BIODIESEL COMBUSTION CHARACTERISTICS UNDER REACTING SWIRL SPRAY CONDITION

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

School of Mechanical Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

JULY 2019

DECLARATION

I declare that this thesis entitled *"Biodiesel Combustion Characteristics under Reacting Swirl Spray Condition"* is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ACKNOWLEDGEMENT

First and foremost, I would like to thank my research advisors Dr. William Chong Woei Fong, Associate Professor Chong Cheng Tung, and Professor Mohammad Nazri Mohd Jaafar for their continuous support and constant guidance throughout my PhD.

I would like to express my appreciation to Associate Professor Ng Jo Han from University of Southampton Malaysia Campus for the valuable discussions and suggestions to my research and thesis preparation. I would also like to acknowledge Mr. Wong Kang Yao for his help in biodiesel characterisation.

Thanks are expressed to Dr. Agustin Valera-Medina from Cardiff University, sharing his precious opinions during journal articles write-up.

I am grateful to all the staffs from Aeronautic Laboratory UTM for their helpful hand throughout my study.

Special thanks are due to Ministry of Education Malaysia for the MyBrain15 postgraduate sponsorship.

Finally, and certainly not least, my family members for their constant support and understandings.

ABSTRACT

Biodiesel portrays plenty of positive combustion properties, which presents itself as an essential alternative fuel to conventional fossil diesel. However, most of the reported works thus far are for automotive applications in internal combustion engines, with little being relevant for gas turbine applications. Therefore, in this study, biodiesel swirl flames are established using a model gas turbine swirl burner under atmospheric condition. The tested biodiesels are produced from palm, soybean, and coconut oils via transesterification process, while diesel is chosen as the baseline fuel. For neat biodiesel investigations, the flame spectroscopic analysis conducted shows that biodiesel swirl flames emit higher OH (Hydroxyl), CH (Carbyne), C_2 (Diatomic Carbon) and CN (Cyanido) radical intensities when compared with baseline diesel. It is also observed that decreasing main air temperature results in substantial nitric oxide (NO) reduction at the expense of higher undesirable emissions of carbon monoxide (CO) for all types of fuels tested. The NO emissions from the tested biodiesels are also found to be approximately 20-60% higher than that of diesel from equivalence ratio (ϕ) 0.65-0.9 at main air temperature of 250 °C. Besides this, the tested biodiesels showed higher CO emission than diesel at near stoichiometric combustion. Present research also unveils that biodiesels enhance flame stability as compared to diesel under lean combustion condition. Besides these, the study also investigated the potential use of biodiesels, being blended with natural gas (NG), under dual fuel combustion system. Introducing NG into palm biodiesel (PME) swirl flame at 90/10, 80/20 and 70/30 PME/NG, the obtained input thermal power proportion using the gas turbine swirl burner results in spectroscopic characteristic that resembles neat PME. However, radical emission intensities from PME/NG swirl flames are found to be typically higher than that of neat PME. 70/30 PME/NG combustions are observed to lower NO emission by a factor of 2-3.5 as compared to diesel and neat PME. Nonetheless, it is also found that the addition of NG reduces flame extinction limit when compared with neat PME and diesel. Finally, the effects of swirl angle variation on PME and PME/NG combustion characteristics were also examined. Increasing swirl angle from 45° to 60° lowers the NO and CO emissions by a factor of roughly 4. Conversely, NO and CO emissions increase by a factor of averaging 1.5-2 as swirl angle reduces from 45° to 30°. Novel empirical models are proposed for estimating NO and CO emissions from PME and PME/NG combustion at different NG proportions and swirl angles. Through this study, it is observed that highly unsaturated biodiesels show NO emission that is averaging 3.1 g/kWh higher than saturated biodiesels. Biodiesel flames also generally exhibit bluish flames, whereas diesel contains aromatics rings that lead to the production of sooty luminous orange-yellow flame brush. The sooty flame brush, however, vanishes when swirl angle increases from 45° to 60°. This research shows that PME/NG combustion using swirl vane angle 60° and 30% NG proportion is a promising way of reducing NO emission against neat PME. Biodiesels and biodiesel/NG can be viable alternative fuels for land-based gas turbine industrial applications, operating under lean combustion mode.

