EXPERIMENTAL STUDIES OF SPRAY AND COMBUSTION CHARACTERISTICS OF BIOMASS DERIVED FUELS IN A CONSTANT VOLUME COMBUSTION CHAMBER

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by

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LIST OF ABBREVIATIONS

AFR	Air fuel ratio
ANOVA	Analysis of variance
BSFC	Brake specific fuel consumption
BTDC	Before top dead centre
BTE	Brake thermal efficiency
CAD	Computer aided design
CCD	Central composite design
CFD	Computer fluid dynamics
CH_4	Methane
CH	CH chemiluminescences (ignition start)
CI	Compression ignition
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CPG	Compressed producer gas
CPO	Crude palm oil
CRI	Common rail injection
CVCC	Constant volume combustion chamber
DI	Direct injection
DME	Di-methyl ether
DOE	Design of experiment
EFQ	Engine fuel quality

EGT	Exhaust gas temperature
EMF	Electromagnetic field
ER	Equivalence ratio
GC	Gas chromatography
H_2	Hydrogen
HAA	Hole-axis angle
HCCI	Homogeneous charge compression ignition
HOME	Hazelnut oil methyl ester
HRR	Heat release rate
ICE	Internal combustion engine
IMP	Indicated mean pressure
LHV	Low heating value
LIF	Laser induced fluorescence
LPG	Liquefied petroleum gas
MIF	Mass increased factor
NA	Naturally aspirated
NOx	Nitrogen oxide
OH	OH chemiluminescences (diffusion flame)
PDPA	Phase Doppler particle anemometry
PG	Producer gas
PIC	Programmable integrated circuit
PIV	Particle image velocimetry
PP	Peak pressure
RBD	Refined, bleached and deodorized
RME	Rape methyl ester

RPO	Refined palm oil
RSM	Response surface methodology
SG	Syn-gas
SI	Spark ignition
SMD	Sauter mean diameter
SO_2	Sulfur dioxide
SOI	Start of injection
TDC	Top dead centre
THC	Total hydrocarbon
USB	Universal serial bus
VOME	Vegetable oil methyl ester

LIST OF SYMBOLS

AFR_a	Actual air fuel ratio
AFR_s	Stoichiometric air fuel ratio
D_d	Droplet diameter (m)
dn	Number of drops with diameter D_d
d_n	Nozzle diameter (m)
D_{SM}	Sauter mean diameter (m)
m_a	Mass of air (kg)
m_f	Mass of fuel (kg)
m_g	Mass of gas (kg)
M_g	Molar mass of gas
M_i	Molecular weight of gas component
P	Pressure (Pa)
Δp	Pressure different (Pa)
p_i	Ambient pressure (Pa)
P_{inj}	Injection pressure (Pa)
$\frac{dP}{dt}$	Rate of pressure changes
r	Inner radius of the cylinder (m)
R	Universal gas constant
r_f	Flame radius (m)
R_g	Specific gas constant
r_i	Weight fraction of gas component
r_0	Unsupported disc radius (m)

S_A	Spray area (mm^2)
S_{max}	Maximum allowable stress (Pa)
t	Time (s)
T	Temperature (K)
t_{break}	Time of spray breakup
t_c	Thickness of the cylinder wall (m)
t_d	Disc thickness (m)
T_g	Temperature of gas (K)
T_i	Ambient temperature (K)
$U_s(t)$	Instantaneous spray tip velocity (m/s)
V	Volume (m^3)
V_i	Initial volume (m^3)
V_f	Final volume (m^3)
v_f	Flame velocity (m/s)
$\frac{dV}{dt}$	Rate of volume changes
$\bar{x}$	Mean
$\frac{dQ}{dt}$	Rate of heat release

ϕ	Equivalence ratio
γ	Ratio of the specific heat at constant pressure and volume
δ	Tip penetration (mm)
θ	Spray cone angle (°)
ρ_g	Density of ambient gas (kg/m^3)

ρ_l	Density of liquid fuel
σ_θ	Hoop stress in the circumferential direction (Pa)
σ_x	Standard deviation
$\sigma_{\bar{x}}$	Standard error

KAJIAN UJIKAJI CIRI-CIRI SEMBURAN DAN PEMBAKARAN BAHANAPI YANG DIHASILKAN DARI BIOJISIM DALAM KEBUK PEMBAKARAN ISIPADU MALAR

ABSTRAK

Keprihatinan terhadap kekurangan bahanapi fosil serta pencemaran alam sekitar telah meningkatkan jumlah penggunaan sumber tenaga yang boleh diperbaharui seperti bahanapi yang dihasilkan dari biojisim untuk kegunaan automotif dan penjanaan kuasa. Dalam kajian ini, ciri-ciri semburan Minyak Sawit Bertapis (MSB) dikaji di dalam Kebuk Pembakaran Isipadu Malar (KPIM), dan dibandingkan dengan bahanapi konvensional seperti petrol dan disel. Untuk bahanapi berbentuk gas, jenis Gas Pengeluar (GP) yang dihasilkan dari penggasan biojisim, dikaji setelah penggunaannya di dalam Enjin Pembakaran Dalam (EPD) mengurangkan prestasi enjin sebanyak 30 – 35 %.

