UNIVERSITI PUTRA MALAYSIA

PLASMA COMBUSTION TECHNOLOGY FOR MICRO GAS TURBINE USING KUWAITI SHEEP FAT BIODIESEL

AHMAD M R N ALRASHIDI

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By

AHMAD M R N ALRASHIDI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

I want to dedicate this project to my beloved family, all my supervisors and lecturers at the Department of Mechanical Engineering and my friends for their guidance and unwavering support. They have been a great inspiration for the actualization of this; Isearch work, I say thank you all

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman : Professor Nor Mariah Adam, PhD PE
Faculty : Engineering

The technology of using only fossil fuel in the operation of a gas turbine engine is facing issues that include low thermal efficiency, poor atomization, low vapour pressure, and high greenhouse gases (GHG). Thus the research motivation is to restructure the design principle of gas turbines for enhancing performance, fuel consumption reduction and GHG emission reduction of a gas turbine. Hence the main objective of this research is to investigate the impact assessment of the plasma combustion technology for a micro gas turbine (MGT) using biodiesel fuel. This is achieved through external integration of hybrid plasma-rich mixture injection at the compressor inlet of the engine system for enhanced combustion of biodiesel fuel through improved thermal efficiency by eight percent. In view of this, the specific objectives are (1) To fabricate, develop and assemble a mini gas turbine (MGT) engine system with an external integrated hybrid Plasma-Torch-Ultrasonic atomizer at the compressor inlet point of the 50kW (67hp) MGT engine in the laboratory. (2) To conduct characterization of Kuwaiti sheep fat biodiesel for the MGT engine operation. (3) To evaluate and validate the combustion performance of the fabricated MGT engine and GHG emission reduction. The methodology involved the design, fabricating and assembling of individual systems (turbo charger, compressor system, ignition system, ultrasound-assisted atomizing system, external integration of hybrid plasma-rich fuel injection at the compressor system, inlet air inlet, oil system, and control unit) for the 50 kW (67hp) MGT test bed in the laboratory. The MGT test bed was meticulously designed with an increase in distance between the inlet of the micro gas turbine engine and plasma torch nozzle and tested for stability with the expansion of the inlet to reduce the speed of air entry. This ensures repeatability, reliability, and accurate data acquisition through in-depth experimental design with output data of components consistent with literature thus fulfilling Objective 1 of this thesis. Secondly, fuel characterization (specific gravity, density, kinematic viscosity, total acid number, water content, total sulfur, flash point, lubricity, cloud point, pour point, calcium and magnesium content was according to the American Society for Testing and Materials (ASTM) standards for six fuels (kerosene, diesel, blends of Kuwaiti sheep fat biodiesel (B20, B50, B75 and B100) performed at the Petroleum Research Center, Kuwait Institute for Scientific Research. Results showed biodiesel has higher kinematic viscosity and density than diesel and kerosene; flash point (B75) closest to kerosene and acid number (B20) value 0.03206 mgKOH/gm in compliance to the ASTM D6751 and EN 14214 standard limits of 0.5 mgKOH/gm that indicates minimal nitrogen and sulphur emissions (less soot). These results show that blended biodiesel is suitable for MGT fuel thus Objective 2 of the thesis is achieved. The MGT engine's general performance for all loading conditions when operated under integrated plasma-rich fuel mixture injection with evaluated results (a) fuel consumption was generally 9% lower than normal conditions higher than pledged value of 1.5% (b) thrust value under normal condition is 1.7 - 4.2 kgf and 1.8 - 4.35 with plasma system (c) achieved average thermal efficiency for biodiesels 15 – 18% higher than 8% as pledged. (d) achieved GHG emissions on average 0.07% for CO; 3% for CO_2; 5% for NO; and 10% for NO_2. (e) B100 exhibits the highest compressor outlet temperature, highest compressor output pressure and best performance in fuel flow rate suggesting unique but desirable features of biodiesel fuel for MGT. Thus the efficacy of integrated plasma-rich fuel mixture assisted combustion operation is presented that fulfils Objective 3 of the thesis. Therefore, Alternative hypothesis H_1 ($\mu_o \neq \mu_1$): Intake integration of hybrid plasma-rich fuel mixture at the compressor inlet of mini gas turbine (MGT) engine with assisted ultrasonic atomiser does improve engine performance and exhaust GHG emissions level control is accepted. The findings of this study can serve as a potential technology for improving the efficiency of fuel combustion and ignition in GT engines. It also presents an efficient way of using sustainable renewable sources of energy (animal fat biodiesel) as a means of reducing GHG emissions level.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PLASMA UNTUK TURBIN GAS MIKRO MENGGUNAKAN BIODIESEL LEMAK BEBIRI KUWAIT