ABSTRAK

Biodiesel menunjukkan banyak ciri-ciri pembakaran yang positif, ini menjadikannya sebagai bahan api alternatif yang penting bagi menggantikan fosil diesel. Namun kebanyakan penyelidikan biodiesel buat masa kini adalah untuk kegunaan enjin pembakaran dalam bidang automotif, di mana pemahaman untuk penggunaan biodiesel di dalam gas turbin masih lagi kurang. Dalam penyelidikan ini, api pusaran biodiesel dinyalakan dengan menggunakan pembakar pusaran model gas turbin pada keadaan atmosfera. Biodiesel dihasilkan daripada minyak sawit, kacang soya, dan kelapa melalui proses transesterifikasi. Diesel pula dipilih bagi tujuan perbandingan. Analisis spektroskopik api pusaran biodiesel menunjukkan intensiti radikal OH (Hidroksil), CH (Carbyne), C_2 (Karbon Diatomik) and CN (Cyanido) yang lebih tinggi berbanding dengan diesel. Penurunan suhu angin pembakaran mengurangkan nitrik oksida (NO) tetapi meningkatkan perlepasan karbon monoksida (CO) disebaliknya bagi semua bahan api yang dikaji. Pada suhu angin pembakaran 250 °C, biodiesel melepaskan NO kira-kira 20-60% lebih tinggi daripada diesel bagi nisbah kesetaraan (ϕ) 0.65-0.9. Pada keadaan hampir stoikiometri pula, biodiesel menghasilkan CO yang lebih tinggi daripada diesel. Kajian ini juga menunjukkan bahawa biodiesel meningkatkan kestabilan api pusaran berbanding dengan diesel pada campuran udara/bahan api miskin. Di samping itu, penyelidikan ini juga mengkaji sifat-sifat pembakaran campuran biodiesel sawit (PME) dan gas asli (NG) dengan menggunakan pembakar pusaran. Api pusaran PME/NG pada nisbah input tenaga haba 90/10, 80/20 dan 70/30 menghasilkan ciri-ciri spektroskopik yang hampir sama dengan PME. Walaubagaimanapun, intensiti radikal PME/NG adalah lebih tinggi daripada PME. Pembakaran 70/30 PME/NG menurunkan pencemar NO sebanyak 2-3.5 kali ganda berbanding dengan diesel dan PME. Namun demikian, penambahan NG didapati melemahkan kestabilan api pusaran PME. Kesan variasi sudut pusaran ke atas pembakaran PME and PME/NG turut dikaji. Pencemar NO and CO didapati menurun sebanyak 4 kali ganda apabila sudut pusaran meningkat daripada 45° ke 60°. Disebaliknya, pencemar-pencemar tersebut nenurun sebanyak 1.5-2 kali ganda apabila sudut pusaran dikurangkan daripada 45° ke 30°. Model empiric juga diperkenalkan dalam kajian ini untuk meramalkan pencemar NO dan CO yang dihasilkan daripada pembakaran PME and PME/NG bagi pelbagai nisbah NG dan sudut pusaran. Dalam penyelidikan ini, biodiesel ketepuan tinggi didapati menghasilkan NO lebih tinggi daripada biodiesel ketepuan rendah sebanyak 3.1 g/kWh secara purata. Biodiesel menghasilkan api berwarna biru manakala diesel menghasilkan api oren-kuning yang menandakan kewujudan jelaga. Walaubagaimanapun, jelaga tersebut didapati hilang apabila sudut pusaran meningkat daripada 45° ke 60°. Penyelidikan ini menunjukkan bahawa pembakaran PME/NG dengan sudut pusaran 60° dan nisbah NG 30% merupakan cara yang menjanjikan penurunan emisi NO terhadap PME. Biodiesel dan campuran PME/NG adalah bahan api gantian yang unggul untuk gas turbin kegunaan industri yang beroperasi pada campuran udara/bahan api miskin.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

3D	-	Three dimensional
AFR	-	Air fuel ratio
AFR_s	-	Stoichiometric air fuel ratio
ALR	-	Air-to-liquid ratio
ATDC	-	After top-dead-centre
B	-	Number of double bonds
B99/B100	-	Neat biodiesel
BTL	-	Biomass-to-liquid
Bx	-	x% biodiesel blend (by volume)
C	-	Numbers of carbon
	-	Carbon mass proportion
	-	Carbon atom/radical
C_2	-	Diatomic carbon radical
C_2H_2	-	Acetylene
C_2H_3	-	Ethenyl radical
C_2H_4	-	Ethylene
C_2H_5	-	Ethyl radical
C_2H_6	-	Ethane
C_3H_2	-	Propynyl
CA	-	Crank angle
CCD	-	Charged coupled device
CH	-	Carbyne radical
CH_2	-	Carbene radical
CH_2NH	-	Methanimine
CH_2N_2	-	Diazomethane
CH_3	-	Methyl radical
CH_4	-	Methane

CI	-	Compression ignited
CL	-	Chain length
Cl	-	Chloride
CN	-	Cyanido radical
	-	Cetane Number
CNG	-	Compressed natural gas
CO	-	Carbon monoxide
CO_2	-	Carbon dioxide
CME	-	Coconut methyl ester/biodiesel
CRZ	-	Corner recirculation zone
CTRZ	-	Central toroidal recirculation zone
DOU	-	Degree of unsaturation
E85	-	85/15 volume-based ethanol/gasoline blend
EU-28	-	European Union of 28 member states
FB	-	Flow-Blurring
FT	-	Fischer-Tropsch
H	-	Hydrogen mass proportion
	-	Hydrogen atom/radical
H_2O	-	Water
H/C	-	Hydrogen-to-carbon ratio
HCN	-	Hydrogen cyanide radical
H_2CN	-	Amidogen
HRJ	-	Hydroprocessed renewable jet-fuel
HVO	-	Hydrogenated vegetable oil
IATA	-	International Air Transport Association
IEA	-	International Energy Agency
K	-	Potassium
Ka	-	Karlovitz number
KH	-	Kelvin-Helmholtz
KOH	-	Potassium hydroxide

