PERFORMANCE OF MICRO GAS TURBINE COMBINED HEAT AND POWER SYSTEMS FUELED BY BIOFUELS

by

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LIST OF ABBREVIATIONS

1X, 2X	Peaks of vibration amplitude
AC	Alternating current
AF	Air fuel ratio
AL-MCM-4	Mesoporous alumina silicates catalyst
ASTM	American standards for testing materials
$C_{12} H_{23}$	Diesel fuel
$C_5 – C_{16}$	Wide range of liquid biofuels
Ca	Calcium
CDC	Colourless distributed combustion
$Ce O_2$	Cerium oxide
CFD	Computational fluid dynamics
CH_4	Methane
CHNS	Carbon, hydrogen, nitrogen and sulphur analysis
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide

DC	Direct current
DFGT	Direct fired gas turbine
DFT	Discrete Fourier transform
DI	Distributed index
DPM	Discrete phase model
EFGT	Externally fired gas turbine
EGR	Exhaust gas recirculation
EN	European union standards
FC	Fully close.
FFA	Fatty-acid feedstock
FFT	Fast Fourier transform
FO	Fully opened
GPH	Gallon per hour
H_2	Hydrogen
HDR	High dynamic range
HHV	High heating value
HiTAC	High temperature air combustion

HRU	Heat recovery unit
IMC	Integrated measurement and control
K	Potassium
LHV	Low heating value
LPG	Liquefied petroleum gas
LPM	Litre per minute
MGT	Micro gas turbine
MILD	Moderate or intensive low oxygen dilution
Na	Sodium
Ni – Cu	Nickel copper catalyst
NO	Nitric oxide
OH	Hydroxide
PDF	Probability density function
PO	Partially opened
PSD	Power spectra density
SFC	Specific fuel consumption
SO_2	Sulphur dioxide

TGA	Thermo-gravimetric analysis
TIT	Turbine inlet temperature
TOT	Turbine outlet temperature
$Zr O_2$	Zirconia
ZSM-5	Zeolite catalyst

LIST OF SYMBOLS

τ	Total aquisation time (sec)
Fs	Sample rate
N	Rotational speed (rpm)
f	Frequency (Hz)
φ	Equivalence ratio
$\dot{Q}$	Heat transfer rate
A_{avg}	Average area
$\sum$ Area	Summation of area
ΔT	Tempreature difference
q	Heat flux (W/m^2)
$C_{p_{water}}$	Specific capacity of water (kJ/kgK)
$\dot{m}_{ew}$	Mass of water equivalent (kg)
$\dot{Q}_w$	Heating value of water (MJ/kg)
$\dot{m}$	Mass flowrate of air (kg/s)
C_p	Specific heat capacity of air (kJ/kg°k)

T_1	Compressor outlet temperature (°C)
T_2	Turbine inlet temperature (°C)
T_3	First turbine outlet temperature(°C)
T_4	Second turbine outlet temperature(°C)
Q_d	Thermal imput
Q_{exch}	Thermal output
$(SFC)_{exh}$	Specific fuel consumption for exhaust (kg/kWh)
$(SFC)_{Hot\ air}$	Specific fuel consumption for hot air (kg/kWh)

PRESTASI SISTEM BAHAN API GABUNGAN GAS TURBIN MIKRO HABA DAN KUASA OLEH BAHAN API BIO

ABSTRAK

Permintaan dunia terhadap penggunaan tenaga boleh diperbaharui dalam turbin gas adalah semakin meningkat untuk memastikan persekitaran bebas pencemaran dan mampan, terutamanya di Malaysia dimana terdapat banyak lambakan bahan bio. Masalah penyelidikan melibatkan kesukaran pembakaran semasa menggunakan bahan api bio dan kekurangan sistem CHP-MGT berskala kecil dalam menjalankan bahan bio gred rendah di kawasan pendalaman. Dalam kerja penyelidikan ini, kebuk pembakaran telah ditambahbaik dan geometri terbaik telah dipilih dengan menggunakan program ANSYS-FLUENT, diikuti dengan verifikasi ujikaji terhadap model. Pencirian semburan bahan api telah dilaksanakan dengan menggunakan empat saiz komersial muncung injektor 1 – 4 galon per jam (GPH) untuk diesel, diesel bio kelapa sawit dan minyak sayuran dicampur dengan diesel (P10-P100). Pembangunan untuk dua-tahap turbin gas mikro berdasarkan kuasa turbo kenderaan dengan menggunakan Garret GT25 untuk tahap pertama dan Holset H1C untuk tahap kedua telah dilakukan. Tambahan pula, ujian ujikaji dan pencirian pembakaran untuk tahap pertama MGT dan tahap kedua CHP-MGT telah dilaksanakan berdasarkan profil suhu, pengukuran perlepasan dan akustik, sementara pembangunan halaju tinggi alternator berdasarkan alternator kenderaan telah dicapai untuk keluaran kuasa elektrikal. Untuk ujikaji analisa muncung dan penyembur menggunakan bahan api diesel sebagai penanda ukur, injektor 2 telah dipilih untuk ujikaji berdasarkan prestasinya kerana ia menghasilkan pembakaran stabil yang terbaik, TIT sederhana dan keluaran kuasa turbin dan kompresor yang boleh diterima. Keputusan daripada analisa tahap pertama MGT perlepasan dan dan pembakaran menunjukkan bahawa prestasi bahan api bio kelapa sawit, P60 dan pra-pemanasan P100 (minyak sayuran) pada 100°C, didapati boleh dibandingkan dengan bahan api diesel dari segi kecekapan, kuasa keluaran dan perlepasan. Sementara menggunakan analisa akustik untuk semua bahan api, peralatan baru telah dibangunkan untuk membandingkan kestabilan api bahan bio terhdap diesel sebagai bahan api rujukan. Pembangunan alternator berhalaju tinggi menunjukkan bahawa geseran gandingan adalah paling sesuai dan seterusnya digunapakai untuk MGT kerana ia menghasilkan paling kurang kehilangan geseran dan getaran paling rendah iaitu 33.5 m/s^2 pada halaju alternator maksima 13037 rpm. Akhir sekali, pencirian penuh sistem MGT-CHP telah tercapai dengan pencapaian parameter berikut iaitu 71.5W electrical output, 18.2kW keluaran tenaga termal, 0.36kg/kWh SFC untuk pengeluaran udara panas, 400ppm perlepasan CO, 48ppm pengeluaran NOx, 43.7% kecekapan HRU and 28.9% kecekapan keseluruhan sistem.

