UNIVERSITI PUTRA MALAYSIA

INVESTIGATION OF ULTRASONIC ATOMIZATION TO ENHANCE PERFORMANCE OF A MICRO JET ENGINE USING BIOFUEL

AMER E. S. E. TH. ALAJMI

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By

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

July 2019

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بسم الله الرحمن الرحيم

DEDICATIONS

This work is dedicated

to

My precious Mother and the blessed momory of my late Father

My lovely Wife my precious Daughter and Sons, for the hardships they endured

My dear Brothers, Sisters and Family, for all their support

Prof. Dr. Nor Mariah Bt Adam, Assoc. Prof. Dr. Abdul Aziz Bin Hairuddin, for their guidance and relentless support during this journey

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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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July 2019

Chairman : Professor Nor Mariah Adam, PhD
Faculty : Engineering

A jet engine is commonly used in aeronautical applications such as civilian airplanes, armed fighters, and helicopters, as it is one of the types of the gas turbine engine. Air enters through the compressor and injected into the combustion chamber to be mixed with fuel under pressure for combustion. This releases the energy of the heat to expand the volume of hot fluids and impact to the turbine wheel and generate the power of the hot gases. Such engines require tremendous amount of biodiesle. The ultrasonic atomization has been applied in different areas and shows positive potential performance. However, this promising atomizer technology has not yet applied in the micro jet engine to use biodiesel blends fuels. This gap in previous studies gave the motivation to investigates the potential of using ultrasonic atomization technology to assist the combustion process as a contribution for promising an alternative to the normal fuel atomization system. Firstly the new combustion equation is developed and validated, followed by determination of optimum conditions for combustion performance including optimum size of ultrasonic droplets. An experimental rig was set up to determine the performance of jet engine using ultrasonic droplets. The four-component set of ultrasonic atomizer devices delivers the fuel through the jet engine intake area, each device can deliver a 5 liter/ hour. The air mass flow was measured using a hot wire anemometer with speed limit 30 m/s fixed in front of the intake area. A load cell was installed to measure the actual thrust from the engine in units kg_f. A gas analyzer was used to measure oxygen percentage, carbon monoxide, carbon dioxide and unburned hydrocarbons (uHC), nitrogen monoxide and nitrogen dioxide of the exhaust gas. The performance of the engine was tested under three levels of load (high, medium, low) starting from 10-psi at steady state to the minimum value. A significant result has been tested for a low value of nitrogen monoxide at the three levels of load, a specific result has been tested for efficiency value of 2% at the three levels of load, carbon dioxide is decreasing at the low level of load. The use of the ultrasonic atomization device to assist in the combustion process was useful in

achieving engine efficiency of 1% of the micro jet performance and the reduce the emission of carbon dioxide exhaust gas to almost 25%.