LDV	-	Laser doppler velocimetry
Le	-	Lewis number
LFL	-	Lower flammability limit
LHV	-	Lower heating value
LPP	-	Lean premixing and prevaporising
MGT	-	Micro gas turbine
MW	-	Molecular weight
N	-	Nitrogen atom/radical
N_2	-	Nitrogen
N_2O	-	Nitrous oxide radical
Na	-	Sodium
NCN	-	Cyanonitrene radical
NCO	-	Cyanato radical
NG	-	Natural gas
NH	-	Imidogen radical
NNH	-	Diazenyl radical
NO	-	Nitric oxide
NO_x	-	Nitrogen oxide
O	-	Oxygen mass proportion
	-	Oxygen atom/radical
O_2	-	Oxygen
O/C	-	Oxygen-to-carbon ratio
OH	-	Hydroxyl radical
PAH	-	Polycyclic aromatic hydrocarbon
PDA	-	Phase doppler anemometry
PID	-	Proportional-Integral-Derivative
PIV	-	Particle image velocimetry
PM	-	Particulate matter
PME	-	Palm methyl ester/biodiesel
Re	-	Reynolds number

RME	-	Rapeseed methyl ester/biodiesel
SMD	-	Sauter mean diameter
SVO	-	Straight vegetable oil
SO_2	-	Sulphur dioxide
SO_x	-	Sulphur oxide
SME	-	Soybean methyl ester/biodiesel
UHC	-	Unburned hydrocarbons

LIST OF SYMBOLS

Roman Letters

D	-	Diameter
D_h	-	Swirler hub diameter
D_s	-	Swirler diameter
K	-	Reaction constant
Q	-	Heat
$\dot{Q}$	-	Heat release rate
S_L	-	Laminar flame speed
S_G	-	Geometric swirl number
T	-	Absolute temperature
$\dot{V}$	-	Volume flow rate
k	-	Reaction constants
$\dot{m}$	-	Mass flow rate
t	-	Residence time scale of reaction products
x	-	Mass fraction

Greek Letters

δ_q	-	Propagated error
δ_x	-	Uncertainty associated with parameter x
η	-	Efficiency
Δt	-	Time interval.
ϕ_{NG}	-	Equivalence ratio for premixed natural gas
ϕ	-	Equivalence ratio
ρ	-	Density
θ	-	Angle

Subscripts

G	-	Geometric
HV	-	Heating value
L	-	Laminar
NG	-	Natural gas
PME	-	Palm methyl ester
S	-	Swirler
a	-	Air
c	-	Combustion
f	-	Fuel
h	-	Hub
i	-	Species i
q	-	Overall
s	-	Swirler
x	-	Parameter x

CHAPTER 1

INTRODUCTION

1.0 Background

Stringent emission requirements along with finite fossil fuel reserves and global decarbonisation efforts have prompted many countries to look into biomass-derived alternative fuels, owing to their potentially carbon neutral, cleaner emissions and sustainable feedstock supply [1, 2]. Figure 1.1 compares the carbon cycle of fossil fuels against that of biomass-derived alternative fuels. It can be observed that carbon dioxide (CO_2) produced by alternative fuels from combustion could be recycled for use in plant growth, achieving a potentially carbon neutral cycle. On the other hand, CO_2 produced from combustion of fossil fuels typically only ends up being expelled into the atmosphere, which undesirably elevates the CO_2 concentration in the atmosphere. Aside from the difference in CO_2 lifecycle, regulated emissions compounds, such as sulphur dioxide (SO_2), particulate matter (PM) and CO, from combustion of biofuels are substantially lower than those of fossil fuels [3].