KPIM beroptik dengan aturan pengukuran semburan telah digunakan untuk mengukur panjang semburan, sudut kon semburan dan luas semburan bahanapi cecair (petrol, disel dan campuran MSB dengan disel). Tekanan suntikan boleh diubah dengan menambah atau mengurangkan ketebalan pengubah kepipis penyuntik. Tekanan suntikan dikaji pada 20, 30 dan 34 MPa. Untuk kajian ciri-ciri pembakaran dan pengoptimuman Gas Pengeluar Termampat (GPT), ia telah diuji pada campuran udara dan bahanapi dengan Faktor Peningkatan Jisim (FPJ) yang berbeza iaitu FPJ = 0, 25 dan 50 %, menggunakan Kaedah Rekabentuk Eksperimen (KRE).

Ciri-ciri semburan petrol, diesel dan campuran minyak sawit dengan diesel pada 20, 40, 60, dan 80 serta 100 % kandungan minyak sawit telah diuji dan didapati pembentukan semburan campuran minyak sawit terjejas dengan peningkatan kandungan minyak sawit di dalam campuran. Panjang semburan dan sudut kon campuran didapati menurun sebanyak 50 dan 30 % masing-masing. Untuk kajian ciri-ciri pembakaran, didapati GPT mempunyai kelajuan nyalaan yang paling rendah berbanding petrol, gas petroleum cecair (GPC), gas asli termampat (GAT) dan syn-gas (SG). Untuk puncak tekanan pembakaran, GPT adalah yang terendah di kalangan semua bahanapi dengan penurunan puncak tekanan sebanyak 42.29, 41.54, 36.83, 38.55 and 32.31 % untuk nisbah kesetaraan 0.8, 0.9, 1.0, 1.1 dan 1.2, berbanding petrol. Untuk kajian pelepasan ekzos, GPT mempunyai NOx yang lebih rendah, tetapi CO yang lebih tinggi. Pencemaran NOx untuk GPT didapati menurun sebanyak 65.00, 58.33, 65.79, 74.03 dan 75.14 % dan pencemaran CO sedikit meningkat sebanyak 7.14, 10.00, 12.50, 11.76 dan 5.26 % untuk nisbah kesetaraan 0.8, 0.9, 1.0, 1.1 dan 1.2, berbanding petrol. Analisis pengoptimuman menunjukkan puncak tekanan GPT setanding dengan petrol pada $\phi = 1.1$ dan FPJ = 35 %.

Kelikatan minyak sawit yang tinggi mempengaruhi evolusi bentuk semburan, panjang semburan, sudut kon dan luas semburan. Pada tekanan suntikan 34 MPa, 20 % minyak sawit di dalam campuran (P20) menunjukkan kenaikan yang ketara. Berdasarkan keputusan eksperimen, tekanan suntikan yang dicadangkan adalah 34.46, 36.45, 50.70, 93.97 dan 110.93 MPa bagi P20, P40, P60, P80 dan P100, masing-masing. Dalam kes kajian pembakaran GPT, didapati Nilai Rendah Kalori (NRK) GPT yang rendah mempengaruhi ciri-ciri pembakaran. Penurunan kuasa boleh diatasi dengan meningkatkan ketumpatan campuran bahan api dan udara.

EXPERIMENTAL STUDIES OF SPRAY AND COMBUSTION CHARACTERISTICS OF BIOMASS DERIVED FUELS IN A CONSTANT VOLUME COMBUSTION CHAMBER

ABSTRACT

Concern with fossil fuel depletion and environmental degradation promotes the use of renewable energy sources in particular biomass derived fuel for automotive and power generation applications. In this study, spray characteristics of Refined Palm Oil (RPO) were studied in a Constant Volume Combustion Chamber (CVCC), and compared to conventional fuel such as gasoline and diesel. For gaseous fuel, Producer Gas (PG) derived from biomass gasification were studied as its usage in IC engines degrades the engine performance at about 30-35 %.

An optical CVCC with spray measurement setup was used to measure spray tip penetration, spray cone angle and spray area of liquid fuel (gasoline, diesel and palm oil blends). Injection starting pressure was varied by increasing or decreasing the thickness of adjusting shims of the injector. The starting injection pressures were studied at 20, 30 and 34 MPa. For Compressed Producer Gas (CPG) combustion and optimization study, it was tested at different Mass Increase Factor (MIF) of 0, 25 and 50 % of the air and fuel mixture. The optimization was conducted using Design of Experiments (DOE) method.

Macroscopic spray characteristics of gasoline, diesel and palm oil blends with diesel at 20, 40, 60, and 80 as well as 100 % pure palm oil were tested separately and it was found that spray development of palm oil blends is highly affected with increasing of palm oil in the blends. Tip penetration and cone angle of blends were found to decrease by about 50 and 30 %, respectively compared to diesel, and

improved at higher injection pressures. In the case of combustion studies, CPG was tested at various equivalence ratios (ϕ). It was found that CPG has a lower flame speed as compared to gasoline, Liquefied Petroleum Gas (LPG), Compressed Natural Gas (CNG) and Syn-Gas (SG). In term of peak pressure, CPG is the lowest among all fuels with degradation of peak pressure for CPG was found about 42.29, 41.54, 36.83, 38.55 and 32.31 % for equivalence ratios of 0.8, 0.9, 1.0, 1.1 and 1.2, respectively compared to gasoline. For emissions study, it was found that CPG has lower NOx, but slightly higher CO when compared to other fuels. The reduction of CPG NOx emission is about 65.00, 58.33, 65.79, 74.03 and 75.14 % and the CO emission were slightly increased at about 7.14, 10.00, 12.50, 11.76 and 5.26 % for equivalence ratios of 0.8, 0.9, 1.0, 1.1 and 1.2, respectively, compared to gasoline. Optimization analysis shows, the CPG peak pressure is comparable to gasoline at ϕ = 1.1 and MIF = 35 %.