PERFORMANCE OF MICRO GAS TURBINE COMBINED HEAT AND POWER SYSTEMS FUELED BY BIOFUELS

ABSTRACT

The global demand for utilisation of renewable energy fuels in gas turbines has been on the increase to secure a sustainable and pollution free environment, especially in Malaysia where abundant biomass is available. The research problems involves combustion difficulties faced while using biofuels and lack of sufficient small-scale CHP-MGT systems in rural locations running on these low grade biofuels. In this research work, a combustion chamber was improved and best geometry selected using ANSYS-FLUENT program, followed by experimental verification of the model. Fuel spray characterisation was performed using four sizes commercial diesel nozzle injectors 1- 4 gallon per hour (GPH) for diesel, palm biodiesel and vegetable oil blends with diesel (P10-P100). Development of two-staged micro gas turbine based vehicular turbochargers using Garrett GT25 for first stage and Holset H1C for second stage was performed. Furthermore, the experimental test and combustion characterisation for the first-stage MGT and two-stage CHP-MGT were performed based on temperature profile, emissions and acoustics measurements, while the development of high-speed alternator based on vehicular alternator was accomplished for electrical power output. For the nozzle and spray experimental analysis using diesel fuel as a benchmark, injector 2 was selected for the experiment based on its performance as it produces best combustion stability, moderate TIT and acceptable compressor and turbines power outputs. The results from first stage MGT emission and combustion analysis shows that performances of palm biodiesel, P60 and pre-heating of P100 (vegetable oil) at 100 °C, were found out to be comparable to that of diesel fuel in terms of efficiency, power outputs and emissions. While using combustion acoustics analysis for all the fuels, a new tool was developed to compare flame stability of biofuels to diesel as a reference fuel. The development of high-speed alternator reveals that friction coupling is most suitable and hence adopted for the MGT, because it produces the least friction losses and lowest vibration value of 33.5m/s^2 at maximum alternator speed of 13037 rpm. Lastly, the full MGT-CHP system characterisation was achieved with the following performances parameters as 71.5W electrical output, 18.2kW thermal power output, 0.36kg/kWh SFC for hot air production, 400ppm CO emissions, 48ppm NOx emissions, 43.7% HRU efficiency and 28.9% overall system efficiency.

CHAPTER ONE

INTRODUCTION

1.1 Background

The influence on global energy market in recent years is due to sharp increase in oil prices, reduction of fossil fuel supply and global warming concerns caused by greenhouse gas emissions. For the reasons above, the interest on the use of renewable energies sources has been increased (Cavarzere et al., 2014)

Biomass is a very important renewable energy source due to its considerable benefits on utilisation in terms of socio-economic, environmental concerns and technology. Because of the predictable nature of its derived fuels, their energy systems do not represent a critical issue for the transmission and distribution of grid. The utilisation of biomass in addition can also encourage economic development, employment in rural areas and reduce greenhouse gas emissions (Cavarzere et al., 2014). However, biomass conversion should be carried out locally due to its dispersed location and low energy density. Thus, in the designing of micro or small-scale plants, priority interest should be on installing them directly on locations with high amount of biomass feedstock. Those plants ideally can be used to supply remote customers with energy independent of grid, and can be cost saving when considering grid infrastructure cost and transmission losses (Loeser and Redfern, 2008).

Biofuels being one of the most advanced alternative energy sources have greatly contributed to the increase in global renewable energy supply in line with sustainable development goals (Acheampong et al., 2016). There has been an appreciable rising trend on the global production of biodiesel in recent years. The expected growth in biodiesel production by 2021 is up to 42 billion litres (Ashnani et al., 2014). Malaysia and Indonesia are the two main palm oil producing countries having the refining capacities for export of biodiesel (Ashnani et al., 2014). **Figure 1.1** shows the world annual biodiesel and ethanol production from 2005 to 2021 (Ashnani et al., 2014).

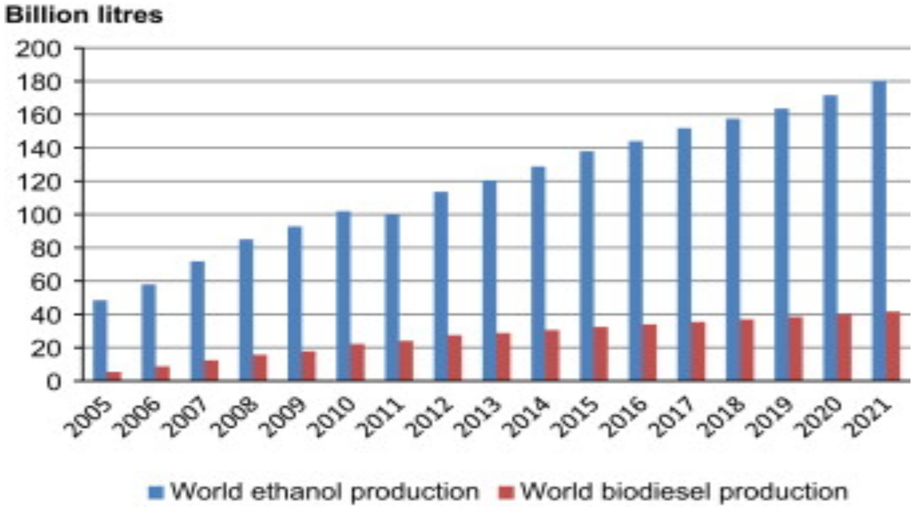

Figure 1.1: Ethanol and biodiesel world production (Ashnani et al., 2014)

Liquid biofuels utilisation for stationery power generation in engines is rapidly diffusing in European union and a further large deployment can be expected in near future (Demirbas, 2011). In the projected future of sustainable energy supply system, bio-derived fuels have assumed increasing role with increasing world energy demand (Xing et al., 2017). Recently, the use of biodiesels for gas turbine operation has received more interest, however, using more heterogeneous and synthetic substances for fuel is a concern in terms of its reliability and operations (Kurji et al., 2016). Locally available liquid fuels including blends of vegetable oil with fossil fuels for combustion stability analysis and evaluating the reliability of biofuels in micro gas turbines (MGTs) has been widely investigated (Calabria et al., 2015; Chiariello et al., 2014; Hoxie and Anderson, 2017).