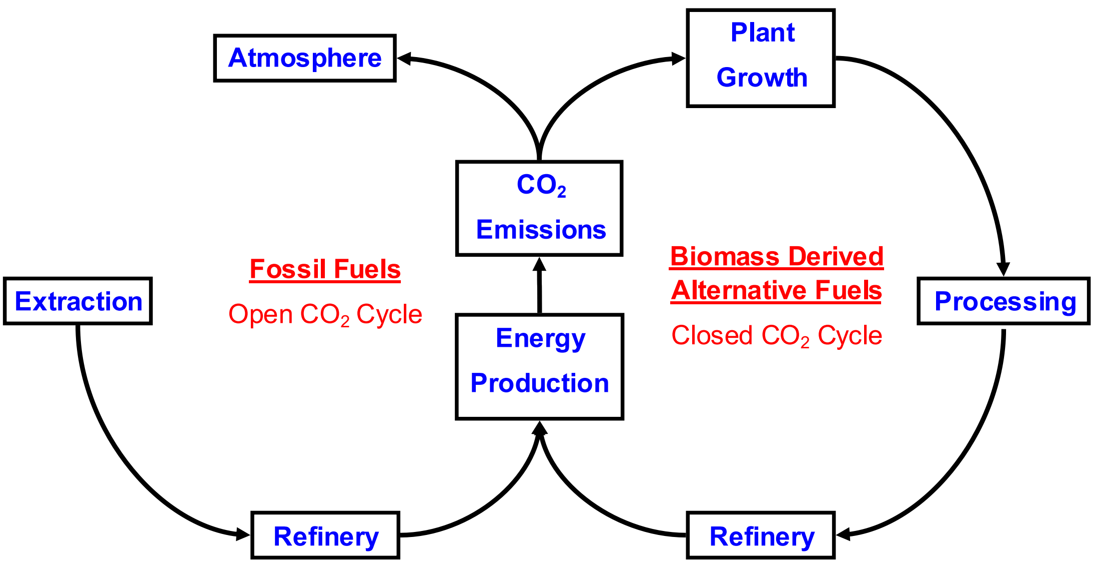

Figure 1.1 CO_2 lifecycle comparisons between fossil fuels and alternative fuels.

In view of the advantages by moving towards biofuels, global bio-energy generation has been observed to exhibit an increasing trend from the year 2006 to the year 2016 throughout major continents in the world, as illustrated in Figure 1.2 [4]. European Union of 28 member states (EU-28) recorded a 115.38 TW-h increase in bio-energy generation over the decade, followed by Asia, South America and North America with 67.31 TW-h, 51.91 TW-h and 16.95 TW-h of escalation in bio-energy generation, respectively [4]. Despite distinct advantages and growing interests over such alternative fuels, the use of biofuels is still not yet as extensive as expected at the present stage. This is mainly due to the higher production cost as compared to the lower fossil fuel price.

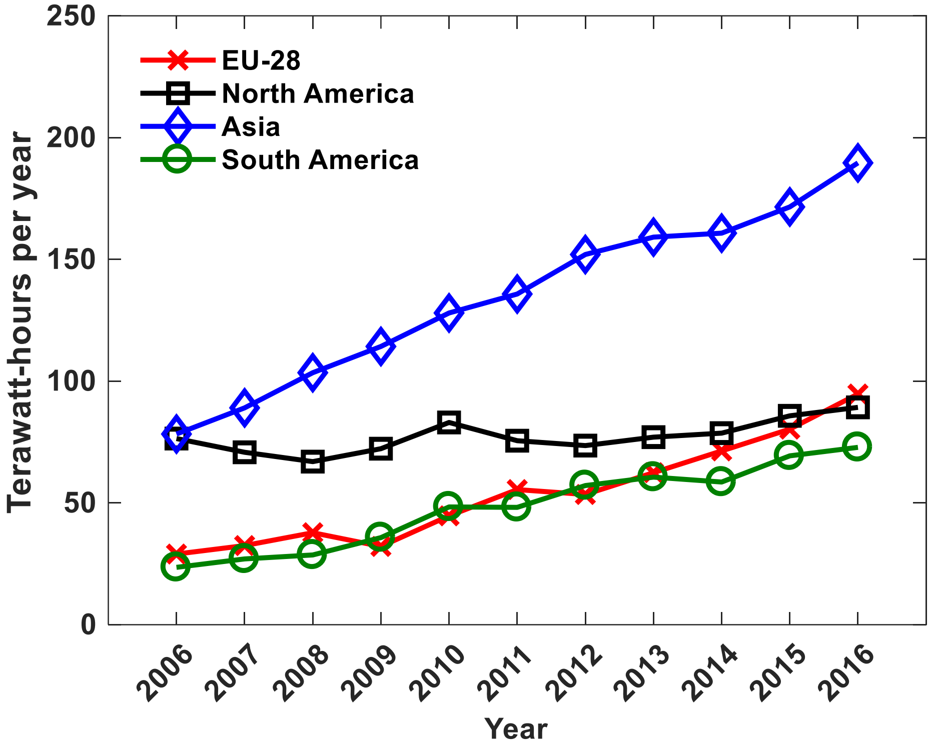

Figure 1.2 Global bio-power generation by regions from 2006 to 2016 (extracted from [4]).

Figure 1.3 compares the prices between diesel and compressed natural gas (CNG) against biodiesel (B99/B100) and 85/15 ethanol/gasoline blends (E85) from the year 2000 until the year 2017 in U.S. [5]. It is shown that biodiesel and bioethanol are consistently more expensive than diesel. Hence, owing to the fuel price deficit, this leaves the utilisation of biofuels at the present stage to be mainly driven only by environmental policy, through blending mandate with fossil fuels at low percentage

[4]. In the European Union, blending legislations are implemented in countries such as Latvia (B7, 7/93 biodiesel/diesel blends) Finland (B5.75), Italy (B5), Norway (B3.5) and the Netherlands (B4) [6, 7]. Among South East Asian countries, blending mandates are implemented in Malaysia, Indonesia and Thailand with emphasis on B7, B20 and B7 blends, respectively [8]. Meanwhile, America, Argentina, Brazil, Canada and Colombia each has current biodiesel mandates of B10, B8, B2 and B10, respectively [8].

