark plug will ignite and the combustion is initiated into a power stroke. The movements of the intake and exhaust valves remain the same for all cycles. These differences are described in Table 2.1.

Table 2.1:Comparison of S.I. engine and C.I. engine (Fernando, 2010; Heywood, 1988)

Factor	**S.I. Engine**	**C.I. Engine**
Intake/compression	Air and fuel	Air only
Ignition method	Spark plug	Compressed air and fuel
Speed control	Nearly homogeneous	Very heterogeneous
Mixture uniformity	Throttle air fuel mixture	Air un-throttled, fuel control only
Equivalence ratio	0.85 to 1.25	0 to 0.7
Exhaust temp.	Higher	Lower
Compression ratio range	7 to 14	15 to 21

2.3 Exhaust gas pollutants

With the tremendous increase of transportation energy consumption, environmental pollutants have posed serious challenges and demands for improving the internal combustion engine, which can cause serious problems towards human health and the environment. Environmental pollutants emanating exhaust gas emissions from road vehicles, typically gasoline and diesel combustion are blamed for most toxic emissions to the atmospheres (Barros Zárante & Sodré, 2009a).

Research has particularly focused on diesel engines, where the exhaust emissions include a wide range of gaseous and particulate organic and inorganic compounds. However, these exhaust gas emissions are dependent on the fuel composition, which varies with operating conditions such as engine types, fuel, current emission control system and the lubricating oil. The diesel engine pollutants can be classified into five main groups consisting of carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NO_X), particulate matter (PM) and carbon dioxide (CO_2)

2.3.1 Carbon monoxide – CO

Carbon monoxide is a colourless, tasteless, odourless, but highly toxic. The CO emissions are strongly dependent on the value of air-fuel ratio (AFR). CO is formed during the combustion process with rich fuel mixtures and when there is insufficient oxygen to fully burn the entire carbon bond in the fuel to CO_2 (Paul *et al.*, 2013). The amount of CO emission increases when the reaction temperature falls below 1500K (S. M. A. Rahman et al., 2013). Moreover, the CO emission in exhaust gases represents the loss in chemical energy that is not fully utilized.

In view of the fact that the CO is a highly toxic gas, direct exposures that exceed the existing standard might have a greater potential to increase the total body burden for CO. As contact with CO increases, the haemoglobin in the body binds to CO and the oxygen carrying capacity of the blood decreases, resulting in unconsciousness and eventually, death (Raub *et al.*, 2000).

2.3.2 Hydrocarbon - HC

Hydrocarbon (HC) is formed when there is unburned fuel passing through the engine exhaust resulting in incomplete combustion (Paul et al., 2013). HC emissions constitute compounds of hydrogen, carbon and occasionally, oxygen. The two main causes of HC emission increase in diesel engines are, firstly, the delay period, where fuel is mixed leaner that the lean combustion limit, specifically ignition timing. Second, the use of EGR can also be a significant contributor.

2.3.3 Nitrogen Oxide – NO_X

Nitrogen oxides (NO_X) comprise of nitric oxide and a small amount of nitrogen dioxide (NO_2). NO is colourless, odourless and tasteless, while in the air it gradually transforms into NO_2. NO_X exists in some levels in the exhaust emissions. The formation depends upon; (a) the temperature of the cylinder, (b) the in-cylinder temperature, (c) the coefficient of air surplus, (d) pressure deferential, (e) Exhaust gas recirculation (EGR), (f) injection timing, (g) time of reaction and (h) the properties of fuel (Heywood, 1988; Pulkrabek, 2004). Ideally, NO_X is produced from burning hydrocarbon fuels with oxygen during the combustion process with a high combustion temperature of about 1800K

NO is not irritant, but the effects are similar to CO emissions. A wide range of health and welfare effects is caused by NO_X emissions such as the irritation of the lungs, which can lower resistance to respiratory infections. Acid rain is also caused by NO_X emissions, which possess a hazardous risk to the ecosystem by increasing irritation and toxic algal blooms and reduces sun light penetration resulting in losses of submerged aquatic vegetation.

2.3.4 Particulate matter – PM

Particulate matter (PM) air pollutants are an air-borne combination of solid and liquid elements that vary in surface area, shape, size, number, chemical composition, and solubility. PM is a highly complex mixture of fine particles and liquid droplets, which include soot, HC soluble organic fraction (SOF), water SOF and ash. The size is significantly small thus allowing deep penetration into the lung, which might result in grave health problem. Many studies have found that exposure to particulate pollution can cause a variety of problems including an increase in respiratory symptoms (coughing, difficulty in breathing), decreased lung function, non-fatal heart attacks, aggravated asthma, irregular heartbeat and premature death in people with heart or lung diseases or lung cancer. PM emissions also influence the atmospheric visibility.

2.3.5 Carbon dioxide – CO_2

Carbon dioxide is not considered an air pollutant. However, it is considered a major greenhouse gas (GHG). Ideally, combustion of hydrocarbon fuel should produce only water (H_2O) and carbon dioxide (CO_2). Thus, the use of fuel with lower carbon content per unit energy has greater potential to reduce the CO_2 emissions.

The increase of CO_2 emissions from engine combustion has recently attracted considerable attention. Due to the growing number of vehicles, the amount of CO_2 in the atmosphere continues to grow (Pulkrabek, 2004). These GHG will create a thermal radiation that allows solar energy to reach the earth. However, some of the thermal radiation will be trapped resulting in the increase of average earth temperature. This phenomenon is known as the “greenhouse effect”, which eventually brings forth “global warming”.

The most effective way to reduce the effect of GHG as proposed by (Andress *et al.*, 2011), are as follows:

a. Improve engine efficiency
b. Introduce low carbon fuels
c. Reduce vehicular miles travelled

However, the use of after-treatment such as catalytic converters is not practical in reducing the CO_2 emissions. Indeed, the catalytic oxidation of CO and HC will only slightly increase CO_2 emissions (Alimin, 2006). Another option in reducing the harmful emissions is by utilizing alternative fuels, such as CNG.

2.4 Demand for CNG vehicles

Today, the use of natural gas engines is becoming popular in the transportation sector (NGV-Global, 2012; NGV-AsiaPasific, 2013) and the demand is expected to growth in the foreseeable future due to new legislation and regulation surrounding emissions as well as the dramatically shift in fuel prices (in the form of gasoline and diesel fuel). According to the EIA; Annual Energy Outlook 2013 with Projections towards 2040 (Energy Information Administration, 2013), the largest potential natural gas vehicle (NGV) demand growth in the transportation sector comes from the heavy duty vehicle segment. The natural gas fuel consumption was forecasted to use more than 1 quadrillion Btu in 2040, at an average annual growth rate of 14.6 percent. The International Association for Natural Gas Vehicles (IANGV) also supported this, whereby the number of vehicles fuelled by natural gas was projected to increase up to 25 million until 2014 as depicted in Figure 2.2.

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