PERFORMANCE OF FLAMELESS COMBUSTION USING PALM OIL MILL EFFLUENT BIOGAS

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ABSTRAK

Biogas yang dihasilkan daripada effluen kilang minyak sawit (POME) adalah sejenis sumber tenaga boleh diperbaharui yang boleh didapati dengan banyaknya di Malaysia daripada industri minyak sawit yang besar. Walau bagaimanapun, disebabkan nilai kalorinya yang rendah, potensi penuh POME biogas masih tidak diterokai sepenuhnya. Pembakaran tanpa api *(flameless)* merupakan kaedah pembakaran baru yang mempunyai kelebihan daripada segi penghasilan gas pencemar oksida nitorgen (NOx) yang rendah. Pembakaran tanpa api juga dipercayai dapat menerima bahan bakar berkalori rendah tanpa sebarang masalah. Dalam kajian ini, pembakaran tanpa api menggunakan POME biogas telah dikaji dan prestasinya dianalisis dan dibandingkan dengan pembakaran tanpa api menggunakan gas asli. Satu sistem pemampatan biogas dan sistem penyimpanan telah direka dan diuji untuk dibekalkan kepada sistem pembakaran tanpa api. Hasil kajian menunjukkan bahawa pembakaran tanpa api berjaya dicapai menggunakan tiga jenis bahan api iaitu gas asli, biogas tiruan (75% gas asli, 25% CO2) dan biogas POME. Suhu purata relau ketika pembakaran tanpa api POME biogas didapati mempunyai suhu purata lebih rendah (2.69% pengurangan) disebabkan oleh peningkatan gas lengai di dalam ruang relau. Pembakaran tanpa api menghasilkan kawasan pembakaran yang lebih besar dan lebih seragam (R_{TU} = 0.097) berbanding dengan pembakaran api konvensional (R_{TU} = 0.21). Ukuran pelepasan NOx telah menunjukkan pengurangan pelepasan NOx dalam pembakaran tanpa api menggunakan gas asli, biogas POME dan biogas simulasi. Magnitud pelepasan NOx dalam pembakaran tanpa api adalah 6 ppm purata bagi ketiga-tiga jenis bahan api. Nisbah setara campuran pembakaran mempunyai sedikit kesan terhadap pembentukan NOx.

ABSTRACT

Biogas produced from palm oil mill effluent (POME) is a type of renewable energy source that is available in abundance in Malaysia from its large palm oil industry. However, due to its low calorific value, POME biogas full potential has not been fully explored. Flameless combustion is new low NOx combustion method which is believed to be able to accept low calorific fuels easily. In this study, POME biogas has been used to fuel a flameless combustor and its performance was analyzed in comparison to flameless combustion of natural gas. A biogas compression and storage system was designed and tested to fuel the flameless combustion system. Results show that mild flameless combustion regime is achieved for natural gas, simulated biogas (75% natural gas, 25% CO_2) and POME biogas. POME biogas flameless combustion has slightly lower average furnace temperature (2.69% reduction) due to increased inert gas in the furnace chamber. Flameless combustion produce a larger and more uniform combustion area (R_{tu} = 0.097) compared to conventional flame combustion (R_{tu} = 0.21). NOx emission measurement has shown reduced NOx emission in flameless combustion of natural gas, POME biogas and simulated biogas. The magnitude of NOx emission in flameless combustion is 6 ppm in average for the three fuel type. Equivalence ratio of combustion mix has little effect of NOx formation.

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LIST OF ABBREVIATIONS

AC	Alternating Current
CDC	Colorless Distributed Combustion
cfh	cubic feet per hour
FELDA	Federal Land Development Authority
FLOX	Flameless Oxidation
HiTAC	High Temperature Air Combustion
LCV	Low calorific value
MILD	Moderate or Intense Low oxygen Dilution
NG	natural gas
NOx	nitrogen oxides
OLR	organic loading rate
POME	Palm Oil Mill Effluent
ppm	parts per million
TG	tail gas

NOMENCLATURE

ϕ	Equivalence ratio
R_{tu}	Temperature uniformity ratio

CHAPTER 1

INTRODUCTION

1.1 Background

Global energy production and consumption in the 21st century is facing two challenging issues: insufficient supply of energy to meet energy demand, as well as environmental pollution from energy production process contributing to global warming. Solutions for the former include sourcing of renewable and sustainable energy to replace the limited carbon based fossil fuels. Renewable energy resources are investigated from wind, solar, ocean, and geothermal energy and some has been successfully implemented. However, deriving energy from these sources are usually geographically bounded and not easily adapted to worldwide local application. In contrast, biomass derived fuels are thought to be able to overcome the limitations and can be easily applied to established conventional method because of its similarity to carbon based fossil fuel.

