EXPERIMENTAL AND NUMERICAL ANALYSES OF FLAMELESS COMBUSTION USING BIOGAS FROM PALM OIL MILL EFFLUENT

SEYED EHSAN HOSSEINI

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Universiti Teknologi Malaysia

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Dedicated to my beloved mother, my wife and my sweetheart beautiful son Amirsam.

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ABSTRACT

Flameless combustion as a clean combustion technology has been recently developed due to simultaneous low emission formation as well as efficient combustion process. Biogas has also recently been identified as a potential alternative fuel for flameless combustion. Biogas has attracted attentions because its generation is not limited to the specific geography. Since Malaysia is currently one of the world's largest producer of palm oil, biogas released from palm oil mill effluent (POME) has great capability to be applied as a source of energy in the country. Since the calorific value of POME biogas is relatively low (around 22 MJ/m^3), producing a stable flame of POME biogas premixed combustion is quite difficult. Indeed, high temperature of flame front and high rates of thermal NO_x formation, complicated setting and low efficiency of the conventional biogas combustion are crucial problems in applying biogas in premixed combustion system. Since upgrading of POME biogas is a complicated and expensive process, direct injection of POME biogas in flameless combustion system is a candidate for efficient POME biogas energy extraction. The objectives of this study are to investigate performance of a laboratory-scale flameless combustion furnace fuelled by POME biogas in terms of flameless stability, temperature distribution and pollutant formation. The effects of burner configuration on the performance of POME biogas flameless combustion are evaluated. Moreover, various aspects of biogas flameless mode in terms of burned gas recirculation inside the chamber and relationship between mixing and chemical reactions, effects of various preheated diluted oxidizer on the flameless combustion system are investigated numerically. The results confirm that flameless combustion of POME biogas is feasible in the lean, stoichiometry and rich fuel circumstances and the axial temperature of the chamber is higher in stoichiometric condition. Extremely low O_2 and CH_4 concentration are recorded in highly diluted oxidizer in ultra-lean flameless combustion. Due to the low calorific value of POME biogas and the distance between fuel/oxidizer jets, Damköhler number is found higher than unity and consequently eddy dissipation method (EDM) is proposed for turbulence chemistry interaction of POME biogas flameless combustion. The numerical results are in good agreement with experimental results. The stability of POME biogas flameless combustion is discussed based on the internally burned gas recirculation. It is found that POME biogas flameless combustion is sustained when recirculation ratio (K_v) is greater than 2.6. Flameless combustion of POME biogas is found to be limited to K_v of less than 4.6 in coaxial burner configuration. In tangential burner configuration, POME biogas flameless combustion is sustained in higher recirculation ratios (K_v =6.3). The efficiency of POME biogas flameless combustion is 62% and 66% in coaxial and tangential burner configurations respectively. Temperature uniformity is calculated 0.92 and 0.96 in coaxial and tangential burner configurations respectively. When equivalence ratio increases from 0.6 to 1.2, NO_x emission decreases from 2.4 ppm to less than 1 ppm in coaxial burner and from 3.1 ppm to 1.1 ppm in tangential burner.