Oleh

AHMAD M R N ALRASHIDI

Ogos 2021

Pengerusi : Profesor Nor Mariah Adam, PhD PE
Fakulti : Kejuruteraan

Teknologi penggunaan bahanapi fosil tunggal untuk operasi enjin gas turbin mengalami isu kecekapan termal yang rendah; pengabusan lemah; tekanan wap yang rendah; gas rumah hijau (GHG) yang banyak adalah menjadi motivasi penyelidikan untuk penstrukturan semula prinsip rekabentuk turbin gas agar prestasi enjin dipertingkatkan; pengurangan penggunaan bahanapi serta pengurangan pelepasan gas turbin. Oleh itu objektif utama kajian ini adalah mengkaji kesan impak teknologi pembakaran plasma untuk gas turbin mikro (MGT) yang menggunakan bahanapi biodiesel dengan cara suntikan campuran bahanapi kaya plasma secara bersepadu kedalam salur masuk pemampat enjin turbin gas mini yang dibantu pengabus ultrasonik dari luar enjin supaya meningkatkan pembakaran bahanapi dengan cara meningkatan kecekapan termal sebanyak lapan peratus. Maka objektif spesifik adalah (1) Membina, membangunkan dan membuat pemasangan sebuah sistem enjin gas turbin mini (MGT) yang dipasang secara luaran system bersepadu bagi kemasukan campuran bahanapi kaya melalui obor plasma ke dalam salur masuk pemampat (*compressor*) yang dibantu pengabus ultrasonik (2) aktiviti mencirikan (*characterization*) biodiesel lemak bebiri Kuwait untuk mengenal pasti kesesuaian sebagai bahanapi enjin MGT engine (3) menilai dan mengesahkan prestasi pembakaran dan pengurangan pelepasan GHG enjin MGT yang telah dipasang. Kaedah kajian melibatkan membina, merekabentuk dan pemasangan sistem tersendiri (*turbo charger*, sistem pemampat, sistem penyalaan, sistem pengabusan bantuan ultrasonic, pemasangan luaran bersepadu yang memberi suntikan campuran bahanapi kaya plasma ke dalam salur masuk pemampat enjin sistem pemampat, sistem kemasukan udara, sistem bahanapi, unit kawalan) untuk MGT berkenaan dengan keupayaan 50 kW (67hp) *testbed* MGT di dalam makmal. Penghasilan testbed MGT telah dilakukan dengan teliti dan rapi, serta telah diuji untuk kestabilan, kebolehulangan (*repeatability*), kebolehharapan, penghasilan data yang tepat dan jitu melalui rekabentuk eksperiman yang mendalam untuk menghasilkan output data yang bertepatan