The latter problem is largely caused from combustion process that has been widely used in the industry as energy extraction process. Combustion of carbon based fossil fuels is notorious due to the combustion products such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx) and unburned hydrocarbons (UHC) being directly linked to health and environment hazards. Due to these issues, active researches on new combustion technology aim for higher efficiency and lower emission.

In this line, the flameless combustion technology has been developed and it is found the emission of NOx can be reduced greatly from thermal path. With promising advantages such as higher efficiency and lower emission, flameless combustion has received high interest in research field as a viable solution for energy crisis and global warming problem. Additionally, the ability for a flameless combustor to accept low calorific value fuels make it a suitable candidate for combusting biofuels, which has been setback due to its low calorific value characteristics. In this thesis, performance of biogas as fuel for a low NOx emission flameless combustion technique will be investigated.

1.2 Motivation of study

1.2.1 POME potential as renewable energy

The tropical climate in Malaysia has encouraged cultivation of oil palm as a commodity crop. Oil palm plantation covers approximately 73% of the agricultural land in Malaysia and Malaysia's palm oil industry production ranked second largest in the world (Ng et al., 2012). A palm oil fresh fruit bunch contains about 25% oil, which is extracted and the rest is treated as waste. Due to this nature, the waste generated from palm oil production in the form of solid, i.e. empty fruit bunch, mesocarp fiber and palm kernel shell, and fluid, i.e. palm oil mill effluent (POME), poses a threat to the environment if it is not efficiently managed. In most cases, the solid waste is disposed of through incineration to make fertilizers or used as solid fuels for steam boilers in palm oil mills (Yusoff, 2006). The energy produced from burning palm oil biomass is enough to power the palm oil mill. However, POME is usually left to decompose in aerated, open ponds until it reach allowable water quality standard before it can be released to the environment.

The energy potential from POME can be extracted by anaerobic digestion of POME and collection of the combustible methane gas that is produced for fuelling combustion systems. Since biomethane produced from POME accounts up to 6.41% of total carbon emission from Malaysia, steps should be taken to integrate this biofuel in daily industrial application (Lam and Lee, 2011). Moreover, with the development of clean development mechanism (CDM) under the Kyoto protocol, there is economic advantage from collection of methane gas in POME treatment to obtain certified emission reduction (CER) credit. However, because of biogas low calorific value, there are some difficulties in applying biogas from POME in conventional combustion system.

1.2.2 Anaerobic digestion

Anaerobic digestion is a degradation process of complex organic matters in the absence of oxygen. The end product of anaerobic digestion is methane, carbon dioxide and water. The reaction occurs in three main sequences: hydrolysis, acidogenesis and methanogenesis. In hydrolysis, the complex molecules such as carbohydrates and proteins are converted into sugar and amino acids. Then acidogenic bacteria will break down the sugar, fatty acids and amino acids into organic acids, hydrogen and carbon dioxide. In the final and rate limiting methanogenesis sequence, hydrogen and carbon dioxide is used by hydrogenotrophic methanogens, and carbon dioxide and acetic acid is used by acetoclastic methanogens, to produce methane.

1.2.3 NOx emission from combustion

The formation of NO is through three pathways: thermal and prompt NO from N_2 and oxidation of fuel-bound nitrogen. Thermal NO formed by the well known Zeldovich mechanism (Zeldovich, 1946):

$$N_2 + O \leftrightarrow NO + N$$

$$N + O_2 \leftrightarrow NO + O$$

$$N + OH \leftrightarrow NO + H$$

In the first reaction, high activation energy is needed and thus high temperature of about 1500 ^{O}C is needed for its initiation. This is the rate-controlling step in NO formation by thermal path.

