PERFORMANCE AND EMISSION TESTS OF BIODIESEL FUELS USING A CONVENTIONAL DIESEL ENGINE

MOHD FARID BIN MUHAMAD SAID

A thesis submitted in fulfillment of the requirements for the award of the degree of Master of Engineering (Mechanical)

Fakulti Kejuruteraan Mekanikal
Universiti Teknologi Malaysia

FEBRUARY 2006

ACKNOWLEDGEMENTS

First of all, I am grateful to ALLAH the Almighty on His blessings for making this project a success.

My thanks go to my project supervisor, Professor Ir. Dr. Azhar Abdul Aziz. His guidance and support makes the entire work possible. I sincerely believe that this work would not exist without his inspiration. I also wish to thank Dr. Choo Yuen May for giving me opportunity to receive the scholarship from MPOB and to provide me the biodiesel fuels during the study.

In addition, I would like to express my appreciation to all the technicians of the Automotive Development Centre (ADC) UTM for their assistance. Also not to forget all my dear friends who always motivate and assist me in studies. Without them, it would be hard for me to complete this thesis successfully and promptly.

Furthermore, I would like to thank to En. Zulkarnain Abdul Latiff, Mazlan Said, Hj. Sairaji and Muhamad Afiq Awang for their willingness to help what ever problem that arose, and have given their moral support in completing my research.

I am left without words to thank to both of my parents. Their support and dedication have always been a great driving force. Finally, I want to thank my wife, Faradilah Abd Rahman, for her patience, love and tolerance during what has been a difficult time for her.

ABSTRAK

Penggunaan bahan api biodisel berasaskan miyak kelapa sawit telah dicadangkan sebagai bahan api alternatif untuk enjin disel di Malaysia. Tujuan utama kajian ini adalah untuk mengkaji prestasi dan tahap keluaran ekzos beberapa campuran biodisel iaitu *neutralized palm oil methyl ester* (NPOME) dari enjin diesel kecil yang tidak diubah seterusnya membandingkan biodisel tersebut dengan bahan api disel Malaysia peringkat 2 (D2). Ujikaji prestasi enjin, tahap keluaran ekzos, tekanan silinder, tekanan salur bahan api, kadar pembebasan haba dan lengah pencucuhan telah dilakukan terhadap beban enjin pada kelajuan enjin yang berlainan. Perbandingan antara D2 dan biodisel terhadap penggunaan bahan api tentu brek (BSFC), kecekapan terma brek, pembebasan haba, tekanan silinder, lengah pencucuhan, karbon monoksida (CO), karbon dioksida (CO_2), nitogen oksida (NOx), hidrokarbon tidak terbakar (uHC), bahan partikel (PM) dan asap ekzos telah dilakukan di dalam kajian ini. Perbandingan antara D2 dan biodisel terhadap pembentukan karbon di muncung penyuntik juga dilaksanakan. Di dalam kajian ini, simulasi telah dilakukan untuk menilai prestasi bahan api disel dan biodisel dalam enjin diesel. Enjin tersebut telah dimodel dengan menggunakan perisian *GT-Power* bagi menghasilkan simulasi prestasi dan tahap keluaran ekzos. Berdasarkan simulasi yang telah dibuat, keputusannya dibandingkan adalah hampir sama dengan ujikaji. Di dalam ujikaji enjin, didapati bahawa bahan api biodisel berasaskan miyak kelapa sawit adalah hampir sama dengan D2 dari segi prestasi (penggunaan bahan api dan kecekapan terma) dan kadar pembebasan haba. Kualiti asap adalah lebih baik apabila dibandingkan dengan hasil keluaran dari bahan api disel pada keadaan operasi yang sama. Pembentukan karbon di muncung penyuntik berkurangan apabila biodisel digunakan pada enjin. Tahap keluaran CO, CO_2, HC dan PM juga berkurangan dengan penggunaan bahan api biodisel, manakala keluaran NOx meningkat dibandingkan dengan bahan api D2.