ABSTRAK

Satu teknologi pembakaran yang bersih yang dinamakan pembakaran tanpa-api (PTA) baru-baru ini telah berkembang disebabkan oleh sifatnya yang mempunyai pembentukan emisi rendah serta menjanjikan proses pembakaran yang lebih cekap. Baru-baru ini juga biogas telah dikenalpasti sebagai bahanapi alternatif yang boleh digunakan dalam proses pembakaran tanpa-api. Tambahan pula, biogas sebagai bahan api alternatif telah menarik perhatian kerana ianya tidak terhad kepada geografi tertentu. Memandangkan Malaysia merupakan antara pengeluar minyak sawit terbesar di dunia, biogas yang dibebaskan daripada efluen kilang minyak sawit (POME) berpotensi besar untuk digunakan sebagai sumber tenaga di negara ini. Walau bagaimanapun, nilai kalori biogas POME adalah agak rendah (sekitar 22 MJ / m^3) menyebabkan penghasilan api yang stabil bagi pambakaran tanpa-api bagi proses pracampuran biogas POME adalah agak sukar. Malahan, masalah seperti suhu api yang tinggi, kadar pembentukan NO_x termayang tinggi dan kecekapan sistem pembakaran konvensional biogas yang rendah adalah masalah kritikal kepada pembakaran pracampuran biogas. Oleh kerana menaik taraf kualiti bahanapi biogas POME sebelum digunakan dalam sistem pembakaran adalah satu proses yang rumit dan mahal, suntikan terus biogas POME ke dalam sistem PTA adalah kaedah yang berpotensi tinggi untuk digunakan bagi mencapai tahap pengeluaran tenaga yang cekap. Objektif kajian ini adalah untuk menyiasat prestasi relau PTA berskala makmal menggunakan biogas POME dari segi kestabilan pembakaran tanpa-api, taburan suhu dan pembentukan bahan pencemaran. Kesan konfigurasi pembakar kepada prestasi POME biogas PTA juga dinilai. Selain itu, pelbagai aspek seperti edaran semula gas pembakaran di dalam kebuk pembakaran, hubungan antara proses pencampuran dan tindak balas kimia, dan kesan pelbagai pengoksida dalam keadaan cair yang telah dipanaskan kepada sistem PTA dikaji secara simulasi. Keputusan kajian mengesahkan bahawa PTA biogas POME boleh dilaksanakan dalam keadaan pencampuran cair, stoikiometri dan kayabahan api, dan suhu paksi ruang adalah lebih tinggi pada keadaan stoikiometri. Kadar kepekatan O_2 dan CH_4 yang rendah telah direkodkan dalam proses pengoksidaan yang sangat cair dalam mod PTA.Oleh kerana nilai kalori yang rendah bagi biogas POME dan jarak antara jet bahan api/pengoksida, nombor Damköhler didapati lebih tinggi daripada nilai satu, oleh itu kaedah pelesapan eddy (EDM) telah dicadangkan untuk proses interaksi kimia turbulent bagi POME biogas PTA. Keputusan simulasi menunjukkan keputusan yang mirip dengan rekod eksperimen. PTA biogas POME tidak terhasil apabila K_v meningkat kepada jumlah lebih daripada 4.6. Dalam konfigurasi pembakar secara tangen, PTA biogas POME kekal dalam nisbah edaran semula yang lebih tinggi (K_v = 6.3). Kecekapan PTA POME biogas masing-masing adalah 62% dan 66% bagi pembakar sepaksi dan tangen. Apabila nisbah kesetaraan meningkat daripada 0.6 sehingga 1.2, pelepasan NO_x menurun daripada 2.4 ppm kepada kurang daripada 1 ppm dalam pembakar sepaksi dan daripada 3.1 ppm kepada 1.1 ppm dalam pembakar tangen.

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LIST OF SYMBOLS

μ	-	Viscosity
P	-	Pressure
Da	-	Damkohler number
M	-	Molecular weight
$\mathrm{m_o}$	-	Mass fraction of oxygen
$\mathrm{\dot{m}_{exh}}$	-	Mass flow rate of exhaust gases
N	-	Stoichiometric coefficient
$\dot{Q}_{sys}$	-	Rate of heat added to a system (kW)
$\dot{Q}_{sur}$	-	Rate of surface heat loss (kW)
$\mathrm{Q_A}$	-	Thermal energy of the air
$\mathrm{Q_{FG}}$	-	Energy lost from flue gases
$\dot{Q}_a$	-	Sensible heat in combustion air
$\mathrm{Q_F}$	-	Chemical energy of the fuel
Q_S	-	Energy loss from surface
$\mathrm{\dot{Q}_F}$	-	Chemical enthalpy in fuel
$\dot{Q}_P$	-	Physical enthalpy in fuel
$\mathrm{R_f}$	-	Flame volume ratio
$\mathrm{R_o}$	-	Oxidation mixture ratio
T_i	-	Measured temperature at the various locations