dengan literatur dan seterusnya memenuhi keperluan Objektif 1 tesis. Kedua, kaedah mencirikan (*characterization*) bahanapi (gravity tentu, ketumpatan, viscositi kinematik, nombor total asid, kandungan air, jumlah sulfur, titik flash, lubrisiti, *cloud point, pour point*, kandungan kalsium dan magnesium menurut standard Persatuan Pengujian dan Bahan Amerika (ASTM) untuk enam jenis bahanapi (minyak tanah, diesel, campuran biodiesel lemak bebiri Kuwaiti (B20, B50, B75 dan B100) telah dijalankan oleh *Petroleum Research Center, Kuwait Institute for Scientific Research.* Keputusan menunjukkan bahawa biodiesel mempunyai kinematic viscosity dan ketumpatan yang tinggi daripada diesel dan minyak tanah; nilai titik kilat (B75) paling hampir minyak tanah dan nombor asid (B20) adalah 0.03206 mgKOH/gm yakni memenuhi *compliance* standard ASTM D6751 dan had standard EN 14214 standard 0.5 mgKOH/gm membawa maksud nilai pelepasan nitrogen dan sulfur adalah tersangat rendah (kurang jelaga). Hasil keputusan ini menunjukkan campuran biodisesel yang dibangunkan sangat sesuai sebagai bahanapi MGT maka Objektif 2 tesis telah tercapai. Secara keseluruhan prestasi enjin MGT untuk semua keadaan beban semasa operasi suntikan campuran bahanapi kaya plasma secara bersepadu telah dinilai dengan keputusan (a) penggunaan bahanapi secara am adalah pengurangan 9% daripada keadaan biasa yakni lebin tinggi daripada nilai ketetapan 1.5% (b) nilai thrust semasa keadaan biasa adalah (1.7 - 4.2 kgf) berbanding (1.8 - 4.35 kgf) dengan penggunaan sistem plasma (c) pencapaian kecekapan termal purata untuk biodiesel adalah (15 – 18%) melebihi nilai 8% yang dijanjikan (d) pencapaian purata pelepasan GHG 0.07% untuk CO; 3% untuk CO_2; 5% untuk NO; dan 10% untuk NO_2 (e) B100 mempamerkan suhu dan tekanan keluaran pemampat tertinggi dengan prestasi kadar alir bahanapi unggul meramalkan ciri idaman bahanapi biodiesel untuk MGT. Yang demikian, efikasi campuran bahanapi kaya plasma secara bersepadu yang dibantu pengabus bantuan ultrasonik telah memenuhi Objektif 3 tesis. Maka, Hipotesis alternatif H_1 ($\mu_o \neq \mu_1$): kemasukan campuran bahanapi kaya plasma secara bersepadu kedalam salur masuk pemampat enjin turbin gas mini yang dibantu pengabus ultrasonik dapat meningkatkan prestasi enjin dan pelepasan GHG ekzos ke tahap rendah adalah diterima. Hasil kajian ini menunjukkan teknologi berpotensi untuk meningkatkan kecekapan pembakaran bahanapi dan penyalaan enjin turbin gas. Ianya juga menengahkan kaedah cekap sumber tenaga bolehdiperbaharui yang lestari (biodiesel lemak haiwan) sebagai cara mengurangkan pelepasan GHG.

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Thank you all

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Nor Mariah binti Adam, PhD PE
Professor, Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Abdul Aziz bin Hairuddin, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohd Khairol Anuar bin Mohd Ariffin, PhD PE
Professor, Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Abdullah M. A. SH. M Alajmi, PhD
Assistant Professor
Public Authority of Applied Education and Training
Kuwait
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 14 April 2022

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ______________________________

Name of Chairman of Supervisory Committee: Professor Ir. Dr. Nor Mariah binti Adam

Signature: ______________________________

Name of Member of Supervisory Committee: Associate Professor Dr. Abdul Aziz bin Hairuddin

Signature: ______________________________

Name of Member of Supervisory Committee: Professor Ir. Dr. Mohd Khairol Anuar bin Mohd Ariffin

Signature: ______________________________

Name of Member of Supervisory Committee: Dr. Abdullah M. A. SH. M Alajmi

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

ASTM	America Society for Testing and Materials
B100	pure biodiesel
B20	kerosene + biodiesel (80:20)
B50	kerosene + biodiesel (50:50)
B75	kerosene + biodiesel (25:75)
Br	bromine
BV	break down voltage
C/H	carbon / hydrogen rate
CO	carbon monoxide
C_2H_2	ethane
C_2H_5 OH	ethanol
C_3H_7 OH	propanol
C_4H9 OH	butanol
Ca	calcium
CCD	charged-coupled device
CH	hydro carbon
CH_3OH	methanol
CH_4	methane
Cl	chlorine
CO	carbon monoxide
CO_2	carbon dioxide
COV	coefficient of variance
CP	cloud point

Cu	copper
DBD	dielectric barrier discharge
DP	discharge power
ECR	electron cyclotron resonance
EEDF	electron energy distribution function
F	fluorine
FEM	finite element method
GT	gas turbine
H_2	hydrogen
H_2O	water
ICEs	internal combustion engines
K	potassium
LCV	low calorific value
LHV	low heating value
LP	langmuir probe
MAS	mixed air steam
N_2	nitrogen
Na	sodium
NH_3	ammonia
NO	nitric oxide
NO_X	nitrogen oxide
NRP	nanosecond repetitively pulsed
NRPP	nanosecond repetitively pulsed plasma
MGT	micro gas turbine

