EXPERIMENTAL ANALYSIS OF PULSE DETONATION ENGINE FUELLED BY BIOGAS MIXTURES

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Dedicated to;

EMAK (SITI RAGAYAH TUMIN), AYAH (GHAZALI TAWIL),
MY WIFE (NORHIDAYAH ABDUL HAK),
***MY SIBLINGS, MY FRIEND** and*
KARKUN UTM

Thank you for your support

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The Prophet sal-Allaahu 'alayhe wa sallam used to supplicate "O Allah! Guide us to having beautiful manners and characteristics, no one can guide us to beautifying them except You, and turn away from us all evil actions and characteristics, no one can turn them away from us except You." ~ Ameen. [Related by an-Nasa'i (no.861)].

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ABSTRACT

The demand on energy conversion system with high efficiency has led researchers to study the technology of Pulse Detonation Engine (PDE). Among the prominent features of PDE are enhanced thermodynamic efficiency, high thrust generation, reduced design complexity, and lightweight. The main focus of this study is to develop a Pulse Detonation Engine with the ability of running on biogas fuel and operating at the minimum frequency of 10Hz. First, the combustion characteristics of biogas in detonation mode is calculated using NASA Computer program of Chemical Equilibrium with Applications (CEA) with two different oxidizing agents: air and oxygen. The equivalence ratio was varied from 0.7 to 1.4 with 0.1 increments. It was found that the increased methane concentration significantly improved performance in terms of pressure, temperature and Mach number of detonation characteristics. Next, an experiment was carried out to assess the effects of hydrogen addition in biogas on detonation characteristics performance. A single detonation tube and fuel with composition of 60% methane and 40% CO_2 was used for the experiment. It was found that the optimal amount of hydrogen addition into the biogas fuel mixture is 15%. For this fuel composition, the detonation pressure is improved by 23%. Finally, the experiment is conducted at a frequency of 10 Hz. At this operating condition, the pressure of 9.87 bar and 20% addition of hydrogen has been identified to provide the most optimal PDE performance. It was found that the detonation characteristics of biogas are affected by the percentage of methane concentration in biogas. CO_2 dilution is identified to have reduced the flame speed, temperature, and pressure of biogas.

ABSTRAK

Permintaan pada sistem penukaran tenaga dengan kecekapan yang tinggi telah membawa penyelidik untuk mengkaji teknologi Enjen Letupan Bernadi (PDE). Antara ciri-ciri yang menonjol pada PDE adalah kecekapan termodinamik, penghasilan teras yang tinggi, mengurangkan kerumitan reka bentuk, dan ringan. Fokus utama kajian ini adalah untuk membangunkan satu enjin PDE dengan menggunakan bahan api biogas dan beroperasi pada frekuensi minimum 10Hz. Pertama, ciri-ciri pembakaran biogas dalam mod letupan dikira menggunakan program *NASA Computer* program of *Chemical Equilibrium with Applications* (CEA) dengan dua agen pengoksidaan yang berbeza: nisbah udara dan oksigen. Kesetaraan telah diubah 0.7-1.4 dengan 0.1 kenaikan. Ia telah didapati bahawa peningkatan kepekatan metana meningkatkan prestasi dari segi tekanan, suhu dan nombor Mach ciri-ciri letupan. Seterusnya, satu eksperimen telah dijalankan untuk menilai kesan penambahan hidrogen dalam biogas prestasi ciri-ciri letupan. Satu tiub letupan tunggal dan bahan api dengan komposisi 60% metana dan 40% CO_2 digunakan untuk eksperimen. Ia telah mendapati bahawa jumlah optimum penambahan hidrogen ke dalam campuran bahan api biogas adalah 15%. Untuk komposisi bahan api ini, tekanan letupan bertambah baik sebanyak 23%. Akhir sekali, uji kaji dijalankan pada frekuensi 10 Hz. Pada keadaan operasi, tekanan 9.87 bar dan tambahan 20% daripada hidrogen telah memberikan prestasi PDE yang paling optimum. Ia telah didapati bahawa ciri-ciri letupan biogas dipengaruhi oleh peratusan kepekatan metana dalam biogas. Pencairan oleh CO_2 dikenalpasti telah mengurangkan kelajuan api, suhu, dan tekanan biogas.