The annually produced stored biomass energy by terrestrial plants is 3 – 4 times greater than the current global energy demand (Guo et al., 2015). The global production and consumption of biodiesel will consistently maintain its increase with the worlds growing demand for biofuels. It is projected that bioenergy will provide 30% of the worlds demanded energy by 2050 (Guo et al., 2015).

For the research on the effective utilisation of liquid biofuels for power applications, MGTs offer several advantages over other types of engines such as the reciprocating piston engines. Some of the advantages are:

- Higher reliability and less maintenance requirement.
- Higher power/volume ratio.
- Continuous injection and combustion that provides smooth and higher combustion quality.
- Low pollutant emissions.
- Higher cogeneration capability.
- No possibility of lubricating oil/fuel mixing due to the use of advanced air and magnetic bearings for the rotating parts (Soo-Young No, 2011).

MGTs have been recently given a significant attention for decentralised generation of renewable energy (Pilavachi, 2002), due to their performance in terms of low emissions, reliability and efficiency. There have been a renewed interest on MGT with emphasis on the development and deployment of small scale distributed cogeneration systems fuelled by renewable fuels (Chiaramonti et al., 2013). MGT is portable but with high power density, hence, several researchers have established it as one of the best mobile power sources for diverse application in future (Do et al., 2017).

1.2 Liquid biofuels production

Liquid biofuels include oils that are liquids at room temperature and solid materials which when heated form liquid containing combustible energy. Some of liquid biofuels source are vegetable oils, such as soya bean oil, rapeseed oil, and palm oil, or animal fats such as, chicken fat and tallow (Electrical Reviews, 2010). These fuels are produced from biomass through thermal or chemical process. The biofuels that have gained commercial potential are biodiesel and bioethanol (Janssen et al., 2004). Biofuels are classified into first, second and third generation fuels based on the biomass chemical and complex nature. Biodiesel and vegetable oils produced from crop plants are the first-generation fuels. The second-generation fuels are bio-ethanol and bio-hydrogen from energy plants and agricultural by-products. Seaweeds, cyanobacterial and marine resources form the third generation fuels (Gaurav et al., 2017).

Recent research developments offer state of the art biofuel production methods from algal biomass including bioethanol, syngas, biogas and biodiesel (Raheem et al., 2018) (Majidian et al., 2018; Onumaegbu et al., 2018; Vo Hoang Nhat et al., 2018). Torrefaction is another thermochemical process for upgrading biomass feedstock for biofuel production (Anuar et al., 2017; Zhang et al., 2018). In addition, a thorough new efficiency type index is used to analyse world biofuel production under a water-food-energy nexus perspective (Moioli et al., 2018).

Biodiesel, a non-petroleum-based diesel fuel is a subset of liquid biofuels. This fuel is utilised as a primary fuel source in most standard diesel engines. They can either be used alone as 100% biodiesel, or blended with conventional petroleum diesel (Electrical Reviews, 2010).

1.3 MGT for combined heat and power (CHP) applications

MGTs are smaller version of gas turbines and considered a promising technology for future distributed power generation. They are suitable to meet electrical and thermal requirement of commercial, educational and multi-residential buildings (Murugan and Horak, 2016).

An efficient alternative to costly generation and transmission of electricity is the MGT, particularly in combined heat and power (CHP) and in remote areas applications (Nikpey et al., 2013). MGT cogeneration as shown in **Figure 1.2** includes additional components such as heat recovery unit to produce hot water and steam, also to increase the electrical efficiency by pre-heating the inlet air (Janssen et al., 2004).

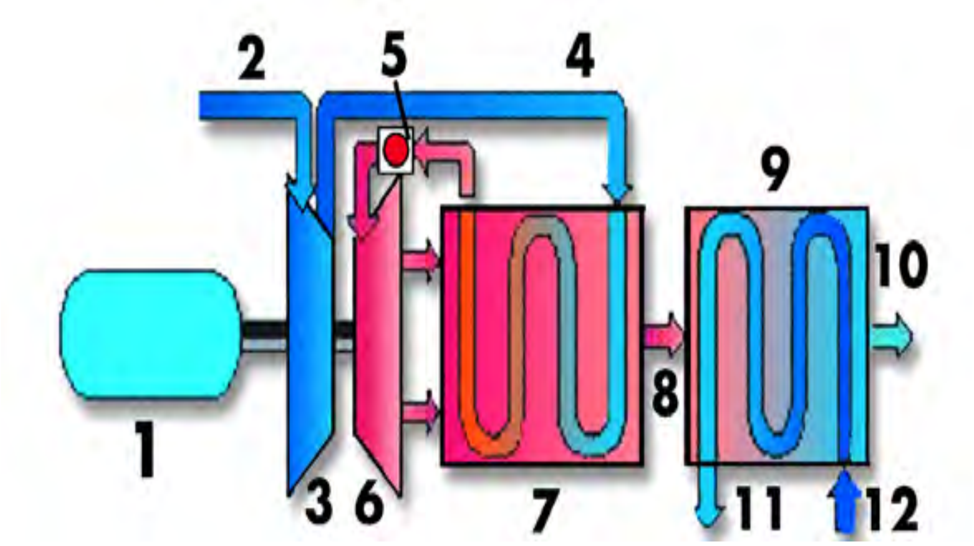

Figure 1.2: Basic MGT elements (Janssen et al., 2004)

1- Generator , 2- Air inlet, 3- Compressor, 4- Air to recuperator, 5- Combustion chamber, 6- Turbine, 7- Recuperator, 8- Exhaust gases, 9- Heat exchanger, 10- Exhaust gas outlet, 11- Hot water outlet, 12- Water inlet. (Janssen et al., 2004).