ABSTRACT

The use of palm oil-based biodiesel fuel has been proposed as an alternative fuel for diesel engines in Malaysia. The main purpose of this study is to investigate the performance and exhaust emissions of several biodiesel blends of neutralized palm oil methyl ester (NPOME) in a small-unmodified direct injection diesel engine, and to compare them to that of a Malaysian grade 2 diesel fuel (D2). Experimental measurements of engine performances, exhaust emissions, cylinder pressure, fuel line pressure, rate of heat release and ignition delay were performed as a function of engine load at different engine speeds. Comparisons between D2 and the biodiesel blends on the brake specific fuel consumption (BSFC), brake thermal efficiency, heat release, cylinder pressure, ignition delay, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NOx), unburned hydrocarbon (uHC), particulate matter (PM) and exhaust smoke were carried out in this study. A comparison between D2 and the biodiesel fuels on the injector tip deposit was also studied. In this study, simulations were performed to evaluate the diesel and biodiesel fuels performance in a diesel engine. The simulation was modelled using *GT-Power* software in order to simulate the performance and emissions. Based on the simulation, the results were comparable to the experimental results. In the engine experiment, it was found that the palm oil-based biodiesels behaved comparably to the D2 in terms of performance (fuel consumption and thermal efficiency) and rate of heat released. Smoke quality showed a better result when compared to that emitted by the diesel fuel (D2) operating under similar conditions. The injector tip deposit was lower when biodiesel fuels were used in the engine when compared to the diesel fuel (D2). The emissions of CO, CO_2, HC and PM were also lower using biodiesel fuels, while NOx emissions were higher when compared to D2.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A	Area
A_o	Orifice area
A_T	Curtain Area
B	Bore
C_D	Orifice discharge coefficient
CR	Compression ratio
D	Valve head diameter
d_o	Orifice plate diameter (airbox)
F	Force
g	Acceleration due to gravity
h	Height
i	i^{th} measurement
L	Valve lift
l	Connecting rod length
m	Mass
$\dot{m}_a$	Air mass flow rate
$\dot{m}_f$	Fuel mass flow rate
$\dot{m}_{exh}$	Exhaust mass flow rate
N	Engine speed
n	Total number of repeated measurement made.
n_c	Number of cylinder
N_m	Minimum engine speed at which measurements are required
n_s	Constant (1 for 2-stroke and 2 for 4-stroke engine)
n^*	Constant derived from chemical equation of fuel combustion
P	Pressure
P_a	Ambient pressure

$\overline{P}$	Average cylinder pressure
p_{sr}	Standard reference saturated water vapor pressure
p_{st}	Ambient saturated water vapor pressure during test
p_t	Ambient total barometric pressure during test
$\dot{Q}$	Heat release rate
Q_{HV}	Heating value
R	Specific gas constant for air
r	Crankshaft throw
$relH$	Relative humidity
r_{hc}	Ratio of hydrogen to carbon in fuel
S	Stroke
S_m	Standard error of the mean
T	Temperature
T	Torque
T_a	Atmospheric temperature
T_t	Ambient air thermodynamic temperature during test
$\overline{T}$	Average cylinder temperature
u	Specific internal energy
V_{box}	Airbox volume
V_c	Clearance volume
V_d	Engine displacement volume
V_s	Swept volume
$\dot{W}$	Rate of work
X_{mean}	Mean Value
ρ	Density
η_{tb}	Brake Thermal Efficiency
β	Hydrogen percentage in fuel
	Empirical factor
γ	Oxygen percentage in fuel
	Ratio of specific heats
δ	Nitrogen percentage in fuel
υ	Velocity

τ_I	Ignition delay
ϕ	Equivalence ratio
Ω	Non-dimensional crank angle,
x_D	Diffusion burning
x_P	Pre-mix burning
ϕ_e	Engine operating equivalence ratio
θ	Angle
ϕ_t	Ambient relative humidity during test
ρa	Air density
ρman	density of manometer liquid fluid
Δp	Pressure drop across the orifice plate

LIST OF ABBREVIATIONS

AFR	Air Fuel Ratio
BDC	Bottom Dead Center
BMEP	Brake Mean Effective Pressure
BP	Brake Power
BSFC	Brake Specific Fuel Consumption
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DI	Direct injection
EGR	Exhaust Gas Recirculation
EVC	Exhaust Valve Closing
EVO	Exhaust Valve Opening
HC	Hydrocarbon
IDI	Indirect Injection
IVC	Intake Valve Closing
IVO	Intake Valve Opening
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NOx	Nitrogen Oxides
rpm	Revolution Per Minute
TDC	Top Dead Center
PM	Particulate Matter
IC	Internal Combustion
MPOB	Malaysian Palm Oil Board
uHC	Unburned Hydrocarbon
NPOME	Neutralized Palm Oil Methyl Ester
D2	Malaysian Diesel Grade-2

