FOOD WASTE CARBONIZATION USING MICROWAVE OVEN

By:

KESAVA RAJ A/L VIJAYA KUMAR

(Matrix No.: 128938)

Supervisor:

Prof. Dr. Zainal Alimuddin Zainal Alauddin

June 2019

This dissertation is submitted to

Universiti Sains Malaysia

As partial fulfillment of the requirement to graduate with honors degree in

BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School of Mechanical Engineering

Engineering Campus

Universiti Sains Malaysia

DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed………………………………………… (KESAVA RAJ A/L VIJAYA KUMAR)

Date……………………………………………

Statement 1

This journal is the result of my own investigation, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/ references are appended.

Signed………………………………………… (KESAVA RAJ A/L VIJAYA KUMAR)

Date……………………………………………

Statement 2

I hereby give consent for my journal, if accepted, to be available for photocopying and for interlibrary loan, and for the title and summary to be made available outside organizations.

Signed………………………………………… (KESAVA RAJ A/L VIJAYA KUMAR)

Date……………………………………………

ACKNOWLEDGEMENT

This thesis completion would have not been possible without the support and aid from a lot of people.

First and foremost, I would like to address my greatest gratitude to my supervisor, Prof Zainal Alimuddin bin Zainal Alauddin. He has aided this project and given his input, which has enabled this project to be materialised. Meetings with him were always fruitful, and not to forget his continous concern of my progress. Besides, he has also shaped me throughout this project to be a matured engineer and also a matured individual.

Another important part of contribution came from behalf of the assistant engineers. Encik Mohd Zalmi Yop has been of great help, being present when any sort of problem has arised thorughout this project. He also invested a lot of his time when helping in performing Thermogravimetric Analysis (TGA) on the specimens. Encik Mohd Zafril Khan, who was in charge of the Bio-Energy Lab in School of Mechanical Engineering has always showed concern regarding the project through this year, arriving on short notice whenver needed. Encik Abdul Latif Hamzah has thought me how to use the bomb calorimeter, allowing me to perform Higher Heating Value test on the specimens. Encik Hashim Md. Nordin has helped me to bypass the microwave oven when asked without any hesitations. This names are just few from the many assistant engineers who have contributed in this project.

Last but not the least, my family and friends. They have motivated me and supported me throught out this project. Their confindence on my, even I myself have doubted myself has built my preseverence to the completion of this project and thesis.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

ABSTRAK

Pengurusan sisa telah menjadi topik penting selaras dengan peningkatan sisa pepejal perbandaran. Dengan sisa makanan yang menghasilkan 50% sisa pepejal perbandaran, usaha telah dilaksanakan untuk menguruskan sisa ini. Torrefaction adalah tindakbalik rawatan termokimia untuk memperbaiki sifat-sifat biomas. Toreffaction dibantu gelombang mikrowave, satu kaedah untuk mengambil tindakan penyemburan telah mendapat populariti dalam menguruskan sisa-sisa ini. Walau bagaimanapun, terdapat kekurangan kajian yang membincangkan torrefaction dibantu oleh mikrowave yang menggunakan ketuhar gelombang mikro domestik tanpa sebarang proses dahulu. Kajian ini mengkaji tingkah laku tulang ayam, sisa makanan, serta penambahan arang untuk mempercepat proses torrefaction. Sifat tulang ayam dan arang diperiksa sepanjang proses torrefaction dibantu gelombang mikro untuk memahami perubahan yang mereka hadapi dan juga untuk menilai sistem torrefaction. Pemboleh ubah yang dimanipulasi yang dilaporkan adalah jumlah tulang ayam yang terlibat, jumlah karbohidrat ditambah, dan jenis campuran, yang bercampur dan tidak bercampur. Telah didapati bahawa 70% arang dan 30% tulang ayam dalam keadaan yang tidak dicampur menghasilkan HHV tertinggi dan juga membuktikan keadaan terbaik untuk memperoleh 77.15% lebih banyak tenaga daripada dilaburkan. Kandungan volatile telah memainkan peranan penting dan bukannya karbon. Ini mungkin mengubah pandangan penggunaan potensi produk ini. Satu lagi sifat yang diperhatikan adalah tingkah laku pemanasan seolah-olah bukan hanya dipengaruhi oleh arang, walaupun ia adalah yang dominan. Lebih banyak penyelidikan perlu dilakukan pada sistem ini untuk lebih memahami sistem torrefaction dibantu gelombang mikro menggunakan arang untuk mengeksploitasinya sebagai sistem pengurusan sisa.