The MGT–CHP being a miniature version and advanced of large cogeneration systems is expected to increase the primary energy savings and curbing of CO_2 emission in the near future (Murugan and Horak, 2016). Research efforts on MGT–CHP systems have shown that they are used to reduce the highly variable thermal demand loads faced by residential sectors (Pereira et al., 2018).

A single-family house to apartments that require energy in the range of 1-500kW can use MGT–CHP in residential applications. These systems designed for residential buildings can deliver useful electrical power and heat with minor modifications (Murugan and Horak, 2016).

1.4 Statement of the problem

The diesel reciprocating engine generators running on liquid biofuels are generally disadvantaged when compared to MGT in terms of mini and micro power generation. The following general problems are observed from use of diesel engines...

- Low-grade waste heat and CHP capacity, hence not suitable for crop drying.
- Produce higher CO emissions greater than 1000 ppm.
- Less tolerance to liquid biofuels and are not flexible to use liquid biofuels without modifications.

In addition to these problems, there is lack of sufficient MGT small scale-CHP system in the market for low-grade liquid biofuels. Therefore, to achieve stable operation with the existing MGT Units with low-grade fuels, significant modifications on combustion chamber are required. This makes this option not attainable for small-scale off-grid applications due to its high cost. The increased attention in Malaysia for decentralised generation of renewable energies, through the development and deployment of small-scale distributed cogeneration systems forms the main motivation behind this research work. It is imperative to improve the problems of demand for electrical and thermal requirements whilst maintaining primary energy savings and reduction of pollutant emissions based on the following reasons:

- For remote locations in Malaysia without secured grid connections.
- For decentralised power generation in small installations.
- For reducing grid power usage and saving cost during peak, demand periods whenever power becomes expensive.
- To reduce the difficulties faced when drying agricultural products in rural areas where high humidity and frequent rainfall makes drying expensive.

1.5 Objectives of the study

The aim of this research is to develop the performance of micro gas turbine combined heat and power system using biofuels with the following objectives.

1. To improve and develop the MGT combustion chamber and verify its performance with LPG and diesel fuel through modelling and experimental tests.
2. To determine the best nozzle size for the experiment through performance of nozzle spray characterisation of all the fuels to be utilised for combustion of MGT.

3. To develop and determine the performance of single staged and two staged MGT along with high-speed alternator and heat recovery unit using diesel and biofuels.

1.6 Scope and limitation

The scope and limitations of this research work are summarised as following

- The improvement of a combustion chamber using Solid-works and ANSYS - FLUENT workbench 16.0.
- Development of a two-staged micro gas turbine engine based on vehicular turbochargers: Garrett GT 25 for the first-stage and Holset HIC for the second-stage.
- Development of a high-speed alternator based on a vehicular alternator for power generation.
- Fabrication and assembly of the system along with available heat recovery unit (HRU) heat exchanger for hot air production as the thermal output of the system.
- Combustion performance test included diesel as the benchmark fuel and liquid biofuels: vegetable oil (preheated and non-preheated), diesel fuel blends with vegetable oil (P10 to P90) and biodiesel.
- Exhaust gas analysis limited to CO and NOx only.
- TIT limited from exceeding 1000 °C and compressor pressure within 0.1 to 0.5 bar for single stage and 0.1 to 0.4 bar for two stage MGT.
- Equivalence ratio not considered as a variable parameter for single stage but is considered for two stage MGT.

1.7 Overview of the study/ Thesis structure

This thesis included five chapters and the description of the following chapters is outlined in this section as follows:

Chapter 2 - Literature review: In this chapter, the innovations and improvements on gas turbine systems with liquid biofuels to achieve complete combustion with low carbon footprint were reviewed. In addition is different biomass conversion technologies, biofuel co-firing in utilisation of biofuel and different clean combustion techniques. Finally is the theory behind micro gas turbine combined heat and power (CHP) systems, liquid biofuel for MGT, combustion chamber design for MGT and misalignment and vibration analysis of high-speed alternator on MGT

Chapter 3 - Methodology of the research: In this chapter, theories and methods implemented during research work were discussed. These include the design and simulation of micro gas turbine combustion chamber, the development of a two-staged MGT based on vehicular turbocharger, fabrication and assembly of the system along with heat recovery heat exchanger. Others include analysis of fuel properties and fuel spray characterisation, first-staged MGT system performances, alignment and vibration analysis of high-speed alternator and two-staged CHP–MGT system characterisation.

Chapter 4 – Results and Discussions: In this chapter, the results obtained from this research work is presented, analysed and discussed. These includes findings of the fuel spray characteristics, experimental combustion performance compared to the numerical analysis, vibration analysis of the high-speed alternator couplings and characterisation of two-stage MGT–CHP system using liquid biofuels.

Chapter 5 – Conclusions and Recommendations: In this chapter, the design decisions and performance findings of the MGT–CHP system were concluded with recommendations for further development

This introduction chapter included the research background, research problems, objectives and the scope and limitation in this research work.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The high global demand of energy has increased expeditiously in the past decade with a reported ratio of annual increment of 2.3% in 2013 (Szalay et al., 2015). The depletion of fossil fuels and global warming concerns encouraged the development of new combustion technologies for alternative fuels utilisation. These technologies should not only cover the demand for power, but also maintain high performance, conversion and efficiency without any environmental impacts (Khalil and Gupta, 2013a). The significance of biomass resources to energy production has shown that 75% of global renewable energy and 13% of world primary energy are from biomass, whereas 25–33% of global energy supply by 2050 is estimated to be from bio-energy contributions (Hossain and Davies, 2013). In addition, Guo et al., (2015) suggest that global utilization and development of biofuels and bioenergy will continue to increase and the expectations are that bioenergy will provide 30% of world demanded energy by year 2050.