B10	Biodiesel (10%)
B20	Biodiesel (20%)
B50	Biodiesel (50%)
SOF	Soluble Organic Fraction
H_2O	Water
B100	Biodiesel (100%)
B2	Biodiesel (2%)
SME	Soybean Methyl Ester
RME	Rapseed Methyl Ester
RBDPOo	Refined, bleached and Deodorised Palm Olein
AD	Analogue to Digital
CH_4	Methane
O_2	Oxygen
SAE	Society of Automotive Engineers
THC	Total Hydrocarbon
DAQ	Data Acquisition System
BSCO	Brake Specific Carbon Monoxide
$BSCO_2$	Brake Specific Carbon Dioxide
BSHC	Brake Specific Hydrocarbon
BSNOx	Brake Specific Nitrogen Oxides
ppm	Parts per Million
CFD	Computational Fluid Dynamic
CA	Crank Angle
CAI	Crank Angle Ignition
BDUR	Burn Duration

LIST OF APPENDICES

CHAPTER ONE

INTRODUCTION

1.1 Introduction

The greatest world summit was held in Kyoto, Japan on environmental issues in the year 1997. The main agenda of the discussion was on the need to reduce the amount of carbon dioxide (CO_2) in the atmosphere which causes global warming. One of the main causes is the combustion of hydrocarbon-based fuel. The fuel crises of the 1970s and 1980s have focused the world attention on the desire to develop alternative fuels and decrease the dependency on fossil fuel. The efforts have been directed towards alternative fuels for the internal combustion (IC) engines. The vegetable oil appears to be the most suitable candidate for diesel engines.

The oils, from rapeseed, linseed, cottonseed, palm oil, soybean, sunflower, castor, peanut, coconut, pal and others are candidates for alternative fuels for diesel engines. During the Second World War many vehicles, primarily in southern France, used vegetable oil as fuel substitutes (Andrzejewski and Sapinski, 1991).

Most vegetable oils are able to be substituted directly as diesel fuel, but may create a variety of practical problems resulting from incomplete combustion and also causing the injector nozzle coking and even failure, excessive engine deposits, lubricating oil dilution, piston ring sticking, scuffing of the cylinder liners and even lubricant failure due to polymerization of the vegetable oil (Knothe *et al*., 1992). Other operational factors such as poor cold starting, unreliable ignition and misfire and reduced thermal efficiency (with certain oils) have added to the general avoidance of unmodified vegetable oils as a long term diesel fuel replacement, especially in direct injection (DI) diesel engines and small capacity indirect injection (IDI) diesel engines where the detrimental effects have been greatest. It has been shown that one hundred percent vegetable oil cannot be used safely in DI engine but can be used in an IDI engine. The direct injection engines are more dependent on the degree of fuel atomization than the indirect injection engines. One of the solutions to this problem is to do blending of various proportions of the oil with petroleum based diesel fuel known as biodiesels.

The general definition of biodiesel is a domestic, renewable fuel for diesel engines derived from natural oils like soybean oil, and which meets the specifications of ASTM D 6751. The technical definition for biodiesel is a fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats, designated B100, and meeting the requirements of ASTM D 6751. The technical definition for biodiesel blend is a blend of biodiesel fuel meeting ASTM D 6751 with petroleum-based diesel fuel, designated BXX, where XX represents the volume percentage of biodiesel fuel in the blend.

Biodiesel can be used in any concentration with petroleum based diesel fuel in existing diesel engines with little or no modification. Biodiesel is not the same thing as raw vegetable oil. It is produced by a chemical process which removes the glycerin from the oil. Biodiesel is typically produced by a reaction of a vegetable oil or animal fat with an alcohol such as methanol or ethanol in the presence of a catalyst to yield mono-alkyl esters and glycerin, which is removed.

1.2 Background of the problem

Malaysia is fortunate to have plenty reserve of crude oil supplies. This source of energy is expected to contribute to the larger share of the commercial energy requirements of the nation. However, the increase in price of petroleum fuels, stringent emission regulations and foreseeable future of depletion of petroleum reserves force us to search for new technologies to meet human's demands for cleaner environment and new energy. At the current rate of production, the average life for Malaysia's oil reserves is 17 years. If no new discoveries of oil wells are made, Malaysia will be a net importer of petroleum oil before 2020 because our consumption is double with economic growth and thus alternative renewable fuel need to be sought immediately (Yamin Vong, 2004).

