THE INFLUENCE OF ADDITIVES ON BIODIESEL BLEND FOR ENGINE PERFORMANCE AND EMISSION IMPROVEMENT

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ABSTRACT

Biodiesel is receiving more and more attention as a renewable fuel; serve as an alternative to mineral diesel. Fossil fuels are depleting with time due to their limited resources. On the other hand; the world energy consumption increases continuously due to the modern life requirements which lead to series energy crises. Although blended biodiesel-diesel fuel can replace mineral diesel satisfactorily at low blending ratios up to 20% biodiesel, problems related to fuel properties persist at high blending ratio more than 20%. The aim of this thesis is to investigate the feasibility of biodiesel-diesel blended fuel at 30% biodiesel, as fuel for unmodified diesel engines. Chemical additives are introduced as a viable option to improve the blended fuel properties. The experimental characterization of the blended fuel properties was conducted with ethanol, butanol and diethyl ether additives at low ratios up to 8% compared to the blended fuel standard ASTM D7467. Furthermore, engine is tested with blended fuel B30 and additives to investigate the engine performance, exhaust emissions and engine cyclic variations using the coefficient of variation and the wavelet analysis method. A statistically significant improvement in blended fuel kinematic viscosity and density was observed with all additives starting at 4% and 6% additive ratios for kinematic viscosity and density, respectively. On the other hand, a significant reduction in the blended fuel heating value was observed with all additive types starting at 6% additive ratio. The least reduction of blended fuel B30 heating value observed at 8% additive ratio is about 4% for B30 with diethyl ether additive. The blended fuel cold flow properties were improved with increasing additive ratios and maximum reduction in pour and cloud point was observed with diethyl ether by 2 ^{o}C and 3 ^{o}C respectively; at 8% additive ratio. The engine brake thermal efficiency was comparable for blended fuel B30 with different additives and mineral diesel. Furthermore, blended fuel with diethyl ether additive showed higher engine power at lower brake specific fuel consumption compared to other additives at similar ratios, and better engine brake power was achieved at 6% diethyl ether with increasing the additive ratio. The formation of NOx and CO_2 emissions was reduced significantly with increasing the additive ratios. Better improvement in these emissions observed with diethyl ether additive at 8% ratio, which was comparable to that of diesel fuel. The significant impact of the additives on reducing the maximum in-cylinder pressure for B30 was observed with increasing additive ratios and the better trend obtained for B30 with 4% to 6% diethyl ether additive, which was comparable to that of the mineral diesel. Both the wavelet analysis and coefficient of variation reveal that increasing the additive ratio would give a noticeable effect on increasing the engine cycle-to-cycle variations which limits their usage at high ratios. It can be concluded that chemical additives are a viable option to introduce the blended fuel B30 as an alternative fuel for diesel engine that meets the blended fuel standard ASTM D7467 specifications.