Due to the increased diffusion of renewable energy sources in recent years, biomass has gained a growing interest in the combined heat and power applications (Barsali et al., 2015). Using different energy conversion technologies, biomass is storable, programmable and can be utilised to meet a wide range of energy needs (Barsali et al., 2015). There are several thermo-chemical processes in conversion of biomass into different biofuels, among which include gasification, pyrolysis, liquefaction and transesterification processes. Focusing on the thermochemical conversion systems, the process technologies for microalgae-to-biofuel production systems were extensively discussed with the benefits of exploiting upstream microalgae biomass development for bioremediation (Raheem et al., 2015). In addition, there is a recent progress in gasification techniques including important pathways for production of biofuels, socio-economic impacts of biofuel generation and process design and integration (Xd and Sikarwar, 2017).

The first generation or advanced biofuels in existing combustion engines are performing well as pure or blended additives. In addition, oxygenated biofuels produces lower NO emissions and soot than hydrocarbon fuels. However, in order to improve fuel efficiency and reduce engine emissions several novel technologies are being developed (Bergthorson and Thomson, 2015). High efficiency, fuel flexibility and ultra-low emission heat engines and fuel cell technologies will in future enable customers to switch to the cleanest fuel available at the lowest cost (Bergthorson and Thomson, 2015).

One of the major power generation technologies with a significant share in global carbon footprint is gas turbine. However, it is still lagging behind when it comes to renewable resources utilization. One of the European Union targets (Ail and Dasappa, 2016) for MGT power generation is the CHP small scale distributed generation. Some of the advantages of gas turbine include; low pollutant emission, high reliability, high power to weight ratio, high flexibility and ability to produce both heat and power in a decentralised manner (Sallevelt et al., 2014). The utilisation of liquid biofuels within a relatively robust burning characteristics of gas turbines is an added advantage (Sallevelt et al., 2014). Moreover, liquid biofuels have emerged as the most promising alternative source of fuel (Joshi et al., 2017). It has been experimentally established that most biofuels can readily be burned in pure form and in standard or slightly modified combustor designs without any significant problems (Sallevelt et al., 2014).

The indirectly or externally fired gas turbine (EFGT) is an interesting option for electricity and heat production. Flue gas coming from combustor through high temperature heat exchanger heats up the compressed air. The expansion of the resulting hot, compressed and clean air takes place at the turbine. Since the combustion takes place at atmospheric pressure outside the cycle, flue gas is not in direct contact with the turbine, allowing for the utilisation of variety of fuels including solid biomass (Baina et al., 2015). Hot clean air at turbine exhaust can be utilised directly for thermal applications with no additional heat recovery equipment needed. Thus, making the biomass EFGT configuration a preferable candidate for CHP applications with a positive contribution to the greenhouse emission reduction (Kautz and Hansen, 2007).

In the internally or directly fired gas turbines (DFGT), the hot combustion gases are in direct contact with the turbine blades. DFGT traditionally contain three main components namely: the compressor, combustion chamber and turbine. **Figures 2.1 a and b** show simple cycle of the DFGT and EFGT system. Air pressure is elevated by the compressor commonly up to the range of 15–45 bar before entering the combustion chamber. Combustion flue gasses leave combustion chamber at high temperature in the range of 850–1200 °C to the expander or turbine. The turbine is connected to the alternator which transforms power from mechanical to electricity (Costea et al., 2012). Numerous efforts on the utilisation of various alternative fuels in existing gas turbine power plants are receiving attention. The properties and quality of these fuels are important as well as the necessity for a fuel flexible gas turbine combustors to attain the increasingly stringent environmental regulation requirement concerning the gas emissions (Khalil and Gupta, 2013a). Combustion engineers are facing challenges in the quest to develop an environmental friendly combustors producing, ultra-low level pollutants such as soot, unburnt hydrocarbons, CO and NOx (Khalil et al., 2012a). New combustor designs have been gaining the attention lately such as the high temperature air combustion (HiTAC) and colourless distributed combustion (CDC) for more uniform and stable combustion with ultra-low CO and NO emissions (Khalil et al., 2012b). Recent researches on flameless combustion in power generation industry such as gas turbines have shown great potential. However, to improve its versatility in using liquid biofuels, there is need for further research and development (Xing et al., 2017). To improve flameless combustion in gas turbine, further research should be on the following areas, developed experimental technology, combustion mechanisms, comprehensive design methods, in-depth flows and advanced modelling aiming at gas turbine flameless combustion (Xing et al., 2017).

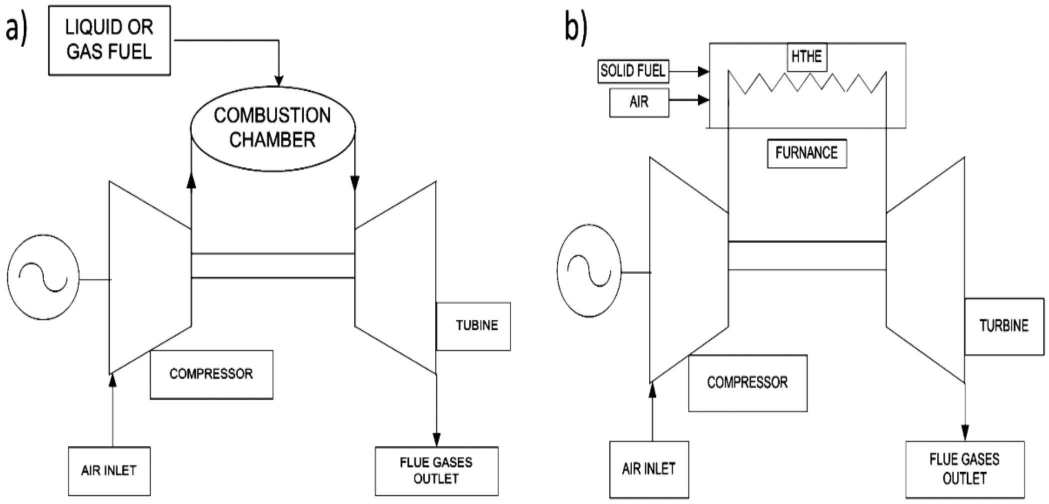

Figure 2.1: Schematic of (a) directly fired Gas Turbine System; (b) externally fired Gas Turbine System

2.2 Externally Fired Systems with Bio-fuels

Majority of the research work on the EFGT concept, is concentrated on biomass either in its solid form or after converting into gaseous form since it is well adapted for the utilisation of biomass (Al-attab and Zainal, 2015). There is a lack of studies on the use of liquid biofuels with EFGT; however, numerous studies have investigated the utilisation of liquid biofuels with other externally fired thermal engines especially with steam boilers. **Table 2.1** summarises several studies on externally fired systems using liquid bio-fuels. Petroleum diesel (Petro-diesel) fuel is one of the preferable fuels for boilers due to its convenient fuel handling and storage without fuel preheating. There has been intensive experimental investigation on the utilization of biodiesel in the existing boiler fired by petro-diesel in the past decade (Bazooyar et al., 2016, 2015, 2011; Ghorbani et al., 2011; Ghorbani and Bazooyar, 2012; Gonza, 2013; José et al., 2011; Macor and Pavanello, 2009; Martin and Boateng, 2014). This is due to its positive effect on carbon footprint and lower sulphur content that reduces SO_2 pollutant emissions significantly. In general, biodiesel shows similar behaviour to petrol-diesel when changing combustion parameters such as pressure, equivalence ratio and swirl angle with slightly lower CO and NOx emissions for the latter (Bazooyar et al., 2016; Ghorbani et al., 2011; José et al., 2011). Numerous studies have also investigated the use of petrol-diesel/biodiesel blends from B0 up to B100 in boilers and its effect on emissions (Ghorbani et al., 2011; Ghorbani and Bazooyar, 2012; Gonza, 2013; José et al., 2011). Other studies investigated the home heating oil-fuelled boilers with oil/biodiesel blends (Macor and Pavanello, 2009) and pyrolysis/ethanol blends (Martin and Boateng, 2014). From the economic point of view with the currently high prices of biodiesel, up to B20 blends are still economically viable. However, with global trend moving towards the use renewable alternative fuels, running boilers on biodiesel can be realized in the near future (Bazooyar et al., 2015).

Table 2.1: Various externally fired systems with liquid biofuels

VARIOUS EXTERNALLY FIRED SYSTEMS WITH BIOFUELS

Developer	Boiler Type	Burner Type	Bio-fuel source	Fuel mass flowrate (kg/h)	Fuel Nozzle Angle (degree)	NOx Emissions (ppm)	CO Emissions (ppm)	Combustion Efficiency (%)	Ref
University of Ahvaz Iran	Semi- industrial Boiler	U.K Sterling 90 pressure burner.	Biodiesel	–	30°- 60°	10 – 70	0 –3000	–	(Bazooyar et al., 2016)
University of Pudua Italy	Fire tube Boiler	RIELLO R138 Two stage Burner	Biodiesel and Home heating oil	10 – 38	60°	110	>10	–	(Macor and Pavanello, 2009)
University of Ahvaz Iran	CSTR Laboratory Reactor	90 U.K Spec liquid fuel Burner	Biodiesel	4.5 – 8	–	30 – 60	> 1500	90 – 93.5	(Bazooyar et al., 2011)
Universidad de Valladolid Spain	AR/25 GT (ROCA) Boiler model	Pressure pulverization burner	Biodiesel blends (B0–B100)	1.86	60°	13	80	68 –74	(José et al., 2011)
University of Ahvaz , Iran	Combustion Laboratory unit -PA Hilton England	Experimental Boiler	Biodiesel Blends (B5 – B100)	–	60°	> 70	> 6000	40 –70	(Ghorbani et al., 2011)
University of Ahvaz Iran	Water jacket Boiler	90 U.K Spec liquid fuel Burner	Biodiesel and Blends	4 –10	60°	> 70	> 5000	40 –65	(Ghorbani and Bazooyar, 2012)
Universidad de Extremadura Spain	AR/25 GT (ROCA) Boiler model	KADET-Tronic (ROCA) Burner	Biodiesel Blends (B5 – B100)	1.86	60°	–	9 – 158	56 – 74	(Gonza, 2013)
Eastern Regional Research centre USA	Low volume waste oil (LVWO) Boiler	Bubbling fluidised Bed Burner	Ethanol/pyrolysis oil Blends	–	–	0 – 1000	3.19 –12.19	–	(Martin and Boateng, 2014)
University of Ahvaz Iran	Semi Industrial Boiler	70 KW Burner	Biodiesel and Blends	4 –10	60°	40 –60	0 –120	–	(Bazooyar et al., 2015)

2.3 Direct Fired Gas Turbine Systems with Biofuels

The design of gas turbine being one of the prime sources of clean electric energy through combined heat and power production continue to receive attention due to its high efficiency (Khalil and Gupta, 2015a). The current gas turbine systems have large power ranges with flexible multi-type-fuel supply systems. Although they are capable of burning such fuels, their developments are normally based on a single specific fuel such as diesel fuel or natural gas (Gupta et al., 2010).

For conventional electrical power generation, gas turbine technology is currently dominating the global market compared to the steam turbine technology in terms of the number of units produced annually as shown in **Figure 2.2** (A forcast international Inc, 2017).