High viscosity of palm oil influenced spray shape evolution, spray tip penetration, spray cone angle and spray area. At 34 MPa injection pressure, 20 % of palm oil in the blends (P20) showed significant increment and nearly achieved the same diesel tip penetration at standard injection pressure. Based on experimental results, the suggested injection pressures are 34.46, 36.45, 50.70, 93.97 and 110.93 MPa for P20, P40, P60, P80 and P100, respectively. In the case of CPG combustion study, it was found Low Calorific Value (LCV) of CPG highly influenced the combustion characteristics. Issue on power de-rating can be solved by increasing the energy density of the air fuel mixture.

CHAPTER ONE

INTRODUCTION

1.0 General introduction

Energy has become a priority to everyone for operation of automobiles, factories and power generation. Oil from petroleum refinery are used to power automobile engines, while electricity being the most convenient form of energy are used for machines in factory, home appliances and lot of other applications. Energy can be divided into 2 categories which are renewable and non-renewable resources. The examples of renewable resources are solar energy, biomass, wind, wave, hydro and tidal. While, for non-renewable resources the examples are: fossil fuel based oil, natural gas and coal. As the main resources of energy which is fossil fuel are getting scarce, researchers are searching other sources of energy that can be used as an alternative fuel to partially replace or complement the overwhelming use of fossil fuel.

Among the alternative fuels biomass comes across as a good choice in replacing fossil based fuel due to its reliability, economic and good waste management. It is one of the indigenous renewable energy resources that are capable of displacing large amount of solid, liquid, and gaseous fossil fuel. It is a non-fossil fuel, energy containing forms of carbon and includes all land and water based vegetation. The sources of biomass fuel are municipal solid waste, forestry and agricultural residues and some industrial waste.

Combustion of biomass fuel is a carbon neutral process, where carbon dioxide (CO_2) produced are absorbed by the trees and plants thus produce zero net CO_2. CO_2 consumed by growing trees are more than the CO_2 produced by their combustion, and combustion of biomass being carbon neutral is only true if there is replanting (Ehrenberg, 2009). One of derived biomass fuel that is widely used for internal combustion engine (ICE) is producer gas (PG). For PG, one of the methods used in producing combustible gaseous fuel in biomass energy system is gasification.

1.1 Biomass energy

Biomass fuel can be converted into solid, liquid or gaseous form and it can be used for generating electric power and industrial processing. There are many biomass energy systems developed around the world, due to its reliability and economics. It has been used since the last century in transportation and non-transportation applications. Transportation applications require high power density provided by ICEs. These engines require clean burning fuels, which are generally in liquid form, and sometime gaseous fuel can also be used. The examples of biomass fuel that had been used in ICEs are plant oil, bio-diesel, bio-alcohols and bio-gas. In the case of gaseous fuel, producer gas has been widely use in ICE for stationary power generation. Producer gas is produced via a gasification process.

1.1.1 Plant oil

Plant oil can be used as alternative fuel in compression ignition (CI) engine, either neat or blended with diesel in a certain proportion without or limited modification to the engine. Several experimental investigations have been done on combustion and emission characteristics of neat and blended diesel fuel with palm oil in diesel engines (de Almeida et al., 2002, Bari et al., 2002). In this work, palm oil blended with diesel has been used to study its macroscopic spray characteristics.

High viscosity and polymerization of palm oil at high temperature produced heavy low-volatility compounds that are difficult to combust initially in the main combustion phase, but produce longer combustion period in the late combustion phase. Moreover, palm oil composition also produced higher CO and NO emissions, compared to those from diesel combustion, due to poor air-fuel mixing process (Bari et al., 2002). The air-fuel mixing process is highly affected by the difficulty in atomization, especially for heavy compound fuel.

Higher CO will be produced due to lack of oxygen in a locally rich mixture during combustion process. Vegetable oil such as palm oil also contains fuel-borne oxygen that favours production of more NO emissions than diesel fuel combustion. Most researchers suggest preheating high viscosity oil slightly above 50°C before injection into the combustion chamber (Prasad et al., 2000, Bari and Roy, 1995, Ahmad and Salmah, 1995). However, using high temperature beyond the usual fuel injection pump operating temperature may damage the injection pump. Previous study reveal, preheating of crude palm oil (CPO) do not benefit engine performance except avoid clogging and maintaining smooth fuel flow. Therefore, effect of preheating the fuel still need more careful study, and will not be done in this work.

Fuel properties of palm oil are different from conventional diesel fuel that may influence spray characteristics in diesel engines. Studies on spray characteristics of various fuels in diesel engine are necessary as they indicate directly the combustion and hence engine performance. Combustion efficiencies rely significantly on quality of air/fuel mixture, which is dependent on fuel injection into the combustion chamber. All of the injected fuel should be in contact with maximum amount of oxygen available to ensure complete and fast combustion. Moreover, emission levels can also be reduced by enhancing the spray characteristics and quality of air/fuel mixing.