ABSTRACT

Waste management has been an important topic with the rise of Munipal Solid Waste (MSW). With food waste making up 50% of MSW, vaious efforts have been employed to manage this waste. Torrefaction is a thermochemical treatment to improve the properties of biomass. Microwave-assisted torrefaction, a method to employ torrefaction has gained interest in managing these waste. However, there is lack of literature review which discusses the microwave-assisted torrefaction using a domestic microwave oven, without any preprocessing. This study examines the behavior of chicken bones, a common food waste, along with the addition of charcoal to accelerate the torrefaction process. The behavior of chicken bones and charcoal are examined throughout the microwave-assisted torrefaction process to understand the changes they go through and also to evaluate the torrefaction system. The manipulated variables involved are the amount of chicken bones involved ,the amount of charcoal involved, and the type of mixture, which is layered and homogenous. It was found that the 70% of charcoal and 30% of chicken bones in a layered condition produced the highest higher heating value (HHV) and also proved the best condition to gain 77.15% more energy than invested. Volatiles have played an important role instead of fixed carbon which might change the views of the potential usage of these torrefied products. Another noticeable behavior observed was the heating behavior seems not only influenced by charcoal, though it is the dominant one. More research needs to be done on this system to further understand the microwave-assisted torrefaction system using charcoal to exploit it as a waste management system.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Continuous urbanization, population growth, and industrialization leads to increase in worldwide waste generation. The emerging speculation of natural resources depletion makes renewable and sustainable energy a topic of interest which will be able to diversify energy resources contribute to preservation of the ecosystem.

According to MSW generation study conducted in Malaysia, about 29,711 tonnes of MSW and it is shocking to know 50% of MSW constitutes of food waste (Samad et al., 2017). The number one source of food waste in Malaysia is domestic waste. This waste is expensive to manage, it sets a high demand on natural resources and is regarded as an untapped opportunity to extract value from these waste. Thus, this readily available waste needs a technique or technology to convert them to high value products. Landfilling has been a common practice in Malaysia to dispose waste with another incineration being another choice. There are number of environmental concerns that makes landfills a worrisome practice. These includes contamination of both ground and surface water from leachate and landfill gases which help play a part in climate change through emission of methane and other greenhouse gases.

Thermochemical treatment process needs materials with high heating or calorific value to result into high process outputs and efficiencies. This high calorific value food waste can be processed through torrefaction. Torrefaction process is a slow thermochemical process which involves heating waste within a temperature range of 200-300˚C in an inert atmospheric condition (Basu et al., 2014, Clausen et al., 2010). Within this range of temperature, the moisture content of the torrefied material decreases, and its low calorific components are driven out.

This makes torrefaction an appealing way of converting food waste into high energy density products. This volumetric energy densification allows cost reductions in terms of transporting and handling them. Another benefit of torrefying food waste is limited or no biodegradation. This solves the problem of production of methane through biodegradation of food waste which has a global warming potential of 21 times more harmful than carbon dioxide (Forbes, 2018). Torrefied biomass, commonly known as bio-coal, is a type of biochar which is receiving a lot of attention recently, thanks to its potential as a soil enhancer. Researchers' have proven that soil with 5% torrefied biomass yielded about 5% more water than soil without any torrefied biomass. This treated soil also showed higher levels of compression stress, shorter relaxation time, and higher nutrient contents which makes it an excellent soil enhancer (Ogura et al., 2016). A more popular application of torrifaction is its role in co-firing power plants (Shankar Tumuluru et al., 2011) . The coal-like material is easy to be transported, stored and handled, increasing its potential in energy applications. Now value can be added to food waste by everyone who has a microwave oven. Similar to how recycling plastic, papers and metals have created economy involving scrap metal industries and recycling centres, by torrefying food waste a new opportunity to create a new industry is opened up. Furthermore, with food waste being the biggest portion in MSW, the goal to achieve zero waste, to make a cleaner earth is a more plausible vision.

1.2 Problem Statement

Microwave is good for drying, hence food waste which comes with high moisture is suitable to be used in microwave oven. Since microwave causes heