HYDROGEN PRODUCTION FROM SEWAGE SLUDGE VIA UPDRAFT GASIFICATION PROCESS IN A BENCH – SCALE FIXED BED REACTOR

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DEDICATION

Specially dedicated to my beloved parents

(Rozuki Bin Abdullah and Tina Binti Zainal Abidin)

who have been an inspiration to me

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ABSTRACT

Sewage sludge, the solid waste produced from the municipal wastewater treatment plant has created environmental problem due to continuous increasing number of sewage sludge production. Thus, finding solutions for sewage sludge treatment and discharge are essential, to address the issues. Nowadays, the utilization of sewage sludge as solid fuel for energy recovery is one of the convenient solutions to improve waste management system whilst the gasification is one of the preferable thermochemical conversion process to convert the sewage sludge to higher yield of combustible light gases due to its simple and efficient process. Therefore, this study focuses on the conversion of sewage sludge into energy via updraft gasification process and to investigate the performance of the fixed bed gasifier (L = 1.549 m, D = 0.114 m) for maximum production of hydrogen and total syngas yield (H_2, CH_4, CO, CO_2 and N_2). The reactor temperature was ranged between 600 to 900°C with equivalence ratio (ER) of 0.10 to 0.20, with different gasifying agents i.e. air and steam. The produced syngas at different operating conditions was collected using gas sample bag and analysed using residual gas analyzer to identify the syngas yield. Results showed that the maximum hydrogen yield of 3.18 % was obtained at 800°C with ER of 0.20 while optimum total syngas yield was obtained at 63.43 % for 800°C and ER of 0.15. For comparison, the steam gasification was also was carried out and it was found that 4.40 % and 70.40 % was observed for maximum hydrogen yield and optimum total syngas yield, respectively. Further, the effect of gasifying agent on total syngas yield was found to be higher for air gasification at reactor temperature of 600 and 700°C while at 800 and 900°C, the total syngas yield was found to be higher for steam gasification. It can be said that steam gasification gives more H_2 yield (> 2.4 %) than air gasification. In conclusion, energy recovery from sewage sludge can be utilized by using gasification process, and thus, minimizing the environmental pollution. In addition, the produced syngas from these processes has a potential to be used for heat and power generation application.

ABSTRAK

Enap cemar kumbahan, sisa pepejal dihasilkan daripada loji olahan air sisa perbandaran menghasilkan masalah alam sekitar disebabkan peningkatan berterusan jumlah pengeluaran enap cemar kumbahan. Oleh itu, mencari penyelesaian untuk rawatan dan pembuangan enap cemar kumbahan adalah penting untuk menangani isu – isu tersebut. Pada masa kini, penggunaan enap cemar kumbahan sebagai bahan api pepejal untuk perolehan tenaga adalah salah satu penyelesaian mudah untuk memperbaiki sistem pengurusan sisa, sementara penggasan adalah salah satu proses penukaran termokimia yang lebih baik untuk menukar enap cemar kumbahan kepada hasil lebih tinggi untuk gas ringan mudah terbakar kerana prosesnya mudah dan cekap. Oleh itu, kajian ini memberi tumpuan kepada penukaran enap cemar kumbahan kepada tenaga melalui proses penggasan arus menaik dan mengkaji prestasi pengegas lapisan tetap (P = 1.549 m, D = 0.114 m) untuk pengeluaran hidrogen maksimum dan jumlah hasil singas (H_2, CH_4, CO, CO_2 and N_2). Suhu reaktor ditetapkan pada julat antara 600 hingga 900°C dengan nisbah kesetaraan (ER) antara 0.10 hingga 0.20, dengan agen penggasan berbeza iaitu udara dan wap. Singas yang dihasilkan pada keadaan operasi yang berbeza telah dikumpulkan menggunakan beg sampel gas dan telah dianalisis menggunakan penganalisis gas sisa untuk menentukan hasil singas. Keputusan menunjukkan bahawa hasil hidrogen maksimum iaitu 3.18 % telah diperoleh pada 800°C dengan ER bersamaan 0.20 manakala jumlah hasil singas optimum telah diperoleh pada 63.43% untuk 800°C dan ER bersamaan 0.15. Untuk perbandingan, penggasan wap juga telah dijalankan dan mendapati bahawa 4.40 % and 70.40 % telah diperoleh masing – masing untuk hasil hidrogen maksimum dan jumlah hasil singas optimum. Selanjutnya, kesan agen penggasan pada jumlah hasil singas telah didapati lebih tinggi untuk penggasan udara pada suhu reaktor 600 and 700°C manakala pada 800 dan 900°C, jumlah hasil singas telah didapati lebih tinggi untuk penggasan wap. Boleh dikatakan bahawa penggasan wap memberi lebih banyak hasil H2 (> 2.4%) daripada penggasan udara. Kesimpulannya, tenaga daripada enap cemar kumbahan boleh digunakan dengan menggunakan proses penggasan, dan dengan itu, meminimumkan pencemaran alam sekitar. Tambahan lagi, singas yang dihasilkan daripada proses ini mempunyai potensi untuk digunakan untuk aplikasi penjanaan haba dan kuasa.