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NOMENCLATURE

Roman Characters

Symbols	Definition	Units
$\dot{m}$	Mass flow rate	kg/s
A	Tube cross section area	m^2
c	speed of sound	m/s
C_v	Constant-volume specific heat	J/kmol
C_p	Constant-pressure specific heat	J/kmol
g	Gravititional acceleration	m/s^2
h	enthalpy	J/kg
MW	Molecular weight	kg/kmol
P	Pressure	Pa
q	Heat addition	J/kg
R	Specific gas constant	J/kg-K
R_u	Universal gas constant	J/kmol-K
X_i	Species' mole fraction	
Y_i	Species' mass fraction	
ν_D	Detonation velocity	m/s
$\nu_{x,i}$	Velocity	m/s

Greeks Characters

Symbols	Definition	Units
λ	Detonation cell width	**mm**
ρ	Density	kg/m^3
ϕ	Equivalence ratio	
γ	Specific heat ratio (C_p / C_v)	
υ	Specific volume	m^3/kg

Acronyms

Symbols	Definition
CEA	Chemical Equilibrium with Application
CJ	Chapman-Jouguet point
DDT	Deflagration to Detonation Transition

CHAPTER 1

INTRODUCTION

1.1 Background

Pulse Detonation Engine is an engine system using detonation wave rather that deflagration to operate. The engine called ‘pulse’ due to the requirements of new mixture inside the combustion chamber for each detonation wave initiated by an ignition source. Since 1990, huge number of research papers on Pulse Detonation Engine (PDE) have been published (Panicker, 2008).This due to the inherent advantages of PDE which operates as a detonation-based combustion engine. The excellent thermodynamic efficiency of PDE is partly due to the operation of the engine that is near-constant volume cycle (Christopher, 2009).

Higher thrust generation with less complexity in design, relatively lightweight and scalability are among the promising features of PDE that are not found in gas turbine (Helfrich, 2006). PDE has the potential to replace gas turbine engine and it can also be combined with gas turbine engine as a hybrid engine. PDE has big potential to be used either for propulsion system or ground based system power generation. In principle, PDE produce thrust at the end of a closed tube that later propagate to an end open tube. Detonation in PDE can be generated using higher ignition energy for direct initiation or using obstacle to promote the transition of deflagration to detonation mode of combustion which is also called detonation to deflagration transition (DDT) technique. The frequency of the detonation can be controlled by controlling the sequence of open and close fuel supply valve, ignition and purging valve. The system does not require turbine to create higher compression for producing higher thrust.

Various types of fuel have been tested in literature which most of the earlier study focused on gaseous fuel and later gradually the interest shifted towards liquid fuels. However, current global needs necessitate the utilization fuels that are renewable, easy to manage, cleaner source, and low environmental impact to ensure environmental protection (Díaz-González et al, 2009). So it was important to discover new technology to utilize renewable energy efficiently like biogas.

One of the biggest sources of the renewable energy in the world is biogas (Sumathi et al., 2008). Biogas can be produced throughout fermentation (anaerobic digestion process) of an organic material like agricultural, domestic and municipal solid waste without the presence of oxygen. The biggest resource of the biogas in Malaysia is the waste from palm oil processing industry. Palm oil is one of the main commodities in Malaysia. The total production of palm oil from Malaysia was 14.96 million ton in 2007 which contributes 45% of the world's palm oil demand. However, the milling process created a number of by-products and the most voluminous and ecologically hazardous waste is Palm Oil Mill Effluent (POME), with roughly 58 million tons of POME produced in Malaysia annually (Sumathi, 2008). The conventional open pond and digester system release huge quantity of methane and significantly contributes to the greenhouse gas emissions. Replacing the current standard method of open lagoons, anaerobic digester for capturing biogas can utilize POME as a promising source of energy.

Biogas has already been utilized to power a boiler, power generator, cooking stove, lighting etc. It is renewable, relatively cheap and extra effective for dropping green house gases unlike other natural resources like coal, nuclear and petroleum fuel due to the pollutants emitted from the combustion of the aforementioned fuels (Soleimani, 2010).