1.1.2 Biomass gasification

Gasification is a thermo-chemical process, where it is a destructive endothermic decomposition of biomass waste into combustible gas called producer gas (PG). Typical combustible components of the gas are: carbon monoxide (CO), hydrogen (H_2) and methane (CH_4). There are 3 types of reactors known as gasifiers that are commonly used to produce producer gas. They are updraft, downdraft and fluidized bed gasifiers. Each of this gasifier has their own function depend on their capability. In this study, only downdraft gasifier system will be considered for producing the producer gas.

Figure 1.1 is a simplified drawing of a downdraft gasifier. In this gasifier, biomass and air both flow in the same direction or co-current through the gasifier's fuel bed. As the wood progresses down through the gasifier it dries and biomass is pyrolyzed. The char is directed into a throated section where air enters and form a combustion zone. The high temperatures crack the tars that are formed in the pyrolysis zone.

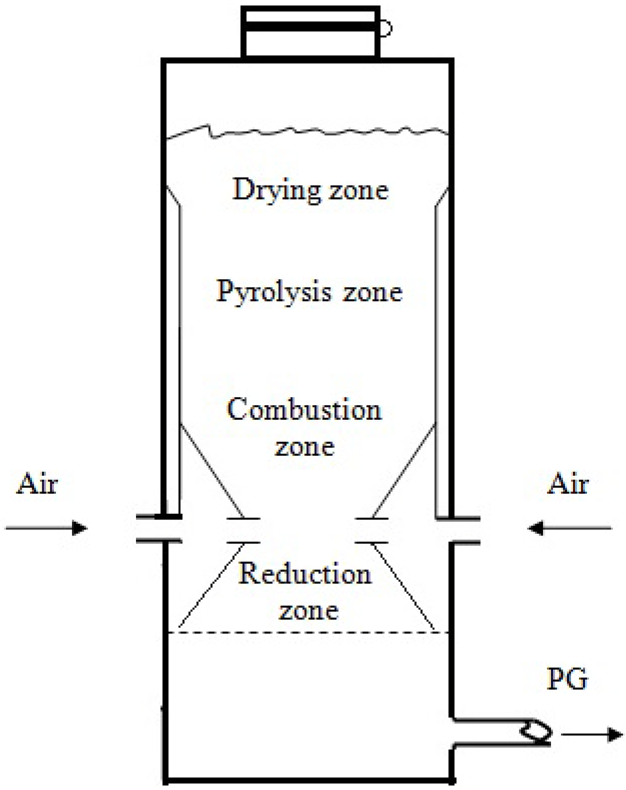

Figure 1.1: Schematic diagram of downdraft gasifier

1.1.2.1 Producer gas

Producer gas is a combustible gas which consists of CO, H_2, CO_2, small amount of CH_4, oxygen (O_2) and nitrogen (N_2). Average gas composition is: 1.69% O_2, 43.62% N_2, 24.04% CO, 14.66% CO_2 and 2.02% CH_4 (Zainal et al., 2002). Typical LHV value of producer is about 4-5 MJ/m^3 (Zainal and Mulkan, 2004). Producer gas is the main fuel that will be studied in this work, and as the producer gas is a gaseous type fuel, its combustion characteristics will be compared to others commonly used gaseous fuel such as compressed natural gas (CNG) and liquefied petroleum gas (LPG).

1.2 Problem statement

Utilization of palm oil blends in ICE would affect both engine performance and emissions. Higher viscosity of palm oil would produce poor injection process that contributes to poor engine performance and higher emission as compared to conventional fuel. In this study, the spray characteristics of refined palm oil (RPO) were studied in a constant volume combustion chamber (CVCC), and compared to conventional fuel such as gasoline and diesel. The information from this study would provide the way in controlling the spray process for better engine performance and emissions.

In the case of producer gas, it’s usage in ICE degrades the engine performance, with power loss at about 30 – 35 % compared to fossil fuel engine performance (Dasappa et al., 2012). Compression ignition (CI) and spark ignition (SI) engines are not designed for the use with PG as fuel. Hence engine performance and emission are badly affected when attempts are made to use PG in the engines. There have been many attempts reported of using a producer gas in internal combustion engine, with adverse effect on engine performance and emission. Using direct visualization techniques, fundamental information of combustion process of PG in a constant volume combustion chamber (CVCC) such as flame colour, speed, and in-cylinder pressure are important to provide ways in controlling combustion process of PG.

1.3 Objective of study

The present study is aimed to fulfil the following objectives:

i. To design and develop a high pressure constant volume combustion chamber with optical measurement setup.
ii. To study the spray characteristics of vegetable oil in a constant volume combustion chamber.
iii. To determine the combustion characteristics and emissions of compressed producer gas and to compare it’s performance with other fuels such as gasoline, CNG and LPG in a CVCC.
iv. To perform optimization studies of CPG by using design of experiment (DOE) software.