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LIST OF ABBREVIATIONS

amu	-	Atomic mass units
C	-	Carbon content
CH_4	-	Methane
CO	-	Carbon monoxide
CO_2	-	Carbon dioxide
d.b. wt. %	-	Dry basis by weight percent
daf	-	Dry ash-free basis
DOE	-	Department of Environment
ER	-	Equivalence ratio
GC-MS	-	Gas Chromatography – Mass Spectrometry
GCV	-	Gross calorific value
GR	-	Gasifying ratio
H	-	Hydrogen content
H_2	-	Hydrogen
H_2O	-	Water vapour
HC	-	Hydrocarbon
HHV	-	Higher heating value
IC	-	Internal combustion
LHV	-	Lower heating value
MFC	-	Mass flow controller
N_2	-	Nitrogen
na	-	Not available
NO_X	-	Nitrogen oxides
O_2	-	Oxygen
PAHs	-	Polycyclic aromatic hydrocarbons
PCBs	-	Polychlorinated biphenyls
RDF	-	Refuse Derived Fuel
RGA	-	Residual Gas Analyzer
S	-	Sulphur content
S/B	-	Steam to biomass ratio
SO_X	-	Sulphur oxides
SS	-	Sewage sludge
STP	-	Sewage treatment processes

SWPCM	-	Solid Waste and Public Cleansing Management
TGA	-	Thermogravimetric analyzer
V	-	Valve
w.b. wt. %	-	Wet basis by weight percent

LIST OF SYMBOLS

%	-	Percentage
% pp	-	Partial pressure percentage
% vol	-	Volume percentage
$m_{H_20(g)}$	-	Produced water vapour mass
$m_{H_20(l)}$	-	Moisture content mass in feedstock
~	-	Approximate
$<$	-	Less than
°C	-	Degree Celsius
bar (g)	-	bar (gauge)
g/g SS daf	-	Gram of gasifying agent mass flow per gram of dry ash-free basis sewage sludge mass flow
g/min	-	Gram per minute
in.	-	Inches
kg/h	-	Kilogram per hour
kg/p.e/year	-	Kilogram per population equivalent per year
kJ/mol	-	Kilo Joule per mole
L	-	Litre
m^3 STP/kg SS daf	-	Standard temperature and pressure cubic meter per kilogram of dry ash-free basis sewage sludge
MJ/kg	-	Mega Joule per kilogram
MJ/m^3	-	Mega Joule per cubic meter
MJ/Nm^3	-	Mega Joule per normal cubic meter
mTorr	-	milliTorr
MW	-	Megawatt
sccm	-	Standard cubic centimetre per minute
V	-	Volt

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Thermochemical and biochemical processes are the two conversion processes that convert biomass to energy. A thermochemical process is the implementation of heat together with chemical processes to produce energy products from biomass while a biochemical process is the involvement of enzymes, bacteria and other microorganisms to produce liquid fuels by breaking down biomass chemical structures. Although biochemical process can generate energy but thermochemical process have some advantages over biochemical process. Thermochemical process allows an extensive range of feedstock while biochemical processes only allows certain type and quality of feedstock. Even though biochemical process or also known as enzymatic process is highly developed but it is still operate in batch process and time consuming. In addition, other advantages of the thermochemical process are that its overall efficiency is higher and the cost of production is lower (Balat and Kirtay, 2010). These reasons caused researchers to work more on thermochemical process for production of energy from biomass.

Techniques of thermochemical process include combustion, pyrolysis and gasification. These techniques are available for the production of secondary fuels (Parthasarathy and Narayanan, 2014). The most common technique for woody biomass is combustion and the process takes place in an oxygen sufficient quantity environment to fully oxidise the fuel for the production of heat energy. Another biomass conversion technique to produce useful products is pyrolysis and the process takes place in the absence of oxygen environment by thermal degradation of a substance to produce bio fuels which are used for transportation and related applications. On the other hand, gasification process takes place in an oxygen insufficient quantity environment or also known as partial oxidation process to allow the fuel to be partially oxidised. Through this technique, both power and heat generation conditions can be met more efficiently, effectively and eco-friendly (Sansaniwal *et al.*, 2017).