T_t	-	Reference temperature
T_u	-	Temperature uniformity
$\overline{T}$	-	Average temperature
τ_R	-	Mean residence time
V_f	-	Flame volume
V_F	-	The volume of the combustion chamber
$\dot{W}_{sys}$	-	Rate of work done by the system (kW)
ρ_f	-	Density of fuel
$\overline{\omega}_i$	-	Mass fraction of each components
η	-	Combustion efficiency

LIST OF ABBREVIATIONS

Ar	-	Argon
CH_4	-	Methane
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide
H_2O	-	Water Vapor
H_2S	-	Hydrogen Sulfide
N_2O	-	Nitrous Oxide
O_3	-	Ozone
NO_x	-	Nitrogen Oxide
ppm	-	Part Per Million
CFD	-	Computational Fluid Dynamic
CDC	-	Colorless Distributed Combustion
CPO	-	Crude Palm Oil
CDM	-	Clean Development Mechanism
CER	-	Carbon Emission Reduction
ED/FR	-	Eddy Dissipation Finite Rate
EFB	-	Empty Fruit Bunches
EGR	-	Exhaust Gas Recirculation
EDC	-	Eddy Dissipation Concept
EDM	-	Eddy Dissipation Model

EEC	-	Excess Enthalpy Combustion
FFB	-	Fresh Fruit Bunches
HiTAC	-	High Temperature Air Combustion
HPAC	-	Highly-preheated Air Combustion
HTB	-	High Temperature Burners
JHC	-	Jet in Hot Co-flow
PAC	-	Preheated Air Combustion
PK	-	Palm Kernels
PSA	-	Pressure Swing Adsorption
POME	-	Palm Oil Mill Effluent
GHGs	-	Greenhouse Gases
LCV	-	Low Calorific Value
LHV	-	Lower Heating Value
LPG	-	Liquid Petroleum Gas
MILD	-	Moderate and Intensive Low Oxygen Dilution
MPOB	-	Malaysian Palm Oil Board
MSW	-	Municipal Solid Waste
NG	-	Natural Gas

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Fossil fuel consumption has increased rapidly throughout the world due to industrial development. Utilization of petroleum as the most common fuel has been developed in transportation, agricultural sectors and industrial factories. More than 80% of energy demand of the world is provided by fossil fuel. Fossil fuel formation process is very slow, taking many years, and current fossil fuel utilization is rapidly depleting the natural reserves [1,2].

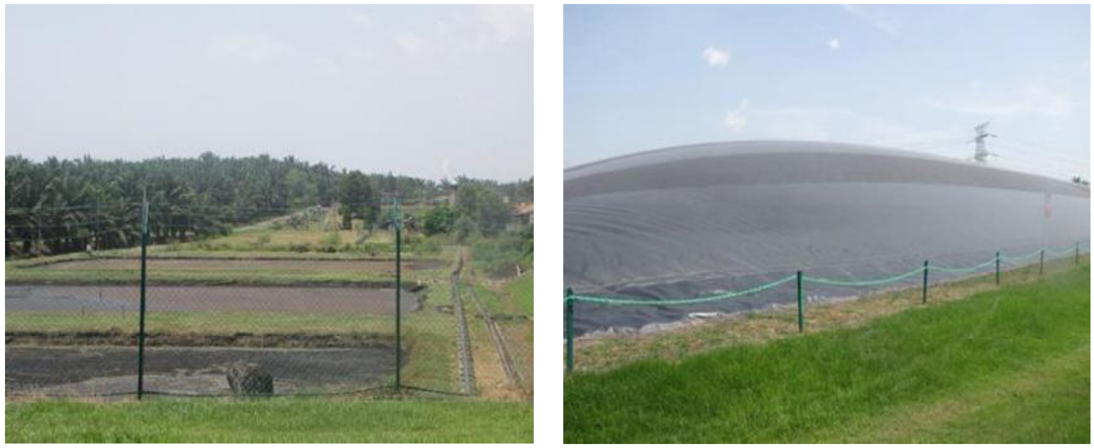
Today, fuel crisis has become one of the main concerns due to fossil fuel resources depletion. Moreover, toxic emissions released from fossil fuel combustion have become a dilemma problem in environmental issues [3]. Greenhouse gases (GHGs) effects, climate change, increasing the sea level, receding of glaciers and lack of biodiversity are the main consequences of more pollutant formation [4]. As a result, more stringent laws have been regulated to cope with global warming and environmental issues. These laws have led industrial factories and academic societies to urgently find new methods for improving conventional combustion systems to decrease emissions. Based on this background, the request of efficient combustors has become more important [5,6]. In this regard some new alternative fuel resources such as animal waste, agricultural products, wastewater effluent, and municipal solid waste (MSW) have been introduced as the sustainable and renewable energy resources [7–10].