1.4 Hypothesis

The hypothesis of this study is described as follow:

i. To measure fundamental spray and combustion characteristics of bio-fuel, CVCC can be used as the measurement tool and it can be easily done compared to real ICE. Direct visualization of spray and combustion process would provide relevant information that can be used for improvement and optimization studies.

ii. For fuel with high viscosity, higher injection pressure would provide higher force to overcome the friction between fuel and nozzle wall. As the injection pressure increase, spray characteristics such as tip penetration, cone angle and spray area would improved and provide better air fuel mixing process.

iii. In the case of producer gas, its combustion characteristics are highly affected due to its low LHV, with low in-cylinder pressure that degrades engine performance. Supercharging/turbo-charging of producer gas would increase the density of air fuel mixture, therefore improved the energy of charging mixture in the CVCC. The producer gas can be compressed using an industrial compressor, to ensure supply of high density of producer gas. High energy of air fuel mixture inside the CVCC would improve the combustion performance and higher in-cylinder pressure can be achieved.

1.5 Scope of research

The scope and limitations of the study were:

i. The experiments will be conducted in a constant volume vessel with optical excess.
ii. The spray characteristics will be studied for liquid fuel such as gasoline, diesel and palm oil blends.
iii. The parameters that involve in spray studies are tip penetration, cone angle, spray velocity and spray area.
iv. For combustion study, spark ignition (SI) mode will be used for; gasoline, CNG, LPG, Syn-Gas (SG) and CPG.
v. The combustion experiment will be conducted in a constant volume combustion chamber at various equivalence ratios, ϕ from 0.8 to 1.2 with the aim to observe flame development, flame speed, in-cylinder pressure and emissions.
vi. Optimization study of CPG will be conducted using DOE software.

1.6 Thesis organization

This dissertation is organized into five chapters. Chapter 2 provides a survey and critical review of relevant literatures on spray and combustion using optical measurement techniques, dealing with experimental works on various types of fuels. Chapter 3 gives a detailed account of the materials and method used in the current research. Analysis and discussion on the results from experiments are presented in Chapter 4, followed by the conclusion and suggestion for future work in chapter 5.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

A review of previous works on fuel characterization in ICEs and optical measurement techniques is reported in this chapter to provide a background for the present study. The chapter is divided into two parts which are biomass derived fuel followed by spray and combustion study. In the field of biomass derived fuel, previous studies had investigated engine performance and its exhaust emissions. In spray and combustion studies, most researchers focus the effects of modifications to the fuel injector itself (for example, varying the injection rate, injection pressure and different type of fuel), on the macroscopic and microscopic fuel spray parameters to provide a better understanding of spray and combustion characteristics. This chapter will describe an outline of all experimental works related to the studies, and critically review them.

2.1 Biomass derived fuel applications

Two types of biomass derived fuels that are considered: plant oil for spray study and producer gas for combustion study. Most of the studies on plant oil were done in diesel engines using diesel blended with plant oil such as palm oil, rubber seed oil and linseed oil. Experimental investigation on performance and emissions of PG were conducted on both CI and SI engines, either in dual fuel or single fuel mode.

2.1.1 Plant oil utilization in ICE

Performances of internal combustion engine fuelled by plant oil had been extensively studied by various researchers. Among the fuels studied were palm oil, rubber seed oil, vegetable oil, linseed oil, hazelnut oil, rice bran oil and non-edible vegetable oil of putranjiva, jatropha, karanja, pongamia. All of the fuels were tested in diesel engines with various blending ratios with diesel at various loads and speeds.

In the case of palm oil, it was found that performance and endurance of the engine was affected with the use of palm oil. High amount of deposits at the cylinder head were observed when the engine was operated with palm oil at 50 °C, but the deposits become acceptable when the palm oil temperature was increased to 100 °C (de Almeida et al., 2002). For rubber seed oil, it was found that rubber seed oil at 50 -80 % proportions in the blends produced the best performance. Endurance test also exposed higher carbon deposits inside the combustion chamber by the blends when compared to neat diesel (Ramadhas et al., 2005).

Studies on vegetable oil show that the power output and fuel consumption of vegetable oil and its blends were comparable to diesel. NOx emissions of vegetable oil and its blends also were found to be lower when compared to diesel (Wang et al., 2006). Moreover, the use of vegetable oil methyl ester (VOME) also produce higher brake specific fuel consumption (BSFC), better ignition quality, higher peak HRR and peak pressure. Moreover, the use of VOME slightly increased the NOx, but reduced exhaust gas temperature (EGT), smoke, and total hydrocarbon (THC) emissions (Lin et al., 2009).

For linseed oil, it was found that long duration would pose durability problem due to high viscosity, low volatility and its polyunsaturated character. To overcome these problems transesterification process had been suggested in reducing the viscosity of vegetable oil (Agarwal et al., 2008). In the case of hazelnut oil, the engine performance was found to be comparable to diesel. Performance and emission of engine fuelled with hazelnut oil methyl ester (HOME) and its blends were improved with increasing injection timing, compression ratio and injector starting pressure (Gumus, 2008).

In the case of rice bran oil, the fuel was preheated before being injected into the combustion chamber. Highest engine efficiency was observed for B60 at higher preheating temperature. The engine efficiency variation when running with rice bran was very small, with the best performance observed at B40 (Kandasamy and Thangavelu, 2009). Non-edible vegetable oils (Putranjiva, Jatropha, Karanja, Pongamia, Mahua and Neem seed oil) need to be treated with degumming to improve their viscosity and cetane number. The degummed fuel then were blended with diesel with the proportions of 10, 20, 30 and 40 %, and were tested in a variable compression ratio diesel engine. From the experiment, it was found that Jatropha produced the best performance and emission, when the engine was operated at high load and injection timing of 45 ° BTDC (Haldar et al., 2009). Furthermore, the use of jatropha, pongamia, mahua and neem seed oil with diesel at proportions of 20, 40, 60, 80 and 100 % (identified as MB20, MB40, MB60, and MB100 respectively) produced comparable results to neat diesel. However, slightly higher NOx and smoke were observed for engine fuelled with these fuel (Duraisamy et al., 2010).

2.1.1.1 Summary of plant oil studies

Plant oil such as palm oil, hazel nut, jatropha and linseed oil had been extensively studied and concluded that vegetable oils had an issue on endurance test demonstrated by deposits formed in the combustion chamber. The main cause for this problem is the poor fuel spray atomization due to its high viscosity. Transesterification of plant oil altered the physical properties of the fuel, and significantly improve engine performance. More studies are needed for vegetable oil especially on its spray characteristics and it will be done in this work.

2.1.2 Producer gas engine

One of the well-known fuels that can be derived from biomass gasification process is producer gas (PG). PG can be used in both SI and CI engine with little modification to the engine. For CI engine, PG is normally used in dual-fuel mode, but for SI engine, it can be used for either single or dual fuel.

2.1.2.1 Performance of producer gas engine

The performance and emission of PG in IC engines had been widely studied experimentally by various researchers. It had been utilized in either CI or SI engines. In CI engines, most researchers investigated the engine performance in dual fuel mode, with various types of fuel such as diesel and palm oil.

Meanwhile for SI engine, PG can be used in single fuel mode as reported on engine performance (Sobyanin et al., 2005, Shah et al., 2010). Different techniques of induction of PG into the SI engine had been studied using CNG injector (Shashikanta and Parikh, 1999) and venturi type carburettor (Tewari et al., 2001). Knowing the incomparable performance to gasoline, researchers had conducted experiments at high compression ratio due to its high octane value that resisted knock (Sridhar et al., 2001, Sridhar, 2008). One of the promising method of increasing the performance of PG engine is by using turbocharged system (Dasappa et al., 2012). Other than that, endurance test of PG engine had been studied to investigate engine wear (Dasappa et al., 2007).

In the case of CI engine operating in dual fuel mode (PG and diesel), it was found that combustion analysis show that dual fuel engine had similar combustion characteristic to diesel alone. However, in-cylinder analysis revealed lower peak pressure of dual fuel engine but showed higher peak heat release. The combustion analysis also revealed longer ignition delay for dual fuel. Despite decrease in engine performance, the system saves 60 % of diesel fuel used (Zainal and Mulkan, 2004). Further study on dual fuel mode had exposed that CO emission was found to increased significantly at low load condition but NO_x and SO_2 concentrations were decreased at all loads (Uma et al., 2004).

As for SI engine fuelled by PG, the results show that the engine ran smoothly during idle mode under ultra-lean condition thus produce low emissions of NOx and CHx (Sobyanin et al., 2005). Further study exposed that PG engine has lower maximum power output when compared to gasoline, but have the same overall efficiency as gasoline at maximum power output. Moreover, the CO and NOx of PG engines exhaust were found to be lower, but higher CO_2 were observed when compared to gasoline engine exhaust emissions (Shah et al., 2010).

Using CNG injector in PG injection process, it had produced a comparable efficiency and power to CNG and diesel. Ignition timing adjustment also showed flexibility of both producer gas and CNG. Moreover, SI PG engine emissions were found to be lower and produce zero smoke when compared to diesel or dual fuel mode (Shashikanta and Parikh, 1999). However PG engine still had higher power de-rating compared to gasoline. CO emissions were found to be lower by 1 % volume when compared to gasoline and the cyclic variations of producer gas in terms of peak pressure were found to be higher (Tewari et al., 2001).

Effect of higher compression ratio (17:1) on PG engine performance revealed that the engine run smoother at higher compression ratio without any events of auto-ignition due to high octane number for producer gas. Moreover, increasing the compression ratio would also increase the maximum brake power of the engine (Sridhar et al., 2001). Further study on higher compression ratios provide guidelines for operating conditions at optimum performance corresponding to various equivalence ratios. Moreover, the exhaust emissions of PG from the engine were found to be within the acceptable limits (Sridhar, 2008).

One of the best ways in increasing the energy density of producer gas is by using a turbocharged system PG that increased the power output by about 35 % compared to naturally aspirated (NA) PG engine. Other than that, the peak load and mass flow in the turbocharged system with intercooler was found to increased by about 30 and 35 %, respectively compared to NA system (Dasappa et al., 2012).

The effects of wear to engine components due to producer gas in IC engine were investigated and the endurance test was conducted for a total of 5000 hours with lubrication inspections done every 1000 hours. The experiments found that, wear of engine's components operating with producer gas were within acceptable limits compared to natural gas engine (Dasappa et al., 2007).

2.1.2.2 Computer simulation studies on producer gas engine

Zainal and Soid (2007) had studied the combustion characteristic of a DI 4-stroke diesel engine using computational fluid dynamic (CFD) software. A model of a combustion chamber was built using IDEAS® and was exported to AVL Fire Version 8.2. By applying certain engine speed, the model analyzes the pressure versus crank angle and rate of heat release versus crank angle with given geometry, operating temperature, injection timing, fuel properties, initial conditions and boundary conditions. The model was subsequently used to investigate the combustion characteristics of diesel engine fuelled by producer gas. Results showed that producer gas-diesel engine experienced some decrease in performance, produced lower in-cylinder pressure compared to diesel alone system, but higher peak heat release.