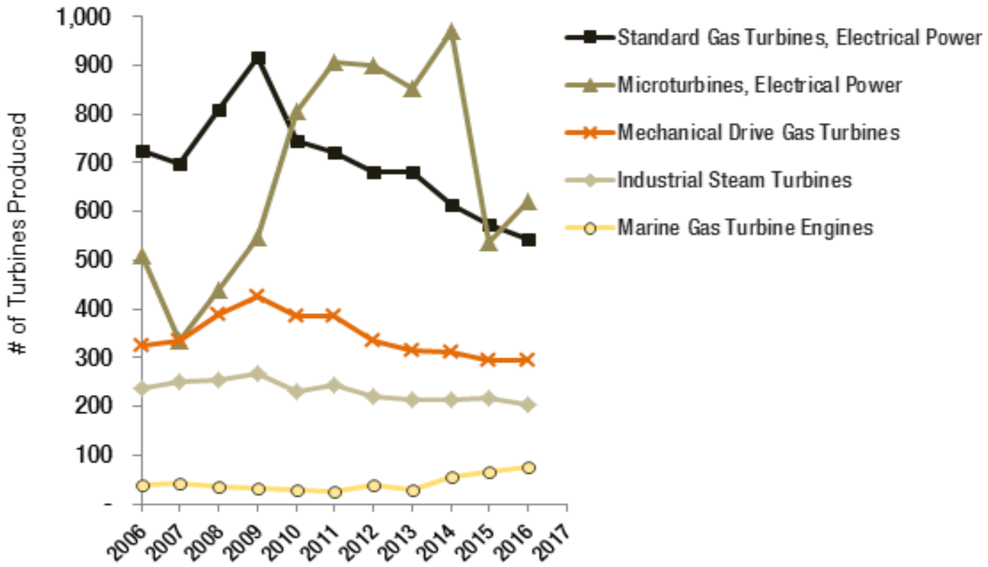

Figure 2.2: Comparing the annual production rate of gas turbines with steam turbines (A forcast international Inc, 2017)

Numerous studies have investigated variety of methods to increase gas turbine efficiency and power output capacity. Most common methods are the combined cycle configuration (Carapellucci, 2009; Chacartegui et al., 2012), regenerative cycle (Editor et al., 2014), and inlet air-cooling (Momin et al., 2016). Increasing turbine inlet temperature is another major aspect to achieve higher efficiency but with the concern of turbine blades damaging and corrosion. Recent development of material requirements used in natural gas engines are also applicable to that of syngas engines despite some difficulties in design issues (Wright and Gibbons, 2007). A study on a combined cycle fuelled by low heating value fuel showed that the use of turbine blade air cooling (using compressor bleeding) resulted in a higher overall cycle efficiency compared to under-firing turbine cooling (Kwon et al., 2013).

Although, utilising liquid bio-fuels in gas turbine is a major goal to achieve lower carbon footprint, many concerns such as fuel properties, flashback hazards, combustion stability and pollutant emissions were addressed in literatures. Many experimental studies have investigated the spray and combustion characteristics of different liquid biofuels on gas turbines and MGTs. Dimethyl ether fuel provides stable combustion with low pollutant emissions. However, higher potential of flashback was observed due to the low ignition temperature and high flame speed, thus, a new injector design was proposed to prevent flash-back risk (Chul and Yoon, 2012; Lee et al., 2009, 2008). The effect of the higher fuel viscosity and surface tension for biodiesel (Tung and Hochgreb, 2017), and pyrolysis bio-oil (Kurji et al., 2016), on spray characteristics, combustion stability and emissions were experimentally investigated. However, high vegetable oil blends (up to B75) with diesel still provided acceptable fuel spray characteristics with stable combustion. The tests results of fuel blend performed on MGT engine, indicated stable engine operation with efficiency comparable to that of diesel fuel (Hoxie and Anderson, 2017). Another study showed that preheating vegetable oils up to 120 °C provides stable MGT operation with CO emissions comparable to those with diesel fuel (Chiaramonti et al., 2013). MGT operation with vegetable oil has also been reported without any fuel preheating, and it was shown that fuel injection pressure doubled compared to diesel with a drop in engine speed (Cavarzere et al., 2014).

Investigating aldehydes emission from alternative and renewable aviation fuels showed that formaldehydes is a major aldehyde specie emitted with a fraction of about 60% of total measured aldehyde for all fuels (Li et al., 2013). Similarly, using blends of butanol/Jet (A) in a gas turbine showed a promising success, providing an alternative fuel similar to that of Jet (A) but with less CO and NO_X emissions (Mendez et al., 2014).

Other studies use computational fluid dynamics (CFD) simulation to investigate combustion stability and emissions of different type of biofuels with exhaust gas recirculation (EGR) technique for NOx emission reduction (Cameretti et al., 2013). The role of biofuel co-firing is technically, economically, and environmentally the most realistic option for power plants and large combined heat and power (CHP) system (Ericsson, 2007). Biofuel co-firing plants can handle disruptions in biofuel supply, which makes their utilisation suitable with perennial energy crops. Therefore, co-firing could serve as an important role in stimulating these perennial crops (Ericsson, 2007). Co-firing of biofuels is in addition a good solution for a steady plant operation, so incorporating it into CHP designs will permit a greater power production than the biofuel corresponding production capacity of a given site (Kang et al., 2014).

2.4 Combustion of Biofuels in Gas Turbines

Gas turbine has a continuous flow combustion process with steady flame. This feature provides clean combustion and allows the use of different fuels, robust mechanical design, moderate compression ratios and versatile combustion systems. The properties of biofuels have influence on combustion design, efficiency and NO_X emissions of gas turbines (Gupta et al., 2010). As alternative fuel for gas turbines, the fundamental combustion characteristics of palm-based biodiesel is similar to those of diesel fuel with reduced NO_X emission (Hashimoto et al., 2008). Similarly, the combustion performance of biodiesel and diesel-vegetable oil (soya bean oil) with animal fat (chicken) resulted in higher CO emissions compared to diesel (Panchasara et al., 2009). However, during accessing the catalytic contribution using a hybrid lean combustion for gas turbines, both NO_X emissions and lean stability were improved (Carroni and Griffin, 2010). Furthermore, the thermodynamic performance of a lean burn catalytic combustion gas turbine produces a higher thermal efficiency for lower regenerator effectiveness at a lower pressure ratio (Yin and Weng, 2011).