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

PENYIASATAN ATOMISASI ULTRASONIK UNTUK MENINGKATKAN PRESTASI ENJIN JET MIKRO MENGGUNAKAN BAHAN API

Oleh

AMER E. S. E. TH. ALAJMI

Julai 2019

Pengerusi : Profesor Nor Mariah Adam, PhD
Fakulti : Kejuruteraan

Enjin jet biasanya digunakan dalam aplikasi aeronautik seperti kapal terbang awam, pejuang bersenjata, dan helikopter, kerana ia adalah salah satu jenis enjin turbin gas. Udara memasuki melalui pemampat dan disuntik ke dalam ruang pembakaran untuk dicampur dengan bahan api di bawah tekanan untuk pembakaran. Ini melepaskan tenaga haba untuk mengembangkan jumlah cecair panas dan kesan roda roda turbin dan menghasilkan kuasa gas panas. Enjin sedemikian memerlukan sejumlah besar biodiesel. Pengisaran ultrasonik telah digunakan di kawasan yang berbeza dan menunjukkan kaedah berpotensi positif. Walau bagaimanapun, teknologi pengaburan yang menjanjikan ini belum lagi digunakan dalam enjin jet mikro untuk menggunakan bahan bakar biodiesel. Jurang dalam kajian terdahulu memberikan motivasi untuk menyiasat potensi menggunakan teknologi pengabusan ultrasonik untuk membantu proses pembakaran sebagai sumbangan untuk menjanjikan alternatif kepada sistem pengabusan bahan api biasa. Pertama persamaan pembakaran baru dikembangkan dan disahkan, diikuti dengan penentuan syarat-syarat optimum untuk prestasi pembakaran termasuk ukuran optik ultrasonik yang optimum. Rig eksperimen telah bangunkan untuk menentukan prestasi enjin jet menggunakan titisan ultrasonik. Set komponen empat alat pengabut ultrasonik menyampaikan bahan api melalui kawasan pengambilan enjin jet, setiap peranti boleh menyampaikan 5 liter/jam. Aliran jisim udara diukur dengan menggunakan anemometer dawai panas dengan had kelajuan tetap 30 m/s di hadapan kawasan pengambilan. Sel beban dipasang untuk mengukur tujah sebenar dari enjin dalam unit kg_f. Penganalisis gas digunakan untuk mengukur peratusan oksigen, karbon monoksida, karbon dioksida dan hidrokarbon tidak terbakar (uHC), nitrogen monoksida dan nitrogen dioksida gas ekzos. Prestasi enjin diuji di bawah tiga tahap beban (tinggi, sederhana, rendah) bermula dari 10-psi pada keadaan mantap hingga nilai minimum. Hasil yang signifikan telah diuji untuk nilai nitrogen monoksida yang rendah pada tiga tahap beban, satu keputusan spesifik telah diuji untuk nilai kecekapan 2% pada tiga peringkat beban, karbon dioksida menurun pada tahap rendah beban. Penggunaan peranti pengabut ultrasonik untuk membantu dalam

proses pembakaran adalah berguna dalam mencapai kecekapan enjin sebanyak 1% daripada prestasi jet mikro dan mengurangkan pelepasan gas ekzos karbon dioksida hingga hampir 25%.

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Declaration by graduate student

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LIST OF ABBREVIATIONS/NOMENCLATURES

ABN	Air Blast Nozzle
ASTM	American Society for Testing and Materials
B100	Pure Biodiesel
B20	Kerosene + Biodiesel (80:20)
B50	Kerosene + Biodiesel (50:50)
B75	Kerosene + Biodiesel (25:75)
C/H	Carbon/Hydrogen Rate
$C_2 H_4$	Ethene
C_2H_5OH	Ethanol
C_3H_7OH	Propanol
C_4H_9OH	Butanol
Ca	Calcium
CCD	Charged-couple device
CH	Hydrocarbon
CH_3OH	Methanol
CH_4	Methane
Cl	Chlorine
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COV	Coefficient of Variation
CP	Cloud Point
Cu	Copper
DBD	Dielectric Barrier Discharge
DI	Direct Injection

DP	Discharge Power
ECR	Electron Cyclotron Resonance
EEDF	Electron Energy Distribution Function
F	Fluorine
FEM	Finite Element Method
H_2	Hydrogen
HC	Hydrocarbons
H_2O	Water
IATA	International Air Transport Association
ICEs	Internal Combustion Engines
K	Potassium
LCV	Low Calorific Value
LHV	Lower Heating Value
LP	Langmuir Probe
MAS	Mixed Air Steam
N_2	Nitrogen
Na	Sodium
NH_3	Ammonia
NO	Nitric Oxide
NOx	Nitrogen Oxides
O_2	Oxygen
O_3	Ozone
OH	Hydroxide
OIG	Outside In Gas
PAH	Poly Aromatic Hydrocarbons
PM	Particulate Matter

PP	Pour Point
PR	Pressure Ratio
SO_X	Sulphur Oxides
TR	Temperature Ratio
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

A gas turbine is a type of internal combustion engine that is used to generate power. It consists of an upstream rotating compressor coupled to the downstream turbine and a combustion chamber (Máša *et al*., 2016). All gas turbines generate thrust by providing a change in momentum to the air that enters and leaves the gas turbine (Badeer, 2000; Habib *et al*., 2010; Langston *et al*., 1997). The higher the difference in momentum, the greater the thrust that the gas turbine produces (Tanbay and Durmayaz, 2015).