ABSTRAK

Biodiesel menerima perhatian yang lebih sebagai bahan api alternatif yang boleh diperbaharui berbanding diesel mineral kerana keperluan semasa. Perkara ini juga berkait rapat dengan krisis kekurangan bahan api fosil dan kenaikan harga. Walaupun sebatian bahan api *biodiesel-diesel* boleh menggantikan diesel mineral secara memuaskan pada nisbah pencampuran rendah sehingga 20% biodiesel, masalah yang berkaitan dengan sifat-sifat bahan api berterusan pada nisbah pengadunan tinggi lebih daripada 20%. Tujuan tesis ini adalah untuk mengkaji keberkesanan biodiesel-diesel bahan api dicampur pada 30% biodiesel sebagai bahan api untuk enjin diesel tidak diubahsuai. Bahan tambahan kimia diperkenalkan sebagai pilihan yang berdaya maju untuk memperbaiki sifat-sifat bahan api sebati. Pencirian ujikaji bagi sifat-sifat bahan api sebati telah dijalankan dengan etanol, butanol dan dietil eter tambahan (additives) pada nisbah yang rendah sehingga 8% berbanding dengan standard bahan api sebati ASTM D7467. Tambahan pula, ujian enjin dengan B30 bahan api dikisar dan bahan tambahan telah dilakukan untuk mengkaji prestasi enjin, pelepasan gas ekzos dan enjin variasi kitaran menggunakan pekali variasi dan kaedah analisis *wavelet*. Satu peningkatan statistik yang signifikan dalam bahan api sebati kelikatan kinematik dan ketumpatan diperhatikan dengan semua bahan tambahan yang masing-masing bermula pada 4% dan 6% nisbah tambahan untuk kelikatan kinematik dan ketumpatan. Sebaliknya, pengurangan ketara dalam bahan api nilai pemanasan sebati diperhatikan dengan semua jenis bahan tambahan bermula pada nisbah tambahan 6%. Pengurangan kurangnya bahan api B30 dicampur nilai pemanasan diperhatikan pada 8% nisbah tambahan adalah kira-kira 4% bagi B30 dengan diethyl eter. Bahan api sebati *cold flow properties* telah bertambah baik dengan peningkatan tambahan nisbah dan pengurangan maksimum *pour point* dan *cloud point* diperhatikan dengan dietil eter sebanyak 2 ^{o}C dan 3 ºC untuk masing-masing; pada 8% nisbah tambahan. Kecekapan haba brek enjin setanding untuk bahan api B30 dicampur dengan bahan tambahan yang berbeza dan diesel mineral. Manakala, bahan api dicampur dengan dietil eter tambahan menunjukkan kuasa enjin yang lebih tinggi pada penggunaan bahan api tentu yang lebih rendah berbanding dengan brek tambahan lain pada nisbah yang sama dan kuasa enjin brek yang lebih baik dicapai pada 6% dietil eter dengan peningkatan nisbah tambahan . Pembentukan NOx dan pelepasan CO_2 telah dikurangkan dengan ketara dengan peningkatan nisbah tambahan. Peningkatan yang lebih baik dalam pengeluaran ini diperhatikan dengan diethyl eter tambahan pada nisbah 8%, yang standing dengan bahan api diesel. Impak yang besar daripada tambahan kepada mengurangkan tekanan maksimum dalam silinder untuk B30 diperhatikan dengan peningkatan tambahan nisbah dan *trend* yang lebih baik diperolehi untuk B30 dengan 4% hingga 6% dietil eter tambahan yang setanding dengan diesel mineral. Kedua-dua analisis *wavelet* dan pekali variasi mendedahkan bahawa peningkatan nisbah tambahan mempunyai kesan ketara kepada peningkatan kitaran ke kitaran variasi enjin yang menghadkan penggunaannya pada nisbah yang tinggi. Kesimpulannya bahan kimia tambahan adalah pilihan yang berdaya maju untuk memperkenalkan bahan api B30 yang dicampur sebagai bahan api alternatif untuk enjin diesel yang memenuhi standard bahan api yang memenuhi spesifikasi ASTM D7467.

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NOMENCLATURES

List of Symbols

Symbol	Meaning
a_j	Wavelet scale
a_o	Smallest wavelet scale
$\dot{m}_f$	Fuel mass flow rate (g/hr)
$p_a d_o$	Observed inlet dry air pressure
a, b	Mother wavelets controlled parameters
f_a	Atmospheric factor
f_c	Factor
f_m	Engine factor
J	Largest scale in the wavelet transform
k_v	Viscometer constant
L	Sliding segment length
N	Engine speed
n	Time index
N_c	Number of cycles
n_p	Polytropic index
P	Engine brake power
P_o	Observed power
p_o	Corrected power
Q_f	Heating value of the test fuel (MJ/kg)
Q_{gross}	Gross heat release rate
Q_{net}	net heat release rate
R	Characteristic gas constant
s_o	Smallest resolvable scale in the wavelet transform
t	Time (s)
T	Engine brake torque
T_{gas}	mean cylinder gas temperature
T_o	Observed inlet air temperature
T_{wall}	mean cylinder wall temperature

Greek Symbols

Symbol	**Meaning**
γ	Specific heats ratio
C_δ	Constant depend on the wavelet function.
k	Frequency index
s	Wavelet scale
w	Frequency (Hz)
w_o	Dimension less frequency parameter
α	Mark-Houwink constant
α_1	lag-1 auto correction coefficient
δj	Constant depend on the wavelet function.
δt	Sampling interval
η	Non-dimensional “time” parameter
η_s	Temporal distance
τ_s	*e*-folding time

LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
ASTM	American Society of Testing Materials
ATDC	After Top Dead Center
BDC	Bottom Dead Center
BSFC	Brake-Specific Fuel Consumption
BTDC	Before Top Dead Center
BTE	Brake Thermal Efficiency
BU	Butanol
CN	Cetane number
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COI	Cone of influence
COV	Coefficient of variation
CP	Cloud point
CWT	Continuous wavelet transform
DE	Diethyl ether
DF	Degree of freedom
DI	Direct Injection
E	Ethanol
EGR	Exhaust Gas Recirculation
EN	European Union fuel standard
F	Probability distribution in repeated sampling
FA	Fatty acid
FAME	Fatty acid methyl ester
GHG	Greenhouse Gas
GWS	Global wavelet spectrum
H	Hydrogen
HC	Hydrocarbon

IDI	Indirect Injection
IMEP	Indicated mean effective pressure
MFB	Mass fraction burned
NOx	Oxides of Nitrogen
OH	Hydroxide
PAHs	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
POME	Palm oil methyl ester
PP	Pour point
Pr	Weight of significance
RoHR	Rate of Heat Release
rpm	Revolution per minute
SD	Standard deviation
SO_2	Sulfur Dioxide
TDC	Top Dead Center
THC	Total Hydrocarbons
UHC	Unburned Hydrocarbons
ULSD	Ultra low sulfur diesel
V_s	Cylinder swept volume (m^3)
WPS	Wavelet power spectrum
WT	Wavelet transform

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

The global energy consumption has duplicated during the recent three decades. Fossil fuels are dominant in the global energy mix, as they represent over 80% of the total energy supplies in the world today (EIA, 2013). A further increase in the utilization of energy sources is expected due to the modern life demands and rapid economic development. This results in the fast depletion of fossil fuel reservoirs as well as unwanted emissions. Oil is the fossil fuel that is most in danger of running out, as it is steadily declining. The sources of this fuel are available only in certain regions of the world, and they are close to their maximum production. A peak in the global oil production is expected in the next few years (Demirbas, 2008). According to the World Trade Organization, in 2010, the fuel market was responsible for a 15.8% share of the total trade in merchandising and primary products. Most are due to diesel fuel that is essential for transportation and heavy-duty engines (WTO, 2010). Besides, the world today is faced with a serious global warming and environmental pollution. The major gas that contributes to the greenhouse phenomena is CO_2 which is mainly emitted from the combustion of fossil fuel. According to the current scenario of increasing CO_2 emissions the target of controlling the global warming phenomenon is becoming more difficult and costly with each year that passes (IEA, 2012). The twin crises of fossil fuel depletion and environmental degradation that arise in the last decades have underscored the importance of developing alternative sources of liquid-fuel energy. Thus, there is an urgent need to find an alternative energy resource that is renewable, clean, reliable and yet economically feasible.

Biodiesel, as a replacement for diesel, is easily made from renewable biological sources, such as vegetable oil and animal fats. Chemically, biodiesel is referred to monoalkyl-esters of long-chain fatty acids, and to a variety of ester-based oxygenated fuels. It is well known that transportation almost depends entirely on fossil fuel, particularly petroleum based fuels such as gasoline, diesel fuel, liquefied petroleum gas (LPG), and natural gas (NG). An alternative fuel to mineral diesel must be technically feasible, economically competitive, environmentally acceptable, and easily available. The current alternative diesel fuel can be termed biodiesel. It can be used in diesel engines with little or no modification (Ong, Mahlia, Masjuki, & Norhasyima, 2011; Ramadhas, Jayaraj, & Muraleedharan, 2004).

The global warming maybe reduced by using alternative fuel, biodiesel is considered as a promising fuel. The best potential future energy source in the transportation sector is biodiesel. It is mainly emitted carbon monoxide, carbon dioxide, oxides of nitrogen, sulphur oxides and smoke. The combustion of biodiesel alone provides a high reduction in total unburned hydrocarbons (HC) and polycyclic aromatic hydrocarbons (PAHs) (Hoekman & Robbins, 2012). Biodiesel further provides significant reductions in particulates and carbon monoxide over mineral diesel fuel. Biodiesel provides slight increases or decreases in nitrogen oxides depending on the engine family and testing procedures that follow (S.A. Basha, Gopal, & Jebaraj, 2009). Currently, global warming caused by CO_2 is the main climatic problem in the world; therefore, environmental protection is important to ensure a better and safer future. Because biodiesel is made from renewable sources, it presents a convenient way to provide fuel while protecting the environment from unwanted emissions. Biodiesel is an ecological and non-hazardous fuel with low emission values; therefore, it is environmentally useful. Using biodiesel as an alternative fuel is a way to minimize global air pollution and in particular reduces the emission levels that potential or probable threats human health (Canakci, Ozsezen, Arcaklioglu, & Erdil, 2009).

Biodiesel properties are one of the noteworthy issues that restrict the use of biodiesel fuel. It has a direct effect on the main engine elements and parameters, such as fuel handling systems and performance (Hoekman, Broch, Robbins, Ceniceros, & Natarajan, 2012; Silitonga et al., 2013). Neat biodiesel contains no petroleum, but it is traditionally blended with mineral diesel to create a biodiesel blend, typically at 20% (by volume), or less. Pure biodiesel is biodegradable, nontoxic, and essentially free of sulphur and aromatics. Biodiesel is the only alternative fuel for compression-ignition that has fully completed the health effects testing requirements of the 1990 Clean Air Act Amendments. Biodiesel, produced to industry and meet the specifications of ASTM D6751, is legally registered with the Environmental Protection Agency as a legal motor fuel for sale and distribution (NBB, 2011).

1.2 BIODIESEL FUEL

Biodiesel is the only alternative fuel with properties that make low concentration biodiesel-diesel fuel blends will run well in unmodified conventional compression ignition engines. Understanding these properties provides key towards evaluating and improving diesel engine performance and emissions. The benefits and technical challenge of the biodiesel as a fuel for diesel engine are revealed through the investigation of their properties relevant to engine performance and emissions. Biodiesel has properties comparable to diesel fuel (Demirbas, 2009; Shahid & Jamal, 2011). It can be stored anywhere, where the mineral diesel fuel is stored (Demirbas, 2007; Scharffbillig & Clark, 2014). Biodiesel can be made from domestically produced and renewable oilseed crops. The risks of handling, transporting and storing biodiesel are much lower than those associated with mineral diesel. Biodiesel is safe to handle and transport because it is biodegradable and has a high flash point, unlike the mineral diesel fuel. Biodiesel can be used alone or mixed in any ratio with mineral diesel fuel (J. H. Van Gerpen, Peterson, & Goering, 2007; Yusuf, Kamarudin, & Yaakub, 2011).

The biodegradability of biodiesel has been proposed as a solution to waste problems. Biodegradable fuels such as biodiesel have an expanding range of potential applications and are environmentally friendly. Therefore, there is growing interest in degradable diesel fuels that degrade more rapidly than the conventional petroleum fuels. Biodiesel is non-toxic and degrades faster than mineral diesel due to its higher oxygen content (typically 11%) (Banga & Varshney, 2010; Sadeghinezhad et al., 2013). Furthermore, the high oxygen content of the biodiesel fuel improves the combustion efficiency due to the increase of the homogeneity of oxygen with the fuel during combustion. Therefore, the combustion efficiency of biodiesel is higher than the mineral diesel (Wang et al., 2011; Yoshimoto, 2009). Biodiesel has good lubricant properties compared to mineral diesel oil, in particular very low-sulphur diesel. This is crucial to reducing wear on the engine parts and the injection system (Fazal, Haseeb, & Masjuki, 2011; Mofijur et al., 2013).

Biodiesel fuel is mono alkyl ester produced from vegetable oil or animal fat by transesterification; most biodiesel fuels have excellent cetane numbers, typically higher than the diesel fuel. It can be blended with diesel fuel as they have similar characteristics with lower exhaust emissions (S.A. Basha et al., 2009; Janaun & Ellis, 2010). Biodiesel properties can vary substantially from one feedstock to another depending on the compositional profile of the feedstock (Atabani et al., 2012; Xue, Grift, & Hansen, 2011). There are many standard specifications have been established for biodiesel fuel, particularly the American standard ASTM and the European Standard EN. ASTM has established standard specifications for biodiesel fuel B100 called ASTM D6751, as well as for biodiesel blends for B6 to B20 in mineral diesel, called ASTM D7467. Blends of B5 and below are permitted under the standard specifications for diesel fuel, ASTM D975 (J. Van Gerpen, Shanks, Pruszko, Clements, & Knoth, 2004; MI & GBC, 2007). To date, the EN standard only establishes standard specifications for B100, called EN 14214. In addition to diesel fuel standard, EN 590 permits the blends of B7 and below, but not for mid-level blends such as B20.

Biodiesel has lower carbon and hydrogen contents compared to diesel fuel, resulting in about a 10% lower mass energy content, and also biodiesel has a higher viscosity and higher density (Hoekman, Gertler, Broch, Robbins, & Natarajan, 2009; Shahid & Jamal, 2008). These properties may result in high nitrogen oxide (NOx) emissions, lower engine efficiency, injector coking, engine compatibility. The high viscosity and low volatility of biodiesel fuel will cause problems in fuel pumping and spray characteristics as well as causing poor combustion in diesel engines. The inefficient mixing of fuel with air contributes to incomplete combustion.

Biodiesel has a higher cloud point and pour point compared to diesel. Therefore, biodiesel fuels are plagued by the growth and agglomeration of paraffin wax crystals