Ultra-low NOx in the range of 1-10 ppm combustor designs for MGT have been widely investigated. Different techniques are used to control NOx emissions such as multi-stage premixed chambers with preheated air (Adachi et al., 2007) as well as recuperation and exhaust gas recycling (Cameretti et al., 2007). In addition, investigations on flameless premixed combustion with an annular nozzle using a recuperative furnace (MI et al., 2010), and the moderate or intense low oxygen dilution combustion showed significant decrease in NO_X emission (Kruse et al., 2015). Although, experimental analysis of combustion behaviour of oxy-fuel flames in a gas turbine combustor shows that there are differences in flame stabilisation mechanism once compared to air-fuel flames in the same combustor (Kutne et al., 2011). The effects of number and location of stabiliser jets on the combustion characteristics proved significant reductions in NO_X emission (Zeinivand and Bazdidi-Tehrani, 2012).

Several works on the liquid biofuels with stable combustion were achieved using low swirl fuel nozzle (Koyama and Tachibana, 2013), fuel-air mixture (Yoon et al., 2013), and atmospheric diffusion of oxy-combustion flame (Nemitallah and Habib, 2013) all in gas turbine model combustor. The enhanced thermal radiation in oxy-fuel combustion are predicted using different radiation models (Kez et al., 2015). However, the impact of spray quality on the combustion of viscous biofuel in MGT, can be significantly improved by fuel preheating (Sallevelt et al., 2014). In addition, the case of a lean premixed pre-vaporised combustor shows great promise in reducing pollutant emissions (Temme et al., 2014).

The investigations on gas turbines also showed stable combustion with alternative fuels using air assisted pressure swirl atomiser for Jatropha oil and Jatropha methyl ester (Hashimoto et al., 2014). The exploitation of refuse derived fuels (Seljak and Katrašnik, 2015) can be achieved only with optimised fuel injection nozzle, regenerative thermodynamic cycles and high fuel preheat temperatures. Furthermore, for liquefied spruce wood (Seljak et al., 2014), the rate of mixture formation, emission formation and droplet penetration depth are greatly influenced by different velocities, temperatures and flow conditions. A new FLOX- combustion system for low calorific fuels was reported to have met the emission limits over the whole operating range, from 80% to 100% turbine speed (Zornek et al., 2015). However, for inter stage combine combustor, a new trapped-vortex combustion technology was used to improve the efficiency of gas turbine (Zhang et al., 2015). Investigating how vortex generator affects the combustion and emission characteristics of a swirl combustor, the results showed positive effects on combustion stability and pollutant emissions (Kim et al., 2015).

2.4.1 Colorless Distributed Combustion (CDC)

The aim of research on distributed combustion is to improve the performance of gas turbine combustors. That includes, alleviation of combustion instability, ultra-low emission of NO_X and CO, enhanced stability, low noise and uniform thermal field while maintaining high combustion intensity (Khalil et al., 2013).

CDC allows the increase in temperature of fresh mixture stream and decrease in oxygen concentration through internal entrainment of hot reactive species within the combustor. The critical component that facilitates distributed combustion includes the internal entrainment and subsequent adequate mixing prior to ignition. The distributed combustion reactions have the characteristics of a lower reaction rates over the entire volume of the combustor. **Table 2.2** shows various input and operational parameters for CDC. From the table it shows that there is an increase in the combustion stability and reduction on the emission of pollutants. This distributed combustion does not avoids the formation of thin reaction zone only, but also the hot flames which reduces thermal NO_X formation and emission (Khalil and Gupta, 2016).

Table 2.2: *Various input and operational parameters for Colourless distributed Combustions (CDC)*

Input parameter	**Type of fuel**	**Comb. Heat Load (KW)**	**Thermal Int. Range (MW/m3-atm)**	**Inlet fuel Injection Velocity (m/s)**	**fuel Injection Velocity (m/s)**	**Equivalent Ratio (ϕ)**	**NO Emissions**		**CO Emissions**		**Ref**
							Pre mixed (ppm)	**Non- pre mixed (ppm)**	**Pre mixed (ppm)**	**Non- pre mixed (ppm)**	
Flow field Effect	Methane	25	–	97	114 – 146	0.7 –0.9	7	7	20	20	(Arghode and Gupta, 2010)
Swirling Air Injection	Methane	6.25	22.5– 27	97	92	0.5 –0.8	5	10	8	10	(Khalil and Gupta, 2011a)
Swirling flow	Methane	6.25	36	97	128– 205	0.7	2.2	3	49	70	(Khalil and Gupta, 2011b)
Hydrogen Addition	Methane +H_2	6.25	85	97 – 136	128– 124	0.5 – 0.8	1	4	–	–	(Arghode and Gupta, 2011a)
Fuel Dilution	Methane +Inert Gas	4.7	156– 198	73 – 133	92	0.6	3	8	100	100	(Arghode et al., 2012b)
Reverse C/Section Geometry	Methane	3.91– 6.25	53 – 85	61 –97	46	0.5 –0.8	1	4	30	30	(Arghode et al., 2012a)
Low Calorific value fuel	Methane	6.25	27 – 36	194	–	0.6	2.8	7	11	21	(Khalil et al., 2012a)
Hydrogen Addition	Methane	4.72	27	96	–	0.5	3.2	–	9	–	(Khalil and Gupta, 2013b)
Novel mixing	Methane	6.25	42	110	137	0.8	2	5	100	100	(Khalil et al., 2013)
Velocity &Turbulence	Methane	6.25	22 – 36	–	46 – 103	0.6 – 0.7	5.6	–	–	–	(Khalil and Gupta, 2014a)
Swirling colourless distributed combustion	Butyl Nanoate (BN)	6.25	36	–	-	0.5 -0.84	8	-	32 -40	-	(Khalil and Gupta, 2014b)