For combustion to occur, the gas turbine requires a combustor. The combustor is a vital component of the gas turbine (Figure 1.1). Unlike automobiles, gas turbines have a continuous flame inside the combustor, which is lit for as long as the engine is running (Domen et al., 2015). Once ignited, the flame is maintained by constantly mixing fuel to the high pressure compressed air from the compressor, using a fuel nozzle. The primary purposed of every fuel nozzle is to atomize the fuel into small droplets, in order to speed up the mixing process of fuel and air (Jiang *et al*., 2015). The differences between various fuel nozzle technologies lie in how exactly the droplets are produced. Thus, the size $d \geq 15$ µm of the droplets affects the effeteness of atomization of fuel in a gas turbine (Zahmatkesh *et al*., 2015; James *et al*., 2016).

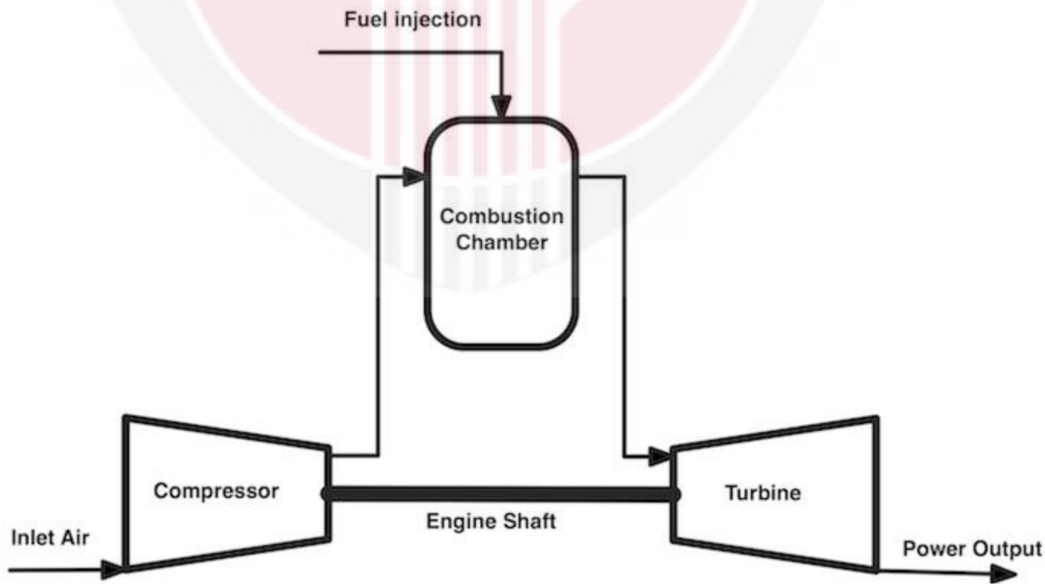

Figure 1.1 : Simple cycle gas turbine block diagram
(Mayank Maheshwari et al, 2019)

Atomization is the breakup of bulk liquid into small droplets using an atomizer or spray (Som *et al*., 2010). Atomizers are generally classified into pressure atomizer, pressure swirl atomizer, air-blast atomizer, air-assist atomizers, twin-fluid atomizer, and rotary atomizer, ultrasonic atomizers, whistle atomizers and electrostatic atomizer (Ma *et al*., 2014; Gemci and Chigier, 2016). Different types of atomizers determined the efficacy of the atomization process which adversely affects the combustion efficiency in a gas turbine engine.

The atomization of fuel is crucial in the combustion and emission of a gas turbine. Because through atomization the surface area of fuel is increased 40,000 times to hasten combustion. For this system, the combustion is continuous (Chong and Hochgreb, 2015), so the atomization in a gas turbine is continuous without any cycles or strokes. However, in order to achieve the desired amount of combustion during this continuous process, the fuel must be added and mixed with the high-pressure air exiting the compressor in the proper proportions. The constraint to make the engine as small and light-weight as possible requires that the injection, mixing, and combustion of the fuel occur within the smallest volume possible. This is inefficient and in most cases, less practicable. Furthermore, in the case of pressure atomizers, a major drawback is the requirement of high injection pressure with a relatively small increase in the flow rate. Thus, the need for non-pressurize alternative means of atomization.

Generally, adequate atomization enhances mixing and complete combustion in a direct injection (DI) engine and therefore it is an important factor in engine emission and efficiency. In the case of biodiesel, which exhibits difficulty during cold start due to its crystallizing property at low temperatures, the need for atomization as an option to overcome some of these challenges cannot be overemphasized. These techniques are having many drawbacks which lead to poor liquid atomization at a low flow rate and low efficient atomization of fuel in gas turbines operations. Therefore, investigating in alternative methods to have adaptable and efficient way of enhancing atomization becomes imperative.