The petroleum diesel demand is expected to increase steadily to keep pace with the industrialization and growth of the economy. As such, if renewable energy sources could be found to supplement the needs of these sectors, then the country would be moving in the direction towards self-sufficiency in energy. In this context, the prospect of a renewable source from biodiesel fuel of palm oil based is promising. It is also in line with our government policy to source for renewable fuel.

Therefore, in this study, the biodiesel blend fuels supplied by Malaysian Palm Oil Board (MPOB) have been tested on the direct-injection (DI) diesel engine in order to examine the effect of engine performance and exhaust emission and also to know the capability of the fuel on the diesel engine.

1.3 Malaysia's Biodiesel Initiatives

Malaysia started work on biodiesel two decades ago, but the idea of using palm oil on a large scale was introduced in the middle of 2005. The Malaysia's experience in using palm oil as fuel dated back to the 1980s. The palm diesel was produced by transforming crude palm oil into palm oil methyl esters. This was then evaluated as diesel fuel substitute from 1983 to 1994 at MPOB. The palm oil methyl esters (palm diesel) was tested in the laboratory evaluation, stationary engine testing and field trials on a large number of vehicles.

The Government recently announced that the use of biodiesel blend from palm oil will be one of the action plans considered to reduce the country's reliance on petroleum fuels. The Government was very interested because this was an opportunity to diversify the use of palm oil and to use as the price stabilizing mechanism in palm oil industry. Several Asian countries including Thailand, Philippines, Indonesia and Malaysia announced initiatives for commercial production of biodiesel. The commercial interest in palm oil methyl esters has also been intense from within the country and also from Korea, Hong Kong, Colombia and Turkey.

The Malaysian Palm Oil Board (MPOB) under the Ministry of Plantation Industries and Commodities (MPIC) is working to establish the biodiesel system. The MPOB has decided to export biodiesel since the experiments have proven it to be a viable effort. There are Europeans companies buying the supply from MPOB to run their trains, and the logo in front of the locomotive is testimony to the collaboration that the train is using palm oil methyl esters.

With the strong demand, MPOB is designing and building a modular palm diesel (palm oil methyl esters) plant, which can be packed and shipped to overseas for installation. The design is based on the MPOB-Petronas patented technology, a palm diesel pilot plant that produces 3,000 tonnes annually, which located at MPOB headquarters in Bangi. The demonstration plant with capacity of 60,000 tonnes of fuel per annum is expected to be ready by June 2006.

By the end of 2005, the Government has announced that the state-owned diesel vehicles, army trucks and the plantation vehicles were requested to use biodiesel blend on a trial basis starting from 1st January 2006. The composition of biodiesel blend will be 5 % of RBD palm olein (refined, bleached and deodorised) and 95 % petroleum diesel, and it is known as B5 fuel. The year 2006 will be a trial period to identify any problems of biodiesel blend before it is fully commercialized and ready for use from 1st January 2007. Around the country, major plantation companies have also drawn up plans to venture into biodiesel. Selected public buses, taxis and army trucks and 4-wheel drive vehicles will use biodiesel.

In January 2006, the Government had agreed to supply the B5 for free for the whole of 2006 to Ministries and government agencies that volunteer to try it out. The B5 will be launched in peninsular Malaysia first, before being eventually supplied to Sarawak and Sabah. The 12 months trial periods will be used to determine the effect of the new biodiesel on engine systems and general performance of the vehicles before it is introduced for public use nationwide.

1.4 The Objectives and Scopes of Research

The objectives of this study is to investigate the effect of a various biodiesel blends fuels on a 0.296 litres DI diesel engine. The main research area was to examine the performance and emission of diesel engine using several proportions of biodiesel fuel (neutralised palm oil methyl ester) with diesel fuel that were prepared by Malaysian Palm Oil Board (MPOB). The comparative works were also studied between these biodiesel blends against a standard Malaysian diesel fuel.

The research detailed activities include understanding the concept of engine diesel operation, identifying the chemical species of emissions, methods of performance and emissions testing, literature reviews on major work in the same area, identifying scope of work, engine servicing, laboratory preparation, fabrication process, running the engine test, presentation of experimental results, produce engine model for simulation, comparison between experimental and simulation results and discussion on the outcome of the overall studies.