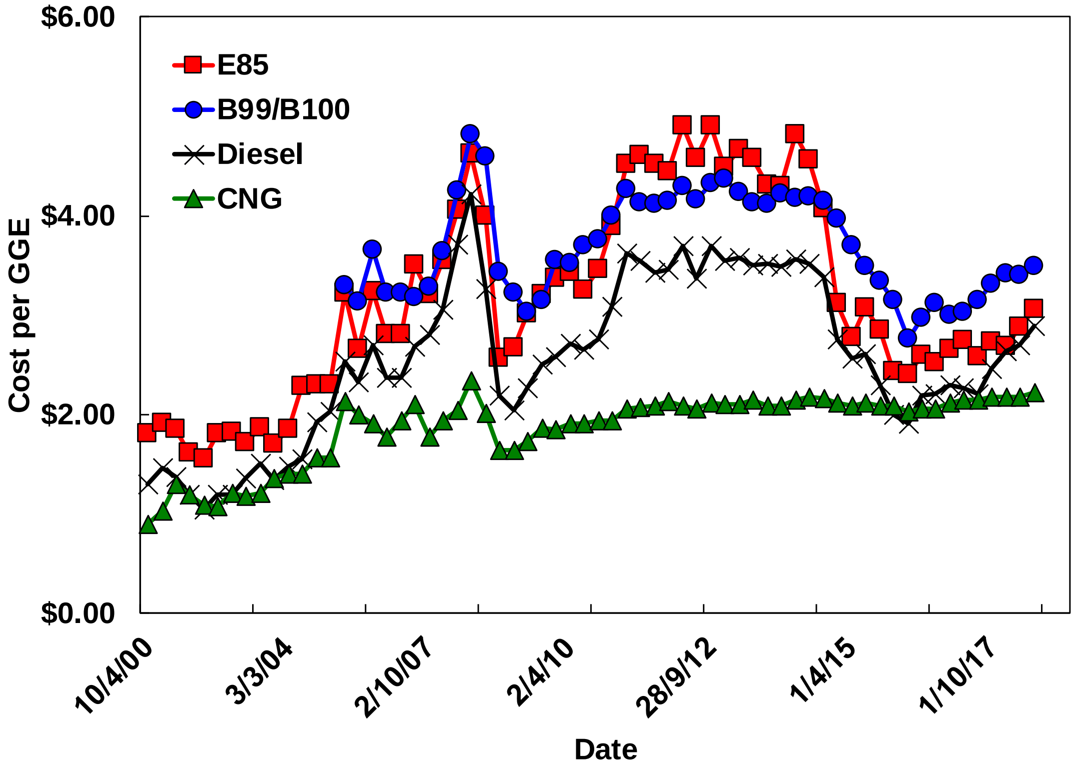

Figure 1.3 Fuels price of various fuels from year 2000 to 2017 in U.S. [5].

In December 2015, utilisation of alternative fuels was pushed forward by the United Nation's Conference on Climate Change in Paris. The conference gathered governments and business leaders from nearly 200 nations where an ambitious goal was set to keep global temperature rise well below 2 ºC. The decision concurrently marked the end of the fossil fuel era and encouraged more investment in renewable energy [9]. Investments in developing production technologies to increase alternative fuels uptake will encourage the development of more environmental friendly production processes and subsequently reduce the production cost through economy of scales [10].

The drive to increase the utilization of alternative fuels also affects the use of gas turbine as the power plant in engineering applications. Gas turbine was originally started exclusively for use in the aviation industry in 1960s. The invention is a combined cycle power plant that merges gas and steam turbines together. It has effectively elevated energy conversion efficiency up to 60% [11, 12], making the cycle power plant into an important power generation system. Figure 1.4 shows that the capacity factor of combined cycle plants powered by NG has increased by an average of 21% from the year 2005 to the year 2015 [13]. The increase in gas turbine usage capacity also implicitly gives rise to greenhouse gases production. Considering the downside of massive greenhouse gases escalation, recent gas turbine development has also began to focus on fuel-flexible technologies, enabling the usage of clean and sustainable biofuels in gas turbines [14, 15], in-line with the direction set during United Nation's Conference on Climate Change in Paris. This also ensures that the current gas turbine could be accommodated to the present rigorous emissions legislations.