Combustion has been an acceptable and popular choice of retrieving chemical energy contained in biogas. Generally a combustible mixture can be activated on both modes of combustion: deflagration and detonation. The combination of biogas and PDE has the potential to reduce Green House Gas (GHG) as biogas is renewable and PDE can operate at a much higher efficiency compared to the conventional gas turbine engine.

1.2 Problem Statement

Theoretically the use of pure biogas in PDE may not result in detonation, due to the presence of CO_2 which is potent antiknock (Deublein and Steinhauser, 2011). Thus, a much reactive gas that serves as an additive should be introduced into the mixture. Among the known reactive gas, hydrogen is known to be much more reactive compared to methane. However, the performance of a biogas fuelled PDE with hydrogen additive is still unknown. Previous research has established the performance of propane fuelled PDE at various operation frequencies but no research has been conducted on low calorific fuel of biogas. Utilization of the biogas to fuel any type of combustors has become one of the global interests due to the depletion of fossil fuel.

Global warming due to emission is another global concern that deteriorates environmental quality. The anaerobic digestion process of biological waste especially palm oil mill effluent (POME) will generate methane that could contribute to global warming once it is released into the atmosphere. However, this supposedly hazardous biogas also contains substantial amount of energy that can be tapped to support energy needs. One of the energy conversion processes to tap the contained energy is combustion that has been widely used steam and power generation in palm oil mill industry.

However, the traditional combustion method (deflagration) is less efficient compared to the detonation combustion mode. To address the problem, experimental study of Pulse Detonation Engine (PDE) of biogas has been conducted in this research project. The detonation combustion mode is the fundamental combustion concept of the PDE system. Detonation is a more energy efficient combustion process compared to deflagration. It consumes less fuel; thus with the same amount of fuel, detonation will produce higher energy compared to deflagration. PDE which is mostly applied in aviation applications could also be used for power generation (Panicker et. al, 2007, Bussing, 2000), metal cord removal from rubber in worn tires, crushing or drilling of rocks (Bazhenova and Golub, 2003), and other potential applications for industry (Nikolaev et al., 2003).

The use of different types of fuels may further add to the potential of PDE as a versatile combustor. There is however some concerns regarding the selection of fuels, especially fuel with lower calorific value, presence of anti-knock compounds and lower fuel's reactivity that may hinder detonation. Since biogas possesses most of the previously mentioned problems, certain adjustment should be made. It is therefore the focus of this study to determine the how can biogas could be successfully used to power PDE. The effect of methane concentration inside biogas was determined by using Chemical Equilibrium with Application (CEA) software. Afterwards the best mixture of biogas and H_2 as the additive has been determined by experiment with single detonation tube. The best mixture was then used in experiment with PDE to produce a relatively higher detonation frequency.

1.3 Objectives of the Study

The objectives of the study are:

1. To develop a Pulse Detonation Engine that is having ability to operate at minimum frequency of 10 hertz.
2. To investigate the possibility of using biogas as fuel for the Pulse Detonation Engine
3. To determine the Pulse Detonation Engine performance using biogas fuel enriched with hydrogen.

1.4 Scope of the Study

The scopes of the study are:

1. A single detonation study to determine detonation characteristic of biogas.
2. Design and fabricate repetitive PDE where it can operate using biogas.
3. Determine the optimum system configuration for detonation by using biogas.
4. The ratio of CH_4 and CO_2 is 60% and 40% respectively.
5. The additive fuel is H_2 which will added in small amount from 0% to 20%
6. The equivalence ratio of synthetic biogas mixture to the oxygen is stoichiometric.

1.5 Significance of the Study

This project purpose as a framework for establishing Pulse Detonation Engine operates using biogas as a main fuel. The further development of this project will contribute to solving the problem of the Green House Gaseous, global warming and depletion of the ozone layer. It will reduce the dependency of the combustion engine to fossil fuel. Furthermore it also will help the relevant industries in attaining efficient performance of the propulsion combustion processes or system. Lastly, it's to increase the potential of the renewable energy application area.

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