In this research, the work was done on the engine test bed for evaluation of diesel fuel and blended biodiesel fuels. The engine was installed on the test bed and coupled to a dynamometer. The instrument that was used to measure air flow rate induced by the engine was developed using airbox and manometer tube, while to measure the fuel flow rate, a burette tube was installed immediately after the fuel tank. The engine cylinder head was drilled to install the in-cylinder pressure transducer. The fuel line pipe was modified in order to place the fuel line pressure transducer. The crank angle encoder was mounted at dynamometer shaft in order to measure the crank angle of the engine. Data acquisition system was used to record the pressures and crank angle signal during the experiment. The thermocouples were installed in the intake pipe, exhaust pipe and in the dynamometer water outlet respectively. The details on the experimental setups were discussed in chapter three.

The scopes of this research cover the effects of engine parameters i.e. engine load and speed of the DI diesel engine, the performance and the exhaust emission. The brake power, the air and fuel consumption were measured to determine the performance of the engine and its thermal efficiency. For the exhaust emissions, nitric oxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO), carbon dioxide (CO_2) and unburned hydrocarbon (uHC) were measured. The measurement of exhaust smoke and the qualitative study on injector tip carbon deposit were also included in this research work. Other measurements of in-cylinder and fuel line pressure were also carried out in order to compare the maximum pressures produced between reference diesel fuel and blended biodiesel fuels. The heat release rate and the ignition delay for biodesel blends were calculated based on the in-cylinder and fuel line pressure data and were compared to reference fuel.

Throughout the study, four test fuels were used including the grade 2 Malaysian diesel designate as the reference fuel (D2). The other three fuels were the biodiesel blends between neutralized palm oil methyl ester (NPOME) and D2 at several volumetric proportions. The neutralized palm oil means that this palm oil is neutral and it has no acid content. These biodiesel blends are designated as B10, B20 and B50 (denotes 10%, 20% and 50% of NPOME in petroleum diesel) respectively. In this study also, the engine simulation model for DI diesel engine was developed using software tools called *GT-Power*^{TM}. This engine model was used to simulate the engine performance and emissions of biodiesel blends and diesel fuel.

REFERENCES

Abdul Monyem. (1998). *The Effect of Biodiesel Oxidation on Engine Performance and Emissions*. Iowa State University: PhD Dissertation.

Andrzejewski J and Sapinski. (1991). *Some Particularities of the Vegetable Oils Combustion in Diesel Engines.* Proceedings of the conference 'Engine and Environment-Which Fuel for the Future?'. 23-24 July 1991, Grazer Congress, Graz, Austria.

ASTM D 6751, *Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels*.

Azhar Abdul Aziz, Mohd Farid Said and Mohamad Afiq Awang. (2004). *Laboratory Evaluation of Palm Oil-Based Bio-diesel with Conventional Diesel using Single Cylinder Direct Injection Engine*. 2004 MPOB National Seminar on Green and Renewable Biofuel, 6 & 7 December 2004.

Azhar Abdul Aziz, Mohd Farid Said and Mohamad Afiq Awang. (2005a). *Performance of Palm Oil-Based Biodiesel Fuels in a Single Cylinder Direct Injection Engine*. Palm Oil Developments, No. 42, June 2005: pg 15.

Azhar Abdul Aziz, Mohd Farid Said and Mohamad Afiq Awang. (2005b), *Performance and Emission Evaluations of Palm Oil-Based Biodiesels with Conventional Diesel using Single Cylinder Direct Injection Engine*. The 11^{th} Small Engine Technology Conference (SETC 2005). Bangkok, Thailand, 12-14 October 2005. SAE Paper: 2005-32-0016.

Bagby, M.O. and Freedman, B. (1987). *Seed Oils for Diesel Fuels: Sources and Properties*. ASAE Paper: 871583.

Benson, R. S. (1982). *The Thermodynamics and Gas Dynamics of Internal Combustion Engines*. VoI 1., Clarendon Press (1982)

Bernard Challen and Rodica Baranescu. (1999). *Diesel Engine Reference Book*. Second Edition: Butterworth Heinemann.

Bruno M. Spessert, Ilka Arendt and Andreas Schleicher. (2003). *Influence of Quality on Exhaust Gas and Noise Emissions of Small Industrial Diesel Engines*. SAE Paper: 2003-32-0005.

Chan S.H. (1996). *An Exhaust Emissions Based Air-Fuel Ratio Calculation for Internal Combustion Engines*. IMechE, Proc. Instn Mech Engrs, Vol 210.

Chang, D.Y. and Van Gerpen, J.H. (1997). *Fuel Properties and Engine Performance for Biodiesel Prepared from Modified Feedstocks*. SAE Paper: 971684.

Chang, D.Y., Van Gerpen, J.H., Lee, I., Johnson, L., Hammond, E.G., and Marley, S. (1996). *Fuel Properties and Emissions of Esters of Soybean Oil as Diesel Fuel*. J. of Amer. Oil Chem. Soc. Vol. 73, No. 11.

Choo Yuen May, Ma Ah Ngan, Cheah Kien Yoo, Rusnani Abdul Majid, Andrew Yap Kian Chung, Harrison Lau Lik Nang, Cheng Sit Foon, Yung Chee Liang, Puah Chiew Wei, Ng Mei Han and Yusof Basiron. (2005). *Palm Diesel: Green and Renewable Fuel from Palm Oil,*. Palm Oils Developments. June 2005. No. 42: pg 3.

Choo, Y M, Ma, A. N and Yusof Basiron. (1995). *Production And Evaluation Of Palm Oil Methyl Esters as Diesel Substitute*. Elaeis Special Issue:5-25.

Choo, Y M, Ong, A S H, Cheah, K Y and Bakar, A. (1992). *Production of Alkyl Esters from Oils and Fats*. Australian Patent No. AU 626014.

Choo, Y.M., Ma, A. N. and Yusof Basiron. (2002). *Palm Diesel*. Paper presented at 2002 Oils and Fats International Congress (OFIC), 7 – 10 October 2002, Putra World Trade Centre, Kuala Lumpur, Malaysia.

David Yu-Zhang Chang. (1997). *Determination of particulate and unburned hydrocarbon emissions from diesel engines fuels with biodiesel*. Iowa State University, Ames, Iowa, USA: Ph.D. Dissertation.

Freedman, B., Bagby, M.O., Callahan, T.J., and Ryan, T.W. (1990). *Cetane Numbers of Fatty Esters, Fatty Alcohols and Triglycerides Determined in a Constant Volume Combustion Bomb*. SAE Paper: 900343.

Gamma Technologies. (2003). *GT-Power User's Manual Version. A GT-Suite-Application for Engine Performance, Acoustics and Control Simulation*. March 2003

Graboski, M.S., Ross, J.D., and McCormick, R.L. (1996). *Transient Emissions from No. 2 Diesel and Biodiesel Blends in a DDC Series 60 Engine*. SAE Paper: 961166.

Greeves G. and Wang H.T. (1981). *Origins of Diesel Particulate Mass Emission*. SAE Paper: 810260.

Hemmerlein, N., Korte, V., Richter, H., and Schroder, G. (1991). *Performance, Exhaust Emissions, and Durability of Modern Diesel Engines Running on rapeseed Oil*. SAE Paper: 910848.

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

Hua Zhao and Nicos Ladommatos. (2001). *Engine Combustion Instrumentation and Diagnostics*. Society of Automotive Engineers, Inc. 2001.

James P. Szybist, Andre L. Boehman. (2003). *Behaviour of a Injection System with Biodiesel Fuel*. SAE Paper: 2003-01-1039.

Jiro Senda, Nobunori Okui, Teppei Suzuki and Hajime Fujimoto. (2004). *Flame Structure and Combustion Characteristics in Diesel Combustion Fuelled with Biodiesel*. SAE Paper: 2004-01-0084.

Khan I. M., Greeves G. and Wang C. H. T. (1973). *Factors Affecting Smoke and Gaseous Emissions from Direct Injection Engines and a Method of Calculation*. SAE Paper: 730169.

Knothe G, M. O. Bagby, T. W. Ryan III, T. J. Callahan and H G Wheeler. (1992). *Vegetable Oils as Alternative Diesel Fuels: Degradation of Pure Triglycerides during the Pre-combustion Phase in a Reactor Simulating a Diesel Engine*. SAE Paper: 920194.

Krawczyk, T. (1996). *Biodiesel – Alternative Fuel Makes Inroads but Hurdlers Remain*. INFORM Vol. 7, No. 8: pg 800.