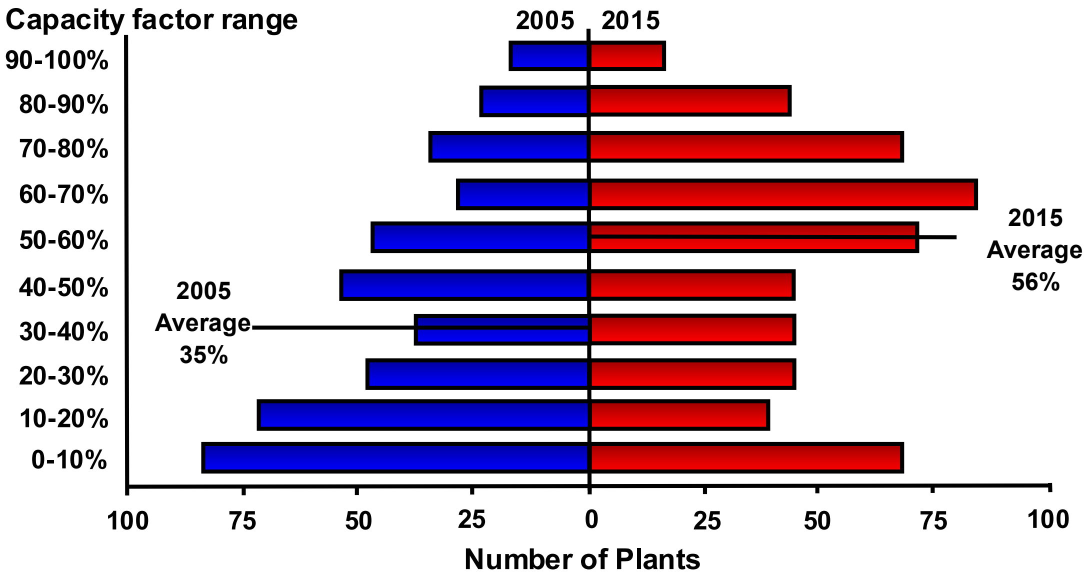

Figure 1.4 Annual capacity factor comparison for NG combined-cycle plants in U.S. (adapted from [13]).

At present, one of the most researched on alternative fuels come in the form of biodiesel. Recent forecast by International Energy Agency (IEA) has also unveiled that the demand on biodiesels is expected to grow by a factor of approximately seven in the year 2035 [16]. This alternative fuel is mainly produced via transesterification process, where alcohol and catalyst are used to convert triglycerides into glycerol and biodiesel at elevated temperature condition. In the automotive industry, biodiesel has been deemed a viable alternative fuel option for compression ignition engine usage to meet future energy demand and stringent emissions requirements [17]. This is because even though the lower heating value (LHV) of biodiesel is approximately 11% lower than that of fossil diesel (see Figure 1.5), the density of biodiesel is still roughly 3% higher than that of diesel, making it a potentially useful alternative fuel to be blended with diesel for compression ignition engines. However, as highlighted in Figure 1.6, due to the lower calorific value and higher fuel density against typical jet fuel requirements, biodiesel currently has a restricted usage in aviation gas turbine [18]. On the contrary, land-based gas turbine for industrial application is fuel-robust in nature, which potentially enables the use of biodiesel in such power plants [19].

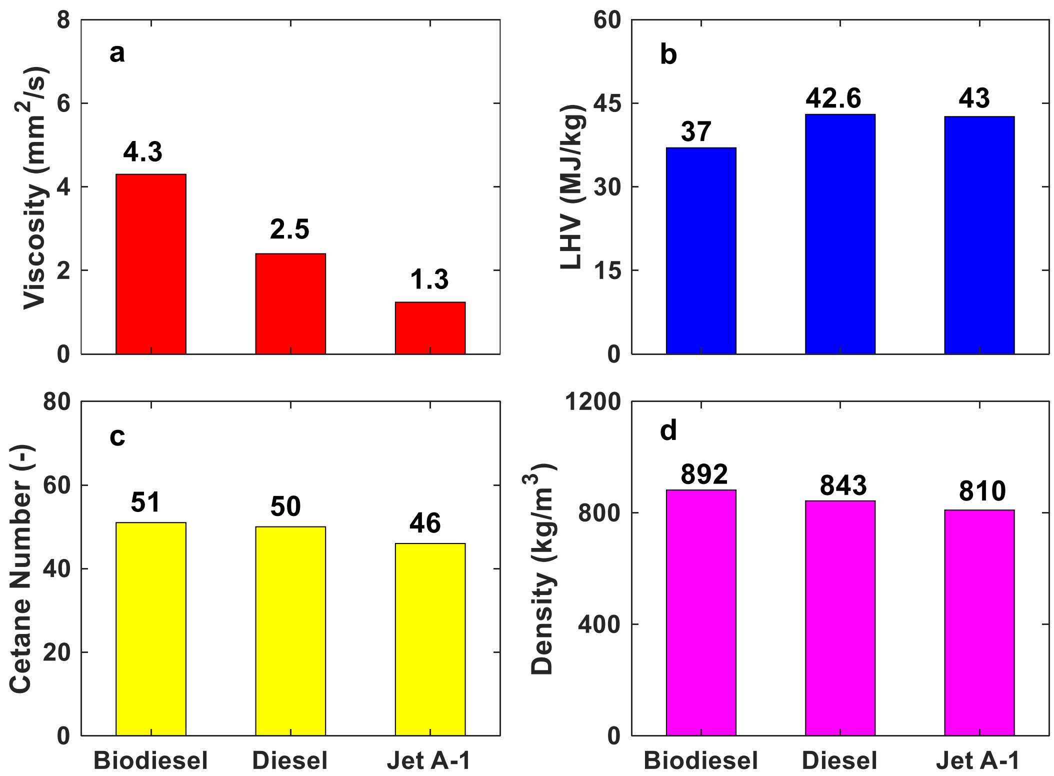

Figure 1.5 Comparison of fuel properties between biodiesel, diesel and Jet A-1 (adapted from [19]).