Palm oil is cultivated in Malaysia, Indonesia and Thailand in South East Asia and some tropical countries in Africa and South America due to their appropriate equatorial climate. Palm oil by around 28% total production per annum has been known as one of the biggest vegetable oil in the world [7]. However, the sustainability of palm oil mills is under question due to huge amount of wastewater production. In the other word, without suitable strategies, the released palm oil mill effluent (POME) from palm oil mills can jeopardize the environment. Huge amount of biogas released from POME in anaerobic digestion (AD) is the most important challenges in production process of palm oil mills [8]. Indeed, biogas production from POME is intensified significantly by adding solid residues like empty fruit bunches (EFB) to the POME [9].

Open pond systems are still commonly applied in most of the palm oil mills. Although relatively cheap to install, these system often fail to meet discharge requirements (due to lack of operational control, long retention time, silting and short circuiting issues). Moreover, the biogas produced during the anaerobic decomposition of POME in open pond systems is not recovered for utilization. The produced gas dissipates into the atmosphere is the main contributor to the GHGs and this is dangerous to global warming (due to the fact that CH_4 is a twenty times stronger greenhouse gas than CO_2) [11,12].

Biogas from POME can be captured using a number of various technologies. The closed-tank anaerobic digester system with continuous stirred-tank reactor, the methane fermentation system employing special microorganisms and the reversible flow anaerobic baffled reactor system are among the technologies offered by technology providers [13]. Gas production largely depends on the method deployed for biomass conversion and capture of the biogas, therefore, approximately range from 5.8 to 12.75 kg of CH_4 per cubic meter of POME. Application of enclosed AD significantly increases the quality of the effluent/ discharge stream as well as the biogas composition. A closed anaerobic system is capable of producing and collecting consistently high quality of methane rich biogas from POME [14,15].

Figure 1.1 shows a typical open and close AD ponds in Felda Maokil palm oil mill located in Segamat, Johor, Malaysia.



(a) (b)

Figure 1.1 (a) Typical open digester and (b) close digester (Felda Maokil Segamat Johor, Malaysia)

The components of biogas are GHGs which absorb and emit specific wavelengths radiation within the thermal infrared radiation spectrum entered from atmosphere or emitted by the earth and clouds [16]. Global warming is attributed to the greenhouse effect. Dioxide carbon (CO_2), methane (CH_4), water vapor (H_2O), nitrous oxide (N_2O), and ozone (O_3) are the most important GHGs in the atmosphere. Global warming potential for GHGs has been defined as the ratio of heat captured by one unit mass of GHGs to one unit mass of CO_2 in a specific period of time [17].

Since combustion is still the most important technique for energy conversion, the improvement of combustion efficiency plays crucial role to preserve fuel resources. It has been proven that in biogas premixed combustion, the net emission of GHGs such as CO_2, CH_4 and N_2O reduces dramatically in comparison with CH_4 [18]. Development of biogas utilization in industrial burners is difficult due to its low calorific value (LCV) [19]. The collected biogas should be upgraded to remove its non-combustible impurities like CO_2, water vapor and H_2S. Furthermore, H_2S and water vapor are corrosive material which their elimination from POME biogas is vital due to their crucial role in burner and boiler corrosion in premixed combustion [20].

Today, water scrubbing systems are applied in most biogas plants due to their simple mechanism. By utilization of water scrubber, the percentage of CH_4 in POME biogas increases to more than 70%. By application of some advanced biogas upgrading technologies such as membrane and cryogenic methods the percentage of CH_4 in biogas raises up to 90%, however the induced costs of these biogas purifications are very high [21]. Therefore, new economic methods should be introduced to extract POME biogas energy with some primary pretreatments.