Last, R.J., Kruger, M., and Durnholz, M. (1995). *Emissions and Performance Characteristics of a 4-Stroke , Direct Injection Diesel Engine Fueled with Blends of Biodiesel and Low Sulfur Diesel Fuel*. SAE Paper: 950054.

McDonald, J., Purcell, D.L., McClure, B.T., and Kittelson, D.B. (1995). *Emission Characteristics of Soy Methyl Ester Fuels in an IDI Compression Ignition Engine*. SAE Paper: 950400.

Michael Plint and Anthony Martyr. (1999). *Engine Testing: Theory and Practice. Second Edition*: SAE International.

Novamont. (1992). *The Novamont Company: Preliminary Fuel Evaluations by Detroit Diesel Corporation of Rapeseed and Soybean Methyl Ester*, Ferruzzi Trading (UK) Ltd.

P.K. Bose, R.A. Beg, B.B. Ghosh, R.K. Chakrabarti and Subodh Kr. Saha. (2001). *Performance and Emissions Characteristics of a Naturally Aspirated Diesel Engine with Esterified Vegetable Oil*. SAE Paper: 2001-01-3386.

Poulton M.L. (1994). *Alternative Fuels for Road Vehicles*: Computational Mechanics Publications, Southampton, UK and Boston, USA.

Reed, T B. (1993). *An Overview of the Current Status of Biodiesel*. Proceedings of the First Biomass Conference of the Americans 1993, Vol. II: page. 797.

Ryan, T.W., Callahan, T.J., and Dodge, L.G. (1982). *Characterization of Vegetable Oils for Use as Fuels in Diesel Engines. Vegetable Oil Fuels*. Proceeding of the International Conference on Plant and Vegetable Oils as Fuels: pg 70.

SAE International. (1994). Reciprocating Internal Combustion Engines-Performance- Part 1: Standard Reference Conditions, Declarations of Power, Fuel and Lubricating Oil Consumptions and Test Method**.** SAE J3046-1.

SAE International. (1995). *Engine Power Test Code – Spark Ignition and Compression Ignition – Gross Power Rating***.** SAE J1995.

SAE International. (2002). *Diesel Engine Emission Measurement Procedure*. SAE J1003.

Schmidt, K. and Van Gerpen, J.H. (1996). *The Effect of Biodiesel Fuel Composition on Diesel Combustion and Emissions*. SAE Paper: 961086.

Sharp, C.A., S.A. Howell, and J. Jobe. (2000). *The Effect of Biodiesel Fuels on Transient Emissions from Modern Diesel Engines, Part I Regulated Emissions and Performance*. SAE Paper: 2000-01-1967, 2000.

Stone, R. (1999). *Introduction to Internal Combustion Engines*. 3rd Edition: Macmillan Press Ltd., London.

Sung Bin Han, Peter C. Hinze, Young Jik Kwon and Sung Soo Mun. (1997). *Experimental Investigation of Smoke Emission Dependent upon Engine Operating Conditions*. SAE Paper: 971658

Tritthart P. and P. Zelenka. (1990). *Vegetable Oils and Alcohols – Additive Fuels for Diesel Engines*. Proceedings from the XXIII FISITA Congress ‘The Promise of New Technology in the Automotive Industry’. Turin, Italy. 7-11 May 1990.

Van Gerpen, J.H. (1984). *The Effects of Air Swirl and Fuel Injection System Parameters on Diesel Combustion*. University of Wisconsin, Madison: PhD Thesis.

Wagner, L.E., Clark, S.J., and Schrock, M.D. (1984). *Effects of Soybean Oil Esters on the Performance, Lubricating Oil, and Wear of Diesel Engines*. SAE Paper: 841385.

Watson, N. and Janota, M. S. (1982). *Turbocharging the Internal Combustion Engine*. Macmillan.

Wong C.L. and Steere D.E. (1982). *The Effect of Diesel Fuel Properties and Engine Operating Conditions on Ignition Delay*. SAE Paper: 821231.

Yamin Vong. (2004). *Running on Cooking Oil*. New Straits Times. December 15, 2004.

Yusof Basiron and Choo, YM. (2004). *Crude Palm Oil as a Source of Biofuel: Its Impact on Price Stabilization and Environment.* 1 1/2 Day Course on Refineries' Crude Palm Oil Purchasing, Hedging, Contractual & its Operational Aspects, Subang Jaya, Selangor, Malaysia. 22 & 23 June 2004.