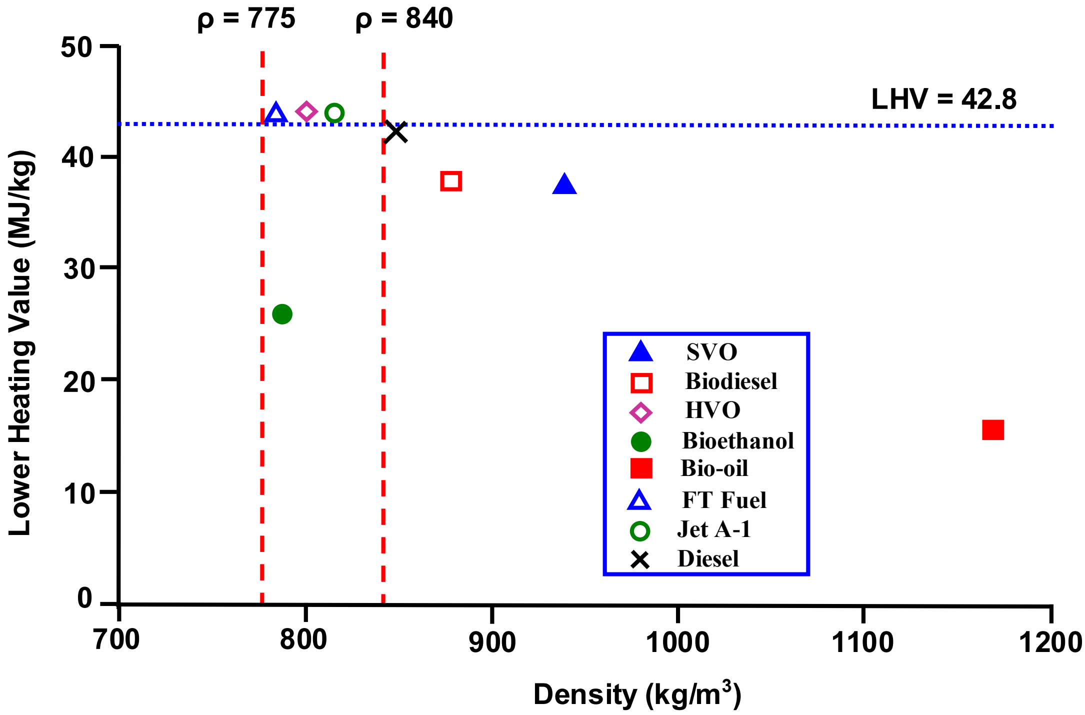

Figure 1.6 Relationship between LHV and density for range of liquid fuels showing limits jet fuel specification (adapted from [18, 19]).

In view of the potential benefits of adopting biodiesel as an alternative fuel, the present study aims to ascertain the combustion characteristics of biodiesel under momentum-controlled swirl flame condition, typically encountered in a gas turbine system. Besides this, considering economic advantages and cleaner emissions of NG, the study will also examine the fundamental combustion characteristics of biodiesel when blended with NG.

1.1 Problem statements

1. How would variation in biodiesel physio-chemical properties and burner operating parameters affect its combustion characteristics under reacting swirl spray condition?
2. How would NG addition affect combustion characteristics of biodiesel swirl flame?
3. How would variation in swirl vane angle affect combustion characteristics of biodiesel and biodiesel/NG swirl flame?

1.2 Objectives

To answer these questions, three objectives have been identified:

1. To determine spectroscopic, emissions and lean blowout characteristics of various degree of freedom (DOU) biodiesel under reacting swirl flame condition.
2. To assess the biodiesel swirl flame characteristic of biodiesel when blended with NG under atmospheric condition.
3. To ascertain the effect of swirl vane angle on biodiesel and biodiesel/NG combustion characteristic.

By the end of the study, it is expected that the findings obtained could be applied in determining the optimum usage of biodiesel and biodiesel/NG fuel under reacting swirl flame conditions. Based on this, suitable application could also be proposed accordingly.

1.3 Research scope

This research contains three objectives. The first objective examines biodiesel reacting swirl spray characteristics using a model gas turbine swirl burner. A lab-scale swirl burner is chosen due to its capability of simulating reacting flow in the gas turbine. This also enables the use of spectrometer through optical accessible quartz glass. Biodiesel derived from coconut, palm and soybean vegetable oils are chosen for this research. The DOU for these vegetable oils vary from 0.12 to 1.59, enabling the present study to examine the effect of DOU on biodiesel combustion characteristics. The biodiesels are produced in-house via alkaline-catalysed transesterification. The No. 2 type diesel fuel, which is typically used in truck, is chosen as the baseline fuel. The study on biodiesel swirl flame includes flame imaging, spectroscopic quantification and analysis of combustion intermediate species, specific emissions quantification and lean blowout analysis.