O_2	oxygen
O_3	ozone
OES	optical emission spectroscope
OH	hydroxide
PAH	polyaromatic hydrocarbons
PM	particulate matter
PP	pour point
PT	plasma technology
SO_x	Sulphur oxides
UAV	unmanned aerial vehicle
UHC	un-burnt hydrocarbons
UHF	ultra-high frequency
VT	vibrational temperature
Zn	zinc
ZSM-5	shape-selective catalyst

CHAPTER 1

INTRODUCTION

1.1 Background of Study

A typical gas turbine is characterized by a continuous-flow engine and steady flame production during the combustion process with high hydrocarbon emissions from using conventional fossil fuel resources. Although these emissions may impact negatively on the environment by depleting the ozone layer, the gas-turbine architecture permits the use of various fuels that also ensures complete combustion in the engine where some of these features include moderate compression ratios, robust mechanical designs and versatile combustion systems that enhance the potential to utilize a wide variety of biofuels such as alcohols, bio-diesel, low calorific value (LCV) gasified biomass, synthetic gas, hydrogen and natural gas. It is worth mentioning that fuel properties influence the performance efficiency of gas turbines and also determine the final composition of emitted greenhouse gases (GHG) like nitrogen-oxide (NOx), and carbon-monoxide (CO) as published (Knothe et al., 2006; Lefebvre, 1984). The current adoption of biofuels as alternative energy sources in an internal combustion engine is facilitated by the overwhelming benefits over conventional fossil fuel sources [(Gupta et al., 2010), (Habib et al., 2010), (Agarwal, 2007)].

The alternative biodiesel sources have proven to be sustainable, cheaper and environmentally friendly with a reduction in the toxic emission level [(Agarwal, 2007), Janulis, 2004)]. Biodiesel does not contain sulphur in the elemental compositions when compared with fossil fuels and has great potential to replace the ever-depleting fossil fuel energy resources (Salamanca 2012). The constant increase in the world population stimulated a relative increase in energy demands across all sectors of the global economy as also required in aerospace applications. The gas turbine also required an alternative fuel that is environmental-friendly with a lower GHG emission impact on the environment. Studies have been conducted on the biofuel application in transportation sectors for vehicles, and aerospace applications in jet engine/gas turbines [(Nayak, 2017), (Gupta et al. 2010]. Biofuel is a liquid or gaseous fuel produced from biomass, waste and other biodegradable plants materials. The technology of using only fuel in the operation of engines is inadequate due to factors ranging from low thermal efficiency, poor atomization or vitalization, the low vapour pressure that may result in rapid evaporation and high operation cost leading to more fuel consumption (Sagás, Maciel, and Lacava, 2016). Several studies have been carried out to enhance the fossil fuel combustion processes in gas turbines (GTs) without the use of plasma technology. This motivated the current proposed study of introducing the plasma combustion technology for the micro gas turbine in combination with the biodiesel fuel.

1.2 Problem Statement

The environmental benefit associated with the application of biofuel alternative energy sources in transportation systems is gradually gaining global awareness and interest. This is reflected in ethanol usage as an alternative biofuel for automobiles in Brazil and other developed nations. Although a significant number of efforts have been vetted in the application of biofuel to power engine systems, the GHG emission control level remains a challenge as established when compared with the acceptable global standard (Yilmaz 2017). Animal fats can be considered a promising alternative source for biodiesel production, but it requires more complex processing than natural oils. In Kuwait, waste sheep fat is the main feed stock for biodiesel production that contain large amounts of free fatty acids (49.1 mgKOH/g) (Fynees Alajmi et al, 2018) which means sustainable, abundant, cheap supply and yet reduce handling and reduce impact to the environment and without economic competition like vegetable oils. There is high emission of NOx resulting from the combustion of biodiesel in a typical gas turbine system operation (Imdadul et al., 2015). Factors such as injection timing, adiabatic flame temperature, radiation heat transfer and injection delay are also responsible for higher NOx emissions in the reciprocating engine [(Imdadul et al., 2015; Narayanan and Jacobs, 2015)]. In addition, the antioxidants used in biodiesel mainly contain phenolic groups, which are more likely to form soot. In addition to glyceride impurities, even though they have the potential to burn with less soot because the biodiesel does not contain sulphur (Salamanca, 2012). The technology of using only jet fuel alone in the operation of engines is inadequate due to factors ranging from low thermal efficiency, poor atomization or vitalization, the low vapour pressure that may result in rapid evaporation and high operation cost leading to more fuel consumption (Sagás, Maciel, & Lacava, 2016). The blend ratio of 15 % of ethanol at 0.5 % emulsion has demonstrated good compatibility with 84.5 % diesel composition to produce ethanol-diesel which increases the efficiency of the engine with a thermal increment of almost 8 % as proposed by [Senthilraja et al., (2016) (Saifuddin et al., (2014)] have shown that there is potential to increase thermal efficiency by employing biodiesel in GT.

To overcome these limitations; effective deployment of biodiesel fuel in gas turbines with considerations to lower NOx emission is desired. There is a need for higher combustion temperature requirement from plasma technology for biodiesel effective combustion and enhanced performance in a gas turbine.

Plasma technology has been applied as one solution based on the principle of free electron formation under high temperatures to enhance the overall combustion efficiency in automotive engines with biofuels [(Chen, 2008), (Starikovskii, 2005)]. Over the years, the advancement of plasma technology has evolved but not for gas turbine applications. Current plasma design can easily reach very high temperatures of over 5000 ^{o}C making it viable to be used on the gas turbine. Therefore, a fundamental understanding of plasma-fuel combination as well as the correlation to the emission level is essential for optimal utilization of biofuel in GT engines. Generally, considerable progress has been made in most recent research works towards an understanding of plasma impact in the improvement of the fuel combustion process. The validation of such mechanisms was achieved through experimentation under controlled conditions and by comparing the results with numerical simulations of discharge and combustion processes. However, there is no detailed review of the recent applications of plasma in internal combustion engines, particularly in GTs engine applications. This knowledge gap is a serious setback in the advancement of the science of plasma technology application in internal combustion (IC) engines. Biodiesel from plant-based oils gives competition for food but biodiesel from animal fat wastes is cost-effective whilst reducing its impact on the environment. Also, integration of cost-effective Kuwaiti sheep fat biodiesel and plasma technology in the operating of GT engines is lacking [(Alajmi et al 2017), ((Zakaria & Kamarudin, 2016), (Tropina et al., 2016), (Serbin et al., 2011). (Takita, Abe, Masuya, & Ju, 2007)]. Therefore, this research aims to investigate the feasibility of using novel external integration of hybrid plasma-rich fuel mixture injection at the compressor inlet to enhance effective GT operation efficiently with reduced GHG emission levels through the use of animal fat biodiesel.

1.3 Research Objectives

The main objective of this research is to investigate the impact assessment of the plasma combustion technology for micro gas turbine (MGT) using animal fat biodiesel fuel through external integration of hybrid plasma-rich mixture injection at the compressor inlet of the engine system for enhanced combustion of biodiesel fuel through improved thermal efficiency by eight percent. In view of this, the following specific objectives were proposed.

i. To fabricate, develop and assemble a mini gas turbine (MGT) engine system with an external integrated hybrid Plasma-Torch-Ultrasonic atomizer at the compressor inlet point of the MGT engine.

ii. To conduct characterization of biodiesel blended fuel for the MGT engine operation.

iii. To evaluate and validate the combustion performance of the fabricated MGT engine with plasma-rich fuel assisted combustion technology under different fuel mixtures, and loading conditions scenarios for improved combustion performance and GHG emission reduction.

1.4 Research Hypothesis

This study on the introduction of plasma combustion technology for MGT engines using biodiesel fuels is proposed to investigate the external-intake integration of hybrid plasma-rich fuel mixture injection at the compressor inlet of the engine. The aim is to enhance combustion performance and GHG emission reduction in an MGT engine powered by biodiesel fuel blends from animal fat. This is achievable by formulating the proposed hypothesis as a statement of the expected result outcome:

Null hypothesis H_o ($\mu_o = \mu_1$): Intake integration of hybrid plasma-rich fuel mixture at the compressor inlet of mini gas turbine (MGT) engine does not improve engine performance and exhaust GHG emissions control level.