Recently, flameless combustion has attracted attentions due to its ability to intensify thermal efficiency and simultaneously pollutant reduction [22]. These characteristics make flameless combustion a unique technology since most other pollutant reduction techniques are associated with low thermal efficiency. Moderate and Intensive Low Oxygen Dilution (MILD) combustion [23], emerged in 1990s, has been successfully utilized, specially, in metallurgy and steel industries. Flameless Oxidation (FLOX) in Germany [24], also known as High Temperature Air Combustion (HiTAC) in Japan [25], or Colorless Distributed Combustion (CDC) [26], Low NO_x Emission Injection in the US is a new combustion technology which is capable to accomplish low NO_x emissions and high efficiency among various techniques [27].

During the development process of new combustion technologies, a particular focus was dedicated to low NO_x burners and engines. Flameless combustion has lately received more attention not only for low NO_x emission, but also in energy saving by heat recirculation [28]. Compatibility between high performance and low NO_x emission is experimented by using preheated air and changing the combustion characteristics from premixed flame to flameless mode. Although, the oxidizer is diluted and low concentration of oxygen can be seen in flameless mode, combustion is sustained if air is preheated higher than the auto-ignition temperature of fuel [29].

Flameless combustion is suitable for different industrial procedures that need a uniform high temperature profile inside the furnace [30]. The main industrial applications of flameless combustion now concern the metallurgy area for which the major issue is energy efficiency. For the other industrial sectors, the issues are sometimes different, but for such as glass-making and cement industry, waste treatment [31], petrochemicals, gas turbines [32] or industrial boilers [33], it is very likely that this new combustion mode will find its place, in the short or medium term. The main reasons for development of this technology in industries can be cited as decreasing the rate of NO_x formation, increasing the rate of heat transfers, and rising the duration of the equipment's life time, which are mostly damaged by very high heat flux.

This high temperature air combustion has achieved approximately 30% reduction in energy consumption and carbon dioxide emission and 25% reduction in the physical size of facilities as compared with the traditional type of furnace. Furthermore, flameless combustion technology has demonstrated extremely low levels of emissions of nitric oxide, which are far below the present regulatory standards [34].

Flameless combustion phenomena occurs based on postponed mixing of air and fuel and flue gas recirculation in the flame zone [35]. Very high temperature of diluted reactants plays crucial role to exceed self-ignition temperature of the fuel and adopt flameless combustion condition. To obtain efficient pollutant mitigation in industrial flameless combustion furnaces, an intense reactants dilution is required. Dilution is done when the oxidizer (air or oxygen) is mixed with inert gases, such as N_2, CO_2, Ar, and H_2O, prior to the combustion process. This dilution substantially reduces the oxygen concentration in the reactants. Therefore, flame quenching occurs due to low availability of fuel or oxygen. These instabilities can be eliminated by supplying so much enthalpy via preheated oxidizer that the self-ignition temperature of the fuel is obtained [36].

1.2 Problem Statement

Current research in the field of combustion technology has been focused on reduction of emissions and improvement in energy efficiency [37,38]. Due to fossil fuel depletion and high emission of fossil fuel combustion, utilization of alternative fuel has attracted attentions [39]. Hence, combustion of LCV alternative fuels has become a new challenge in combustion community [40]. There are many methods and approaches to reduce pollutant emissions such as NO_x, CO and CO_2 and flameless combustion is a new technology which recently has received more attention due to simultaneous low emissions formation as well as more energy saving [41]. In the field of LCV alternative fuel, biogas has received especial attention because unlike fossil fuels and other renewable energy resources, biogas generation is not limited to the specific geography [42]. Since Malaysia is currently one of the world's main producer and exporter of palm oil [43], POME biogas has great capability to be applied as a source of energy in the country. However, the calorific value of POME biogas is around 22 MJ/m^3 (which is lower than NG with 39 MJ/m^3) [44], thus making a stable flame of POME biogas premixed combustion is difficult to be applied in industry. Beside LCV of biogas, complicated setting and low efficiency of the conventional biogas combustion systems could disappoint biogas users from biogas utilization [45]. Combustion instability, high temperature of flame front and high rates of thermal NO_x formation are the main problems of biogas premixed combustion in industrial burners [46]. In the other hand, upgrading of POME biogas is a complicated and expensive process [21]. Therefore, flameless combustion could be a candidate method for energy extraction from POME biogas because LCV fuel could be injected directly to the flameless combustion systems without any primary process (such as upgrading and purification) and any changing of the combustion system (burner and other equipment) [47]. Although the concepts of fossil fuel flameless combustion have been extensively investigated experimentally and numerically [48,49], biogas flameless combustion has received little attention. The most important problems in biogas flameless combustion which have not been developed yet, are summarized as below:

- The stability of POME biogas flameless combustion, temperature distribution inside the chamber and pollutant formation in biogas flameless mode are the main crucial problems in this field of combustion.
- Combustion model, chemical reaction and heat transfer model, recirculation ratio, burned gas recirculation inside the chamber and the relation between chemical time scale and mixing time scale in biogas flameless combustion have not been discussed yet.
- The effects of burner configuration on POME biogas flameless combustion has not been considered yet.

- The possible ways to enhance the efficiency of biogas flameless combustion has not been developed properly.

1.3 Research Objectives

Implementation of a successful low NO_x flameless combustion system has always been a challenge especially when LCV fuel is employed. The current study focuses on the stability of POME biogas flameless combustion experimentally and numerically. The objectives of the current research are:

- To determine experimentally the performance of laboratory-scale flameless combustion system fueled by POME biogas in terms of flameless stability, temperature distribution inside the chamber and pollutant formation (CO, CO_2, NO_x).

- To investigate the effects of burner configuration on the stability of POME biogas flameless combustion, recirculation ratio and pollutant formation.

- To evaluate numerically the detailed flow field, the effects of mixing and chemical reactions on temperature distribution and burned gas recirculation (recirculation ratio) inside the chamber with respect to various burner configurations.

1.4 Scopes of the Project

The research scope covers, design and manufacture of coaxial and tangential burner configurations for a laboratory scale flameless combustor. POME biogas was obtained from Felda Maokil palm oil mill located in Segamat, Johor, Malaysia (Appendix B). Flameless combustion system with various burner configurations (coaxial and tangential) is fueled by POME biogas experimentally. CO, CO_2, CH_4, NO_x and O_2 concentration are measured during the experiment. Effects of the preheated air entry on the performance of POME biogas flameless combustion are studied. Since burned gas recirculation inside the furnace plays significant role on the stability of flameless combustion, the recirculation of burned gases inside the chamber and the effects of burner configuration on the enhancement of recirculation ratio are studied numerically. ANSYS Fluent 14 is employed to numerically solve biogas flameless combustion. The effects of various equivalence ratios (0.6, 0.8, 1 and 1.2) as well as preheated oxidizer temperature on the temperature distribution inside the chamber are studied.

1.5 Thesis Outline

Five chapters are covered in the present thesis. Literature review and research methodology are considered in the second and third chapters respectively. Experimental setup and measurement instruments as well as numerical procedure of POME biogas flameless mode are presented in third chapter. Results and discussions of the present thesis are presented in chapter four. In the same chapter, the validity of numerical model is illustrated. Then, a comprehensive investigation is conducted for the POME biogas flameless combustion using coaxial and tangential burner configurations. The consequences of the investigation are presented in chapter four. This chapter encompasses discussions of the modeling of turbulent non-premixed flameless combustion using the eddy dissipation model. The effects of mixing and chemical reactions with respect to the burner configuration are developed numerically. The experimental measurements of temperature inside the chamber, wall temperature, temperature uniformity, nonvisible flame volume and emissions (NO_x, CO_2 and CO) are reported in chapter four where the research work is finalized. Chapter five has conclusive concept and provides discussion of the whole thesis. In this chapter summary of the major findings, contributions and recommendations are presented.

vii. Industrialization of power generation in a palm mill using POME biogas flameless combustion technique.

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