Ultrasonic technique has been used in many applications, such as medical sprays, surface coatings, liquid fuel spray, metal powders and jet ink printing (Deepu *et al*., 2018). The vibrations in an ultrasonic nozzle are created by the piezo-ceramic element, which converts electrical energy being fed into the nozzle into mechanical energy in the form of vibrations. The capillary wave design consists of a vibrating surface, which basically replaces the two transducers in the previous design. The vibrations in the liquid will increase surface tension forces, and small, uniform droplets will eject one by one from the liquid stream to relieve the stream from the surface tension. This process will continue as long as the surface below keeps vibrating. The energy source from which the vibrations originate is usually electricity, much like the standing wave design.

Feasibility of biodiesel as a renewable fossil fuel replacement for gas turbine operations is currently been research on due to an earlier report on some oxides of nitrogen, oxides of sulfur, carbon monoxide (CO), emission levels. Ultrasonic as an atomization approach for environmentally preferred alternative fuels like biodiesel have yet to be fully optimized for emissions. As a result, the feasibility of using ultrasonic technology with biodiesel as a low emission alternative fuel option is still being evaluated. With improved atomization, gas turbines operations can realize improved emissions as compared to those using conventional diesel (Senda *et al*., 2008; Lefebvre and McDonell, 2017).

1.2 Problem Statement

Most atomization techniques, though with lots of merits, have shown inadequacies in the atomization of both diesel and biodiesel in the operation of gas turbines (Ferreira et al., 2011; Anwar et al., 2013; Tan et al., 2013; Bayvel, 2019). This is due to a relative increase in dynamic viscosity and surface tension, especially for biodiesel. Both of these fluid properties are heavily tied to atomization behavior in that the increased viscosity and surface tension limit droplet breakup and lead to larger average droplet sizes which in turn increase residence time and nitrogen oxides (NO_x) formation.

Although there are other modes of improving emissions by using fuel injector design and fuel additive (Nieman et al., 2012; Imtenan et al., 2014; Imdadul et al., 2015). However, the use of the additive for atomization increased HC emission at larger particle size, and also increased smoke opacity when compared to conventional method (Javed *et al*., 2016). Other researchers have tried to improve the atomization of fuel using different designs of atomizers (Arghode *et al*., 2012; Khalil *et al*., 2012; Mlkvik *et al*., 2015). The result of their studies showed that depending on the gas-to-liquid ratios, the flow rate was enhanced leading to improve combustion. However, this method is far from efficient because it depends on complex designs and cannot be used for most engines.

The conventional techniques used to improve the atomization are pressure burners and spray heads (Guillaume et al 2019). These techniques are affected by varying either the pressure under which to deliver supply liquid or the area of the nozzle outlet opening. These lead to poor liquid atomization at a low flow rate (under a low pressure). In order to overcome the drawbacks to the efficient atomization of fuel in gas turbines operations, adaptable and efficient way of enhancing atomization becomes imperative.

Recently, more attempts have been made to impart ultrasonic waves to the liquid material as it is injected out through the jet of the injection nozzle under pressure. This technique has shown high results and led to a good performance in the applications used in. However, many applications of ultrasonic decomposition waves for many industrial processes such as medical sprays, surface coatings, liquid fuel spray, metal powders and jet ink printing (Deepu *et al*., 2018). There is no known study on the development of new ultrasonic assisted atomization designs to accommodate and optimize the performance of micro gas turbines, for both diesel and biodiesel, with a view to enhance the combustion efficiency, by generating fuel fog, with particular focus on flow rate, engine performance, spraying capacity, and emissions level. There is also no known study on the effect of ultrasonic intensity and dosage on atomization. Therefore, the current study attempts to fill these gaps, while providing a comparison between ultrasonic assisted gas turbine atomization, and conventional method of atomization.

1.3 Hypothesis

Null hypothesis H_o : $\mu_o = \mu_1$ use of ultrasonic device does not improve jet engine performance.

Alternative hypothesis H_1 : $\mu_o \neq \mu_1$ use of ultrasonic device dose improve jet engine performance.

1.4 Research Questions

Can the ultrasonic atomization increase the efficiency of the micro gas turbine?

It is expected that the ultrasonic technology is the main driver for small droplets size. It is known that the atomization is generally used to have a very efficient performance of combustion in the gas turbine. Ultrasonic uses high-frequency sound energy to create wide vibrating waves. It has been stated that ultrasonic atomizers produced fuel sprays with small droplets sizes while consuming small quantities of power. The spray from such atomizers carries low momentum and penetrates less, resulting in reduced wall wetting. This enables operation of the engine with lean mixtures, due to the absence of the capacitance effect which is usually caused by wall films, especially during transients. This leads to the high performance of micro gas turbine due to the better mixture of fuels and air and this leads to high efficiency.

How does the ultrasonic atomization can be used in biodiesel fuels?

The ultrasonic atomization in the micro gas turbine can perform very well using biodiesel fuels. This can be explained due to the capability of ultrasonic to work with any kinds of liquids regardless of their viscosity, density, cloud point, pour point, temperature and pressure. It just needs to change in the operating frequency to have significant results as requested. While the other conventional atomization techniques used in gas turbines, they just design for one type of liquid. Thus, if it needs to use for different liquids or fuels, it has to redesign. For this, ultrasonic is the potential alternative novelty method in the application of using biodiesel in a micro gas turbine.

1.5 Objectives

The goal of this research is to establish the viability of ultrasonic technique as a more efficient by the use of ultrasonic wave to break up fuel droplets and generate atomization that applied to gas turbine engine operation. This novel technique will be used to break up fuel particle into small drops in the small scale gas turbine. Based on the available research gap existing in regards to the atomization of gas turbines, and the goal of this research, the specific objectives of achieving this goal are:

1. To determine the pertinent parameter that used atomization diameter, for both ultrasonic and conventional optimum atomizer system using morphology chart.
2. To fabricate micro jet engine test rig that accommodates the atomizer system.
3. To evaluate the engine in fuel atomization for both modes (ultrasonic and conventional) in terms of emissions with fuel types through measurements of carbon monoxide, carbon dioxide, nitrogen oxide and nitrogen dioxide.

1.6 Scope and Limitations

To achieve the goal and objectives set out as described above, this study exclusively involved the use of ultrasonic atomization of fuel droplet diameter between $6\mu m$ to $20\mu m$ Burak Tanyeri et al (2014), this study use four single ultrasonic device atomizaer the total capacity of producing atomization is (18 kg/hour total), for safety and reasons, a quantity that using in this study between 1-2% of the total amount of fuel used is assumed, fuel that using ultrasonic atomization is kerosene and the main injector used kerosene, diesel and biodiesel blends. Set up micro jet engine was used to run this technology in a special gas turbine laboratory in the State of Kuwait. The turbine wheel used is 96 mm, air pressure ratio is 1.32, and compressor wheel is 71 mm, airflow rate is 0.468 kg/s. The engine has selected is jet engine, rotational speed start from 43000 rpm to 82000 rpm (Appendix A4)

1.7 Significance of the Study

In this study, the applicability of utilizing the atomization of fuel in micro gas turbines was investigated. Unlike previous work, this technique was able to atomize the fuels, by using the ultrasonic technology, which provides an alternative method that can be used to improve fuel combustion, reduce CO_2 and NO_x emissions and increase the overall efficiency of jet engines. The conventional diesel fuel is costly and results in high level of greenhouse emissions. The biodiesel in gas turbine presents the cleaner energy for engine operations. This will not only reduce greenhouse emissions by reducing climate change, but also will reduce the overall cost of energy supply. In addition, the use of ultrasonic atomization helps in improving the mixing ratio of different fuel blends.

1.8 Organization of the Thesis

This thesis consists of five chapters, and each chapter was divided into several sub-sections. The thesis starts with Chapter One gave information about the background of the research, problem statement, specific objectives and the scope of the study. The first part of Chapter Two covered the literature review of gas turbine. Then, this chapter discussed different types of gas turbines and also the component of the gas turbine. Later, fuel types and more focused on atomization technology were also discussed in Chapter Two. Chapter Three focused on methodology used in the investigation of gas turbine engines, including setup discussion, ultrasonic atomization systems, data collection system, engine performance and experimental summarize. Meanwhile, Chapter Four presented the findings of the research with some discussion explaining the results. Finally, the conclusions and recommendations are presented in Chapter Five.

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LIST OF PUBLICATIONS

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