Alternative hypothesis H_1 ($\mu_o \neq \mu_1$): Intake integration of hybrid plasma-rich fuel mixture at the compressor inlet of mini gas turbine (MGT) engine does improve engine performance and exhaust GHG emissions level control.

1.5 Research Scope and Limitations

This research study focused on the study of plasma combustion technology for micro gas turbines using biodiesel. The fabrication of MGT engine systems within the laboratory setup using individual engine components (selection MGT, selection plasma torch and assemble modifications, compressor system, fuel system, air intake system, atomiser, engine test bed) to test the viability of adopting plasma technology and alternative renewable biodiesel fuel (from animal fat) in MGT engine, in order to enhance the effective engine performance, operation cost reduction and reduction in the NOx emission level.

The scopes of the study are:

i. The accurate parameter selection for the MGT engine design using fundamental theorems, composite flow map, and ASTM standard compliance for proposed fuel characterization. Adequate safety precaution measures were taken.
ii. The proposed MGT has 78 % maximum mechanical efficiency, a turbo charger with a maximum pressure ratio of 2:6, and a mutually coupled rotary compressor with a maximum compressing flow rate of 58 ips/s (26.31kg/s).
iii. The external fabrication of the attached exhaust to the MGT was adapted to enhance effective engine thrust performance and exhaust GHG emission level measurement with the application of fuels from fossil kerosene, fossil diesel and biofuel blend mixtures.
iv. The external integration of plasma torch and ultrasonic atomizer devices with temperature specifications range from 5000 - 8000 ^oC at the compressor inlet, and electrically powered atomizer.

v. This hybrid integrated plasma-rich fuel mixture into the MGT with both fossil fuel and biofuel adopted to examine the combustion performance of the engine.

vi. The novel plasma technology at the intake of the compressor of the MGT engine for ionized hydrogen gas formation in combination with external air. Hence addressees the GHG emission control level, enhancing engine performance efficiency and operation cost based on a reduction in fuel consumption by 1.5 % is the novelty of the study.

The study is limited to a lab-scale MGT engine fabrication and evaluation under different operating conditions with external integration of hybrid plasma-rich fuel technology at the compressor inlet point, under four operational conditions with fossil and biodiesel fuel blended mixtures. The emitted GHGs monitored and analyzed were limited to nitrogen oxide (NOx), sulphur oxides (SOx), and carbon monoxide (CO). This study also investigates the rate of fuel consumption, combustion temperature and products of the combustion exhaust.

1.6 Research Contributions

The following contributions were added to the existing body of knowledge on the introduction of plasma combustion technology for micro gas turbines using biodiesel fuel. The proposed external integration of plasma-ultrasonic atomizer technology at the compressor inlet of the MGT engine powered by conventional fossil and biodiesel blended mixtures from animal fat was conducted. The impact assessment analyses on the MGT engine efficiency performance level based on selected operation parameters and GHG emission control level were divulged accordingly. The following are the contribution from the study.

i. Successful fabrication and assembly of laboratory-scale MGT engine with external integrated plasma torch technology and ultrasonic atomizer at the compressor inlet of the MGT.

ii. Comparative reduction in the GHG emission measurement level of NOx, SOx, and CO with the introduction of plasma combustion technology for the MGT engine using biodiesel fuel compared to conventional approaches.

iii. Performance improvement of MGT at a reduced operational cost

1.7 The Layout of the Thesis

Chapter 1 presents the background of the study, the knowledge gap discovery, problem statement, research objectives, significance and scope of research are described in detail. Chapter 2 (Literature Review) contained a comprehensive literature review on the application of biodiesel, plasma technology and combustion performances of various fuels in gas turbines in order to discover the research gap to be filled as motivation for this current study. Chapter 3 (Methodology) presents the materials/ equipment, fabrication procedure, experimental layout, parameter measurement and relevant data extraction. The procedure employed in fuel characterizations and external technological integration of plasma and ultrasonic atomizers were explained in detail. The final operation testing of the complete assembled unit for onward analysis was executed. Chapter 4 (Results and Discussions) presented the analytical method applied to investigate the significant effect of the measured factors discovered by the research. The results and discussions were reported in a sequential order based on the specific objectives. Comparison with relevant literature was included in the discussion of the results. Chapter 5 (Conclusion and Recommendations) finally present the conclusions, suggestions and recommendations based on the current research

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