The same framework is subsequently extended to study biodiesel/NG dual fuel combustion, which is the second objective of this research. NG is chosen as secondary fuel due to its economic advantage and cleaner emissions when compared with that of diesel [20, 21]. Three biodiesel/NG blending proportions are examined in this study, namely 90/10, 80/20 and 70/30. The blending proportions are based on the input thermal power, where contributions of NG to total input thermal power is varied from 10-30% [22]. The method is chosen in such a manner since both fuels are of different phases, whereas density of NG is approximately three orders of magnitude lower than that of biodiesel. This lowers the NG flow rate beyond the minimum flow range of the regulator.

The third objective of this research is to examine the effect of swirl vane angle variation on biodiesel and biodiesel/NG combustion characteristics. Swirl vane angle 30°, 45° and 60° are chosen for this study, representing low, medium and high swirling air flow, respectively. Flame appearance, radical intensities, and emissions produced under different swirl vane angles are analysed. Furthermore, empirical models are proposed to estimate emissions from biodiesel and biodiesel/NG swirl flames.

1.4 Thesis structure

This thesis consists of six chapters. Chapter 1 introduces biomass-derived alternative fuels, objectives and scopes for this research. Chapter 2 reviews relevant and significant studies on biodiesels spray combustion in gas turbine and model swirl burner. Previous studies examined the effect of swirl vane angle are also reviewed. Chapter 3 describes the experimental setup for establishing reacting swirl flame. Furthermore, fuel preparation, measurement techniques and operating conditions are also delineated in Chapter 3. Chapter 4 and 5 present results, analysis and discussions from the experimental investigations of biodiesels and biodiesel/NG combustions, respectively. Chapter 6 presents the findings from swirl vane angle investigations. Finally, conclusions and suggestions for future research based on the present findings are provided in Chapter 7.

1.5 Research contributions

This research will contribute towards improving the fundamental understandings on:

1. The effects of biodiesel DOU, main air temperature, global flame equivalence ratio and air-to-liquid ratio (ALR) on biodiesel flame appearance, combustion intermediate species, post-combustion emissions and lean blowout limit under the reacting swirl spray conditions.
2. The effects of NG proportions, global flame equivalence ratio and ALR on fundamentals combustion characteristics of a biodiesel/NG swirl flame.
3. The effects of swirl vane angle variation on biodiesel and biodiesel/NG combustion characteristics under atmospheric conditions.

1.6 Research hypothesis

1. Variation in biodiesel physio-chemical properties, such as degree of unsaturation (DOU), volatility and viscosity will affect its combustion characteristics.
2. Burner operating parameter, such as global flame equivalence ratio, atomiser air-to-liquid ratio (ALR) and main air temperature, will alter biodiesel and biodiesel/NG combustion characteristics.
3. NG addition into biodiesel swirl flame, at optimum blending proportion and swirl vane angle, will improve the combustion characteristics of the dual fuel combination.

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LIST OF PUBLICATIONS

Refereed Journal Articles:

1. **Meng Choung Chiong**, Cheng Tung Chong, Jo-Han Ng, Su Shiung Lam, Manh-Vu Tran, William Woei Fong Chong, Mohammad Nazri Mohd Jaafar, Agustin Valera-Medina (2018). Liquid Biofuels Production and Emissions Performance in Gas Turbines: A Review. Energy Conversion and Management, vol. 173, pp. 640-658.
2. **Meng Choung Chiong**, Cheng Tung Chong, Jo-Han Ng, Manh-Vu Tran, Su Shiung Lam, Agustin Valera-Medina, Mohammad Nazri Mohd Jaafar (2018). Combustion and Emission Performances of Coconut, Palm and Soybean Methyl Esters under Reacting Spray Flame Conditions. Journal of the Energy Institute, vol. 92(4), pp. 1034-1044.
3. Cheng Tung Chong, **Meng-Choung Chiong**, Jo-Han Ng, Mook Tzeng Lim, Manh-Vu Tran, Agustin Valera-Medina, William Woei Fong Chong. Oxygenated Sunflower Biodiesel: Spectroscopic and Emissions Quantification under Reacting Swirl Spray Conditions. Energy, vol. 178, pp. 804-813.

Conference Abstracts:

1. **Meng Choung Chiong**, Zhe Yong Teyo, Jo-Han Ng, Manh-Vu Tran, Agustin Valera-Medina, Cheng Tung Chong. Pool Fire Burning Characteristics of Palm, Soy and Coconut Biodiesels. *6th Conference on Emerging Energy & Process Technology 2017.* Johor Bahru. 27-28th November 2017. (Oral Presentation)
2. **Meng Choung Chiong**, Jo-Han Ng, Mohammad Nazri Mohd Jaafar, Agustin Valera-Medina, Cheng Tung Chong. Combustion and Emission Characteristics of Palm, Soy and Coconut Methyl Esters under Swirling Spray Flame Conditions. *6th Conference on Emerging Energy & Process Technology 2017.* Johor Bahru. 27-28th November 2017. (Oral Presentation)