Similar results also were obtained using simulation work by Tinaut et al. (2006). In this work, computer simulation was used to predict the performance of internal combustion engine fuelled by producer gas and other low heating gas. The performance of the engine, a so-called engine fuel quality (EFQ) parameter has been developed. EFQ considers the combined effect of stoichiometric mixture heating value, both depending on the producer gas composition. Estimation of engine power at full load was reduced to at about 67 % of the maximum obtained with a conventional liquid fuel. The analysis had found lower peak pressure and indicated mean pressure (IMP) when compared to isooctane and methane.

2.1.2.3 Compressed producer gas (CPG) engines

For CPG, the preliminary investigation work was done by Hassan et al. (2010b). They had experimentally studied the characteristics of CPG that was derived from a downdraft gasifier. The producer gas was compressed using a single stage industrial compressor to provide more stable high pressure producer gas source to the engine. The producer gas was induced from a gasifier at 670 L/min, and compressed to a pressure of 7.6 bar. It can be discharged from the compressor to any specified flow rate and pressure, thus provide more convenient way in controlling the producer gas flow.

Results from the preliminary studies was used to investigate the effects of injection timing on engine performance and emission of supercharged producer gas-diesel fuel (supercharged dual fuel) (Hassan et al., 2010a). In this work, the effects of injection timing on engine performance and emission of supercharged producer gas-diesel fuel (supercharged dual fuel) were investigated. The diesel injection timing was advanced at three injection timings which were 17, 20 and 23, compared to its original injection timing of 14 BTDC. Analysis showed that supercharging and advancing the injection timings increased both the brake thermal efficiency (BTE) and diesel displacement. Moreover, CO and CO_2 were found to decrease when compared to natural aspirated dual fuel mode.

As an extension work, the effect of supercharged producer gas in dual-fuel mode with palm oil blends had also been studied (Hassan et al., 2011). Same injection method was used in introducing the producer gas into the engine. For palm oil blends, diesel with refined, bleached and deodorized (RBD) palm oil was used in mixture proportions of 25, 50, 75 and 100 %. From the experiment, it was found the use of supercharged producer gas and palm oil blends degraded engine performance, and increased its emissions when compared to supercharged producer gas and diesel mode.

2.1.2.4 Summary of producer gas engine studies

From previous studies, it can be concluded that producer gas has been proven as an indigenous renewable energy resource that is capable of displacing fossil based fuel in ICE. However, it degrades the engine performance, decrease the in-cylinder peak pressure, thus producing lower engine overall efficiency. Emissions of CO, NOx and CO2 in PG engine are within acceptable limits. Therefore, it is necessary to understand combustion behaviour of PG to optimize its performance in internal combustion engines.

2.2 Spray and combustion characteristics

The fast depletion of fossil based fuel resources and their contribution to environmental pollution from ICE are the major issues that led to increasing demand for efficient and eco-friendly energy management schemes to be implemented in industrial, commercial and domestic sectors. Study on macroscopic and microscopic parameters of fuel spray is one of the feasible ways to tackle the aforesaid problems, to ensure high engine performance with low emission levels. Using this technique will provide better understanding on the spray and combustion thus making it possible in controlling the combustion process.

Studies on fundamental spray and combustion characteristics using optical measurement techniques have increased due to various alternative fuels available such as CNG, biodiesel, hydrogen, natural gas and oxygenated fuels. In the case of gasoline and diesel fuels, studies were focused on ensuring better air/fuel mixtures preparation during fuel spraying process (Sankar et al., 1999), to provide homogeneous mixture, thus produce optimum performance and cleaner combustion. During the fuel injection process, it is essential to ensure that all of the injected fuel has maximum contact with the available air to produce complete combustion (Su et al., 1995). Researchers have studied methods of reducing the emissions and simultaneously improving the combustion efficiency. The techniques that have been studied were pulsed injection (Nehmer and Reitz, 1994), pilot injection (Zhang, 1999, Tanaka et al., 2002), homogeneous charge compression-ignition (HCCI) (Onishi et al., 1979), controlling the mixing process and injection process modification.

Methods such as visualization, PIV (particle image velocimetry), LIF (laser induced fluorescence) and PDPA (phase Doppler particle anemometry) have been used as diagnostic tools, to understand the fundamentals of spray and combustion characteristics in ICEs. For spray and combustion visualization study, measurements can be carried out in optical engines and most of researchers had used a high pressure and temperature CVCC.

Studies on the spray characteristics can be categorised as macroscopic and microscopic. The macroscopic parameters such as tip penetration, cone angle and spray area can be determined using direct visualization techniques (Shao et al., 2003). While, for microscopic parameters, either PIV or PDPA techniques can be implemented to measure parameters such as velocity, scalar field and droplet size. All of these techniques can be used in controlling the injection process with the aim to ensure that all of the injected fuel be in contact with the maximum amount of available oxygen for complete combustion (Pierpont and Reitz, 1995).