The prompt pathway goes through reaction between N_2 and hydrocarbon radicals to form volatile-N species (Fenimore, 1971). The volatile-N is then either oxidized to become NO or reduced to form N_2. This pathway occurs mainly in fuel-rich condition.

The third pathway, which is conversion of fuel-bound nitrogen, is the biggest contributor of NO in solid fuel system. In this process, the fuel-bound nitrogen is split into volatile- and char-N during devolatilization. Afterwards, the volatile-N turned into either NO or N_2, and the char-N reacts in a set of heterogeneous reaction during char oxidation. The rate of this reaction depends on several factors, namely nitrogen content of fuel, combustion temperature and the fuel/air mixing pattern (Glarborg et al., 2003).

Among the three pathways, prompt NO formation is the least significant in a combustion system and only occurs in fuel rich combustion. Meanwhile, thermal NO and NO formation from fuel-bound nitrogen is found to be dependent on each other. As more fuel-bound nitrogen is changed to NO, the thermal NO formation is decreased since the initiating step in thermal NO formation may be reversed. Therefore, thermal NO formation is more likely on combustion at temperature more than 2200K, and negligible at low combustion temperatures (Pershing and Wendt, 1976).

1.2.4 Flameless combustion

Flameless combustion is a stable combustion mode which avoids a flame front by increasing the reactant temperature to above the self ignition temperature and entraining enough inert gases (usually by recirculating flue gas) to reduce the final reaction temperature well below the adiabatic flame temperature (IFRF, 2012). Researchers related to this combustion mode have also published in different terms such as High Temperature Air Combustion (HiTAC) (Katsuki and Hasegawa, 1998), Moderate or Intense Low oxygen Dilution (MILD) combustion (Cavaliere and de Joannon, 2004), Flameless Oxidation (FLOX) (Wunning and Wunning, 1997), high temperature reactant combustion and colorless distributed combustion (CDC) (Arghode and Gupta, 2010).

Flameless combustion is a new technology which has the advantage of higher efficiency (Galbiati et al., 2004), and low NOx emission (Schaffel et al., 2009). NOx is a dangerous chemical component which causes surface ozone formation, smog and global warming. Flameless combustion can also process low calorific value fuel which makes it an ideal candidate for combustion of renewable energy which usually has low calorific value

(Danon et al., 2010, Effuggi et al., 2008). However, since biofuels, particularly biogas, calorific value is dependent on the raw source, there is a need to study the suitability of biogas derived from POME as fuel for a flameless combustor. In this thesis, focus is given to flameless combustion of POME derived biogas with a long term aim for industrial application.

1.3 Problem statement

Greenhouse gas emission from Malaysia palm oil industry is one of the major contributors of emission for Malaysia. As one of the signee of the Kyoto Protocol, Malaysia is obliged to reduce its carbon footprint either through carbon storage or mitigation. The methane produced from anaerobic digestion of POME will cause global warming if it is not exploited for energy production. Combustion of biogas still produces some polluting components such as NOx unless a new combustion technology is applied.

1. Malaysia needs to sustainably process its POME to reduce the carbon footprint of the palm oil industry which is one of its main economic activities. This can be done through anaerobic decomposition of the POME to produce combustible methane gas. This biogas will need to be stored effectively for use in conventional system. While biogas digesters and use as fuel has been implemented in the palm oil industry, most of the application is by direct combustion and efficient storage and transport system which is economically feasible has not been established. A study for a biogas production and storage system which can be easily mobilized is important to make biogas use as fuel more widespread and acceptable.

2. Flameless combustion of renewable fuel has been investigated by some researchers; however, there is little knowledge on the performance of biogas in a flameless combustion. Since the calorific value of biogas is dependent on its source, a study for the performance of POME derived biogas is essential for flameless combustion to be accepted by the local palm oil industry as a mean for reducing NOx emission.

1.4 Research objectives

The objective of this research is to study the flameless combustion performance of POME biogas in terms of NOx emission in comparison to flameless combustion of conventional natural gas.

1.5 Scope

The scope of the project is limited to

1. Design and implementation of biogas storage system for fuelling the flameless combustor
2. Biogas derived from POME will be used as fuel in a flameless combustor
3. Flameless combustion performance will be measured in terms of average temperature and measurement of NOx emission
4. Comparison with flameless combustion of natural gas and flameless combustion of simulated biogas

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