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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 ^{o}C 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.

TABLE OF CONTENTS

		Page
SUPERVISORS' DECLARATION		ii
STUDENT'S DECLARATION		iii
ACKNOWLEDGEMENTS		v
ABSTRACT		vi
ABSTRAK		vii
CONTENTS		viii
LIST OF TABLES		xiii
LIST OF FIGURES		xv
NOMENCLATURES		xxi
LIST OF ABBREVIATIONS		xxiii
CHAPTER I	**INTRODUCTION**	
1.1	Introduction	1
1.2	Biodiesel Fuel	3
1.3	Problem Statement	5
1.4	Objective of the Study	7
1.5	Scope of the Study	7
1.6	Organisation of Thesis	8
CHAPTER 2	**LITURATURE REVIEW**	
2.1	Introduction	9
2.2	Diesel Engine	10
	2.2.1 Early Diesel Engine Development	11
	2.2.2 Types of Diesel Engines	12
	2.2.3 Modern Diesel Engines	13
	2.2.4 Diesel Engine Combustion	14
	2.2.5 Diesel Engine Fuel history	15
2.3	Biodiesel Fuel Trends	16
2.4	Biodiesel Production and Standardization	17

2.5	Potential of Palm Oil Biodiesel	21
2.6	Biodiesel Fuel Properties	25
	2.6.1 Kinematic Viscosity	26
	2.6.2 Density	27
	2.6.3 Energy Content	27
	2.6.4 Cetane Number	27
	2.6.5 Cloud and Pour Point	28
	2.6.6 Flash Point	29
	2.6.7 Lubricity	29
	2.6.8 Sulphur Content	30
2.7	Biodiesel Fuel Blending	30
2.8	Biodiesel Fuel Additive	35
	2.8.1 Effects of Additive on Cold Flow Properties	38
	2.8.2 Effect of Additive on Fuel Characteristics	42
	2.8.3 Effect of Additive on Oxidation Stability	43
	2.8.4 Effect of Additive on Power Output	46
	2.8.5 Effect of Additive on Fuel Economy	48
	2.8.6 Effect of Additive on Engine Thermal Efficiency	49
	2.8.7 Effect of Additive on NOx Emissions	50
	2.8.8 Effect of Additive on CO Emissions	52
	2.8.9 Effect of Additive on CO2 Emissions	54
	2.8.10 Effect of Additive on HC and PM Emissions	54
2.9	Conclusions	56

CHAPTER 3 EXPERIMENTAL SETUP AND TEST PROCEDURES

3.1	Introduction	58
3.2	Strategy of Work Frame	58
3.3	Fuel Test Experimental Details	60
	3.3.1 Materials	60
	3.3.2 Sample Preparation	60
	3.3.3 Viscosity	62
	3.3.4 Density	63

	3.3.5 Heating Value	64
	3.3.6 Acid Value	66
	3.3.7 Cloud and Pour Point	67
3.4	Engine Test Experimental Details	68
	3.4.1 Diesel Engine Setup	70
	3.4.2 Dynamometer Setup	71
	3.4.3 Engine and Dynamometer Cooling Systems	73
	3.4.4 Fuel Lines and Measurement System	75
	3.4.5 Air Intake System	76
	3.4.6 Engine Wiring and Thermocouples	77
	3.4.7 In-Cylinder Pressure Measurement and Data Acquisition	78
	3.4.8 Exhaust Emissions Analyser	81
	3.4.9 Engine Testing Analysis	82
	3.4.10 Combustion Analysis	84
3.5	Engine Cyclic Variation Analysis	87
	3.5.1 Coefficient of Variation	87
	3.5.2 Wavelet Analysis Model	88
3.6	Tested Fuel Matrix	96
3.7	Engine Test Operation Conditions	97
3.8	Summary	98

CHAPTER 4 RESULTS AND DISCUSSION

4.1	Introduction	99
4.2	Experimental Analysis of Fuel Properties	100
	4.2.1 Kinematic Viscosity	102
	4.2.2 Density	104
	4.2.3 Heating Value	107
	4.2.4 Acid Value	109
	4.2.5 Pour Point and Cloud point	111
4.3	Analysis of Engine Performance	113
	4.3.1 Brake Power	113
	4.3.2 Brake Specific Fuel Consumption	118

	4.3.3 Brake Thermal efficiency	121
4.4	Experimental Analysis of Fuel Combustion	125
	4.4.1 In-Cylinder Pressure Traces	125
	4.4.2 In-Cylinder Temperature	131
	4.4.3 Rate of Heat Release	135
	4.4.4 Rate of Pressure Rise	139
	4.4.5 Mass Fraction Burned	142
4.5	Analysis of Engine Emissions	143
	4.5.1 NOx Emissions	143
	4.5.2 Carbon monoxide Emissions	145
	4.5.3 Carbon dioxide Emissions	146
4.6	Analysis of Engine Cyclic Variations	148
	4.6.1 Required Sample Size	148
	4.6.2 Engine Cyclic Variation Analysis	152
	4.6.3 Wavelet Analysis	157
4.7	Summary	171

CHAPTER 5 CONCLUSION AND FUTURE WORK

5.1	Introduction	172
5.2	Summary of Findings	172
	5.2.1 Fuel Properties Characterization	172
	5.2.3 Engine Performance and Combustion Characteristics	174
	5.2.3 Engine Cyclic Variation	176
5.3	Novel Contribution of the Study	177
5.4	Recommendations for Future Work	178

REFERENCES 179

APPENDICES

A	ASTM and EN Biodiesel Fuel Standards Specifications	194
B1	Kinematic Viscosity Measurement Procedures	196

B2	Density Measurement Procedures	198
B3	Heating Value Measurement Procedures	200
B4	Pour Point and Cloud Point Measurement Procedures	202
C1	Dynamometer Performance Curves	204
C2	Dynamometer Specifications	205
C3	Dynamometer Calibration Procedures	206
C4	Dynamometer Cooling Tower Specifications	207
C5	Specifications of AIC Fuel Flow Meter	208
D1	Specifications of Kistler Crank Angle Encoder	209
D2	DEWE-800 DAQ System Specifications	210
D3	DEWE-Orion 1624 Data Acquisition Card Specifications	211
E1	Measured Properties of Blended Fuel B30 with Different Additives	212
E2	Tukey Grouping Test For Variable Viscosity	213
E3	Tukey Grouping Test For Variable Density	214
E4	Tukey Grouping Test For Variable Heating Value	215
E5	Tukey Grouping Test For Variable Acid Value	216
F	List of Publications	217

LIST OF TABLES

Table No.	Title	Page
2.1	Effect of blending on fuel properties	31
3.1	Properties of chemical additives	61
3.2	Mitsubishi 4D68 diesel engine specifications	71
3.3	K-type thermocouple specifications	78
3.4	Pressure sensor specifications	79
3.5	KANE gas analyser specifications	82
4.1	Blended biodiesel-diesel fuel properties	101
4.2	Analysis of variance (ANOVA) for viscosity	103
4.3	Tukey Grouping test for variable viscosity	103
4.4	Analysis of variance (ANOVA) for density	106
4.5	Tukey Grouping test for variable density	106
4.6	Analysis of variance (ANOVA) for heating value	108
4.7	Tukey Grouping test for variable heating value	108
4.8	Analysis of variance (ANOVA) for acid value	110
4.9	Tukey Grouping test for variable acid value	110
A1	ASTM and EN biodiesel fuel standards specifications	194
B1	Viscometer size and constant value *k* for different viscometers	197
B2	Portable Density/Specific Gravity meter technical specifications	198
B3	Calorimetric thermometer technical specifications	201
B4	Cloud and pour point measuring instrument specifications	203
C2	Eddy current dynamometer specifications	205
C4	Dynamometer cooling tower specifications	207
C5	Fuel flow meter specifications	208
D1	Kistler crank angle encoder specifications	209

D2	DEWE-800 DAQ system specifications	210
D3	DEWE-ORION 1624 data acquisition card specifications	211
E1.1	Measured properties of blended fuel B30 with ethanol additive	212
E1.2	Measured properties of blended fuel B30 with butanol additive	212
E1.3	Measured properties of blended fuel B30 with diethyl ether additive	212
E2.1	Tukey Grouping test for variable viscosity at 6% additive ratio	213
E2.2	Tukey Grouping test for variable viscosity at 4% additive ratio	213
E2.3	Tukey Grouping test for variable viscosity at 2% additive ratio	213
E3.1	Tukey Grouping test for variable density at 6% additive ratio	214
E3.2	Tukey Grouping test for variable dnsity at 4% additive ratio	214
E3.3	Tukey Grouping test for variable dnsity at 2% additive ratio	214
E4.1	Tukey Grouping test for variable heating value at 6% additive ratio	215
E4.2	Tukey Grouping test for variable heating value at 4% additive ratio	215
E4.3	Tukey Grouping test for variable acid value at 2% additive ratio	215
E5.1	Tukey Grouping test for variable acid value at 6% additive ratio	216
E5.2	Tukey Grouping test for variable acid value at 4% additive ratio	216
E5.3	Tukey Grouping test for variable heating value at 2% additive ratio	216

LIST OF FIGURES

Figure No.	Title	Page
2.1	Four stroke diesel engine cycles	12
2.2	Direct (DI) and Indirect (IDI) combustion systems in diesel engines	14
2.3	Transesterification reaction for biodiesel production	18
2.4	Schematic flow chart for the biodiesel production process	19
2.5	Average oil yields for major oil sources	22
2.6	Comparative cost for the production of selected oils	23
2.7	General cost breakdown of biodiesel production	24
2.8	Typical greenhouse gas emission saving among types of biodiesel	24
2.9	Average impact of biodiesel blends on emissions from pre-1998 heavy duty on highway engines	34
3.1	Strategy of the work frame for the current research methodology	59
3.2	Electric magnetic stirrer (ERLA)	61
3.3	digital constant temperature kinematic viscosity bath (K23376 KV1000)	62
3.4	Cannon-Fenske Routine Viscometer for Transparent Liquids	63
3.5	Portable Density/Specific Gravity Meter (DA-130N)	64
3.6	Oxygen Bomb Calorimeter (Parr 6772)	65
3.7	Vessel cylinder assembly	65
3.8	Acid value test apparatus (Metrohm 785).	66
3.9	Cloud and pour point measurement apparatus (K46195)	67
3.10	Test jar and cooling bath assembling	68
3.11	schematic of the test cell for the experimental setup	69
3.12	Engine test rig	70

3.13	Engine characteristics curves at partial engine throttle position	70
3.14	Eddy current dynamometer	72
3.15	Dynalec dynamometer controller	73
3.16	Engine cooling system diagram	74
3.17	(a) Engine cooling system (b) Dynamometer cooling tower	75
3.18	Schematic diagram of the integrated fueling system	76
3.19	(a) AIC fuel flow meter (b) Board computer (BC-3033)	76
3.20	Air intake system	77
3.21	In-cylinder pressure transducer	79
3.22	(a) DEWECa graphical user interface (GUI) (b) DEWEsoft graphical user interface (GUI)	80
3.23	KANE gas analyser	81
4.1	Diethyl ether and butanol chemical composition	101
4.2	Effect of increasing additives percent on blended fuel B30 viscosity	102
4.3	Effect of different additive type on blended fuel B30 viscosity	104
4.4	Effect of increasing additives percent on blended fuel B30 density	105
4.5	Effect of different additive type on blended fuel B30 density	106
4.6	Effect of increasing additives percent on blended fuel B30 heating value	108
4.7	Effect of increasing additives percent on blended fuel B30 acid value	110
4.8	Effect of increasing additives percent on blended fuel B30 cloud point	112
4.9	Effect of increasing additives percent on blended fuel B30 pour point	113
4.10	Variation of engine brake power with speed for different ethanol additive ratios	114

4.11	Variation of engine brake power with speed for different butanol additive ratios	115
4.12	Variation of engine brake power with speed for different diethyl ether additive ratios	116
4.13	Percentage decrease of engine brake power for B30 with different additives compared to diesel fuel	117
4.14	Variation of engine brake specific fuel consumption with speed for different ethanol additive ratios	118
4.15	Variation of engine brake specific fuel consumption with speed for different butanol additive ratios	119
4.16	Variation of engine brake specific fuel consumption with speed for different diethyl ether additive ratios	120
4.17	Percentage increase of BSFC for B30 with different additives compared to diesel fuel	121
4.18	Variation of engine brake thermal efficiency with speed for different ethanol additive ratios	122
4.19	Variation of engine brake thermal efficiency with speed for different butanol additive ratios	123
4.20	Variation of engine brake thermal efficiency with speed for different diethyl ether additive ratios	124
4.21	Percentage increase of brake thermal efficiency (BTE) for B30 with different additives compared to diesel fuel at 2,500 rpm and half load	125
4.22	Experimental in-cylinder pressure traces at 2,500 rpm	127
4.23	Experimental in-cylinder pressure traces with ethanol additive at 2,500 rpm	128
4.24	Experimental in-cylinder pressure traces with ethanol additive at 2,500 rpm	129
4.25	Experimental in-cylinder pressure traces with diethyl ether additive at 2,500 rpm	130
4.26	In-Cylinder gas temperatures with ethanol additive at 2,500 rpm	132
4.27	In-Cylinder gas temperatures with butanol additive at 2,500 rpm	133

4.28	In-Cylinder gas temperatures with butanol additive at 2,500 rpm	134
4.29	Rate of heat relase with ethanol additive at 2,500 rpm	136
4.30	Rate of heat relase with butanol additive at 2,500 rpm	138
4.31	Rate of heat release with diethyl ether additive at 2,500 rpm	138
4.32	Rate of pressure rise with ethanol additive at 2,500 rpm	140
4.33	Rate of pressure rise with butanol additive at 2,500 rpm	140
4.34	Rate of pressure rise with diethyl ether additive at 2,500 rpm	141
4.35	Mass fraction burned (MFB) for diesel and B30 with different additives at 2,500 rpm engine speed and half load	142
4.36	NOx emissions for diesel and B30 with different additives at 2,500 rpm engine speed and half load	144
4.37	CO emissions for diesel and B30 with different additives at 2,500 rpm engine speed and half load	146
4.38	CO2 emissions for diesel and B30 with different additives at 2,500 rpm engine speed and half load	147
4.39	Variation of *COVimep* in groups of ten samples against the cycle number over 200 consecutive cycles for diesel and blended fuel B30	149
4.40	Variation of *COVimep* in groups of ten samples against the cycle number over 200 consecutive cycles for blended fuel B30 with different ethanol ratios	150
4.41	Variation of *COVimep* in groups of ten samples against the cycle number over 200 consecutive cycles for blended fuel B30 with different butanol ratios	151
4.42	Variation of *COVimep* in groups of ten samples against the cycle number over 200 consecutive cycles for blended fuel B30 with different diethyl ether ratios	151
4.43	Variation of *COVimep* for diesel fuel and blended fuel B30 with different ethanol additive ratios at 2,500 rpm	153
4.44	Variation of *COVimep* for diesel fuel and blended fuel B30 with different butanol additive ratios at 2,500 rpm	154
4.45	Variation of *COVimep* for diesel fuel and blended fuel B30 with different diethyl ether additive ratios at 2,500 rpm	155

4.46	Comparison of variation in *COVimep* of blended fuel B30 for different additives with increasing additive ratios at 2,500 rpm	156
4.47	Wavelet power spectrum (*WPS*) and global wavelet spectrum (*GWS*) of the *IMEP* time series for diesel at 2,500 rpm engine speed	160
4.48	Wavelet power spectrum (*WPS*) and global wavelet spectrum (*GWS*) of the *IMEP* time series for blended fuel B30 at 2,500 rpm engine speed	161
4.49	Wavelet power spectrum (*WPS*) and global wavelet spectrum (*GWS*) of the *IMEP* time series for blended fuel B30 with 2% ethanol at 2,500 rpm engine speed	162
4.50	Wavelet power spectrum (*WPS*) and global wavelet spectrum (*GWS*) of the *IMEP* time series for blended fuel B30 with 4% ethanol at 2,500 rpm engine speed	162
4.51	Wavelet power spectrum (*WPS*) and global wavelet spectrum (*GWS*) of the *IMEP* time series for blended fuel B30 with 6% ethanol at 2,500 rpm engine speed	163
4.52	Wavelet power spectrum (*WPS*) and global wavelet spectrum (*GWS*) of the *IMEP* time series for blended fuel B30 with 8% ethanol at 2,500 rpm engine speed	164
4.53	Wavelet power spectrum (*WPS*) and global wavelet spectrum (*GWS*) of the *IMEP* time series for blended fuel B30 with 2% butanol at 2,500 rpm engine speed	165
4.54	Wavelet power spectrum (*WPS*) and global wavelet spectrum (*GWS*) of the *IMEP* time series for blended fuel B30 with 4% butanol at 2,500 rpm engine speed	165
4.55	Wavelet power spectrum (*WPS*) and global wavelet spectrum (*GWS*) of the *IMEP* time series for blended fuel B30 with 6% butanol at 2,500 rpm engine speed	166
4.56	Wavelet power spectrum (*WPS*) and global wavelet spectrum (*GWS*) of the *IMEP* time series for blended fuel B30 with 8% butanol at 2,500 rpm engine speed	167
4.57	Wavelet power spectrum (*WPS*) and global wavelet spectrum (*GWS*) of the *IMEP* time series for blended fuel B30 with 2% diethyl ether at 2,500 rpm engine speed	168
4.58	Wavelet power spectrum (*WPS*) and global wavelet spectrum (*GWS*) of the *IMEP* time series for blended fuel B30 with 4% diethyl ether at 2,500 rpm engine speed	168

4.59	Wavelet power spectrum (*WPS*) and global wavelet spectrum (*GWS*) of the *IMEP* time series for blended fuel B30 with 6% diethyl ether at 2,5000 rpm engine speed	169
4.60	Wavelet power spectrum (*WPS*) and global wavelet spectrum (*GWS*) of the *IMEP* time series for blended fuel B30 with 8% diethyl ether at 2,500 rpm engine speed	170
A1.1	Blended fuel samples	195
B1.1	Digital Constant Temperature Kinematic Viscosity Bath	196
B2.1	Portable Density/Specific Gravity meter	199
B3.1	Calorimetric thermometer (Parr 6772)	201
B4.1	Cloud and pour point measuring instrument (K46195)	202
C1.1	Dynamometer Power Curve	204
C1.2	Dynamometer Torque Curve	204
C3.1	Dynamometer calibration	206
D1.1	(a) Crank angle encoder (b) Signal conditioner.	209

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