2.2.1 Historical background on optical measurement technique

Study on the spray and combustion characteristics of various types of fuel has been reported since 1970s. In the late 70s and in the early 80s, few review papers related to this study have been published. The optical measurement techniques have evolved to become more sophisticated over the last 40 years. More detailed with important information on macroscopic and microscopic parameters can be obtained from the fuel spray that makes optimization of the spray parameters possible to researchers. The historical background on optical measurement setup is shown in Table 2.1.

Table 2.1: History of spray and combustion studies using optical measurement technique

Year	Topic	References
1976	Review on fuel droplet size measurement	(McCreath and Beér, 1976)
1976	Review on fuel atomization and burning	(Chigier, 1976)
1977	Review on fuel droplet size measurement	(Jones, 1977)
1980	Flame propagation through an air-fuel spray mixture with transient droplet vaporization in a closed combustor	(Seth et al., 1980)
1981	Interaction between fuel spray and surrounding combustion air	(Banhawy and Whitelaw, 1981)
1982	Study of turbulent kerosene sprays using laser tomographic light scattering technique	(Yule et al., 1982)
1991	Study of fuel spray using laser Doppler technique	(Nakabe et al., 1991)
1991	Study of fuel property effects on the spray flame structure using phase/Doppler technique	(Presser et al., 1991)
1994	Fuel vapour concentration using visualization and exciplex fluorescence technique	(Senda et al., 1994)
1998	Review on LIF technique	(Zhao and Ladommatos, 1998)
2001	Three component PIV	(Stella et al., 2001)

2.2.2 Conventional techniques in spray and combustion measurement

Conventional techniques for droplet size measurement can be categorized into three classes: mechanical, electrical and optical methods. The examples for each method are shown in Table 2.2. There is not much information that can be obtained for the conventional techniques from previous studies except for the techniques that use large scale model (Walzel, 1982, Soteriou, 1995). Large scale model can only helped in understanding the break up and atomization mechanism but might be inaccurate for diesel spray characteristics (Rantanen et al., 1999).

Table 2.2: Classification of conventional methods and techniques of spray studies

Method	Mechanical	Electrical	Optical
Techniques	droplet capture	Wicks-Dukler	Photography
	cascade impaction	charged wire probe	Holography
	frozen drop and wax	hot wire anemometer	laser diffraction
	Sedimentation		laser anemometry
			various other techniques based on light scattering

Presently the most commonly used techniques for macroscopic and microscopic fuel spray and combustion characterization is the optical technique. This technique can often be difficult to implement and very expensive. The spray, especially in the neighbourhood of the nozzle, is very dense; making the use of optical measurement technique very difficult (Roisman et al., 2007). Other examples of optical techniques that were widely used by other researchers are visualization, PIV, LIF and PDPA. Visualization and LIF techniques have been reviewed by Chigier (1991) and Zhao and Ladommatos (1998) respectively, and their works are very useful, to understand better techniques that might be suitable for this work.

2.2.3 Macroscopic spray parameters

Figure 2.1 shows the typical spray structure of a DI (direct-injection) fuel spray (Suh et al., 2007). The injection process started when the fuel is introduced into the engine cylinder through a nozzle. As the liquid fuel leaves the nozzle, the fuel spray becomes turbulent and at the same time the outer surface of the spray breaks up into droplets. The turbulent eddies are form in the shear layer and engulf the surrounding fluid in the jet core, and mixing subsequently takes place on the molecular level at the two-fluid interface (Kawano et al., 2002), thus making the transport phenomenon of the fluid motion the dominant process in turbulent mixing. The distribution of the jet fluid concentration and its vortex motion can be determined directly the turbulent transport of the jet fluid (Kawanabe et al., 2008). The mass of air within the spray increases, the spray diverges, its width increases, and the velocity decreases as the spray moves away from the nozzle. As this air-entrainment process continues, the fuel droplets evaporate and the spray tip penetrates further as the injection proceeds at a decreasing rate.

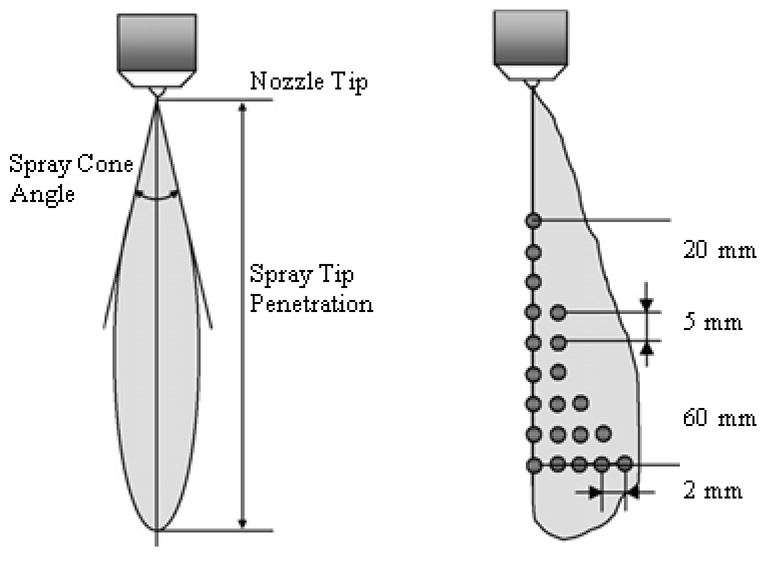

Figure 2.1: The definition of macroscopic spray characteristics (Suh et al., 2007)