During biomass gasification process, biomass is converted in a gasifier into a mixture of combustible and non-combustible gas (producer gas) with the presence of oxygen (lower than the stoichiometric combustion). Various advantages including wider variety of feedstock, high efficiencies and higher commercial value of produces syngas are offered by gasification. Currently, biomass is the common feedstock that widely studied for gasification process due to its low cost and relatively easier preparation and it has been acknowledged as the most preferred feedstock for the production of heat and electricity. Biomass can be roughly categorized as wood and woody biomass, animal and human wastes, aquatic biomass, herbaceous and agricultural biomass, contaminated biomass and industrial wastes as well as biomass blends (Ramos et al., 2018). Municipal solid waste such as sewage sludge is categorized under contaminated biomass and industrial wastes.

Nowadays, urban communities are producing a large volume of municipal wastewater and urging greater technology for sewage treatment and discharge as well as residual sludge safe handling and disposal. Sewage sludge is the solid waste produced from the municipal and industrial wastewater treatment plant. It is estimated that the production of solid waste is generated at 1.2 kg per capita per day in 2007 and more than 1.7 kg per capita per day in 2010 (Fauziah and Agamuthu, 2010). Although there are methods to consolidate, stabilize and dewater the sewage sludge but most of the sludgeis ended up to be disposed by landfill even after treated. Landfill has become importance in municipal solid waste management. However, landfill is only a temporary solution for the disposal of sewage sludge waste because there is limited space for the sludge waste to be disposed (Kang, 2016).

Recently, an increasing number of researches on sewage sludge thermochemical conversion have been reported due to its inherent improvement in the reduction of waste volume and energy production (Jayaraman and Gökalp, 2015) and gasification is one of the most preferred thermochemical conversion used to convert sewage sludge into high yield of combustible light gases. Gasification offers cleaner alternative solution for waste treatment with energy recovery as compared with the predominant applied technology of combustion (incineration) where problems commonly encountered with incineration such as emissions of sulphur oxides, nitrogen oxides and heavy metals can be circumvented (Manara and Zabaniotou, 2012). Besides, gasification also offers fast process and large volume reduction as compared to anaerobic digestion, a common way of revaluating bio solids (Oladejo *et al.*, 2018).

The following types of gasifier are the most commonly used gasifier: fixed bed and fluidized bed gasifier. Fluidized bed gasifier has been frequently used as it tolerate wider particle size range (Bosmans *et al.*, 2013). However, this gasifier produced high dust content in the gas phase and required additional cleaning (Warnecke, 2000). Hence, this study was focusing on fixed bed gasifier and this gasifier can be categorized into two modes: updraft and downdraft mode. The downdraft mode has been widely studied for small-scale applications because the producer gas has relatively low quantity of tars compared to other types of gasifiers (Pang, 2016). Meanwhile, the updraft mode seems to attract less attention from the researchers might be due to high tar levels in the gases (Bridgwater, 2003). However, the disadvantages of downdraft gasifier are related to difficulties in handling biomass with high moisture contents and relatively low overall thermal efficiency while updraft gasifier able to handle biomass with high moisture content and is thermally efficient (Bermudez and Fidalgo, 2016; Richardson *et al.*, 2015).

Thus, in this research, the gasification of sewage sludge for the production of hydrogen was investigated and the effect of reactor temperature and equivalence ratio using air and steam as gasifying agent via updraft fixed bed gasifier was thoroughly studied.

1.2 Problem Statement

The most popular method to store dewatered and treated sewage sludge is by transferring the sewage sludge from the dewatering unit to sludge storage area names hopper or yard where the sewage sludge is stored before off – site disposal. In Malaysia, the simplest route for sewage sludge disposal is landfilling (Malaysia, 2015). However, the sewage sludge production has been dramatically increased due to urbanization and economic development thus requiring more space and creating environmental problem such as water, soil and air pollution. In Malaysia, sewage sludge is produced mostly from domestic with the generation rate amount of 7.40 million m^3 and light industrial area with the generation rate amount of 9.90 million m^3 (Ujang and Salmiati, 2011).

The sewage sludge production has been estimated to increase to 7 million metric tons in the year of 2020 (Roslan, Ghazali and Asli, 2013). This increasing trend hits Malaysia's waste managers due to absence of an integrated waste management system. Therefore, it is crucial to improve waste management system especially landfilling practices as it become unsustainable and is challenging sector for waste managers to invest in thus resulting in many premature shutting down of these disposal sites. Moreover, non-sanitary landfills and open dumps are now prohibited and are being eliminated. These stringent regulations are stated in the Solid Waste and Public Cleansing Management (SWPCM) Act 2007. Hence, converting sewage sludge into useful energy is one of the solution to solve the sewage sludge disposal problem as well as produced useful energy recovery for the mankind.

Presently, energy recovery from sewage sludge using gasification process has been catching more attention from the researchers as growing technologies had emerged. Previously, most of the researchers focus on the gasification of biomass and only little focus on the sewage sludge. In Malaysia, the oil-palm solid waste gasification have been widely studied but only scarce studies dealing with gasification of sewage sludge. Moreover, a limited number of studies deal with updraft gasification of sewage sludge as compared to downdraft gasification of sewage sludge. In addition, the studies on reactor temperature using updraft gasifier are rarely found as compared to the studies on equivalence ratio.

Therefore, to utilize energy from sewage sludge as well as to reduce environmental problem, gasification offers an attractive solution in which sewage sludge is converted to syngas or fuels. In this study, gasification of sewage sludge in updraft gasifier was conducted to investigate the effect of reactor temperature and equivalence ratio for potential production of syngas.

1.3 Research Objectives

The main aim of this study is to investigate the effect of gasification process parameters (reactor temperature and equivalence ratio) and gasifying agents (air and steam) on the conversion of sewage sludge into potential syngas, mainly on hydrogen via updraft gasification in a bench-scale fixed bed gasifier. The sub-objectives of this study are as follows:

(a) To investigate the effect of reactor temperature at fixed equivalence ratio

(b) To investigate the effect of equivalence ratio at optimum reactor temperature of maximum hydrogen yield

(c) To study the effect of gasifying agents (air and steam)

1.4 Research Scopes & Limitations

To achieve the objectives of this study, the following scopes have been identified:

(a) Preparation and characterization (ultimate and proximate analysis as well as calorific value) of sewage sludge

(b) Conduction of air gasification experiments of sewage sludge at reactor temperature of 600 – 900°C and equivalence ratio of 0.10 – 0.20

(c) Conduction of steam gasification experiments of sewage sludge at reactor temperature of 600 – 900°C at fixed steam to biomass ratio of 1.09

(d) Collection and characterization of syngas by Residual Gas Analyzer (RGA)

(e) Comparison and evaluation of the syngas production produced at different reactor temperature, equivalence ratio and gasifying agent

The limitations of this research are as follows:

(a) The mass flow controller (MFC) of air can vary from 0 to 3000 standard cubic centimetre per minute (sccm)

(b) The Residual Gas Analyzer (RGA) cannot precisely determine the nitrogen and carbon monoxide mass as both have overlapping peaks patterns at 28 amu. Thus, at the mass of 28, the total of N_2 and CO are applied (a mixture of N_2 + CO)

1.5 Significant of Study

A reuse and recover sewage by-product into potential syngas production for proper disposal management of sewage sludge. The findings of this study will redound to the benefit of society considering that the utilisation of sewage sludge as energy carrier via gasification technique is feasible and a good way to solve a problem related to sewage sludge disposal management.

Gasification offers a flexible and attractive way converting sewage sludge into potential syngas, which can be used for heat and power generation. The results of this study reveal that the optimum syngas production could be achieved through the use of gasifying agent. Depending on the process parameters (e.g: Temperature and ER), the final product also could be targeted.

1.6 Thesis Organization

Chapter 1 of introduction elucidates the research background, the problems related to this research area, research objectives, scopes of research, significant of study and research contribution.

Chapter 2 of literature review provides a comprehensive review covering gasification principles, gasification of biomass as well as gasification of sewage sludge and factors affecting the gasification process.

Chapter 3 of research methodology provides the experimental procedures such as sewage sludge preparations and characterizations, air and steam updraft gasification as well as characterization of syngas.

Chapter 4 of results and discussion explains the findings on the conversion of sewage sludge into potential syngas via air and steam updraft gasification process at various factors such as reactor temperature and equivalence ratio. The comparison of air and steam updraft gasification is also included in Chapter 4.

Finally, Chapter 5 concludes the findings and highlights the significance of this study. In addition, recommendations for the future works of this research are also suggested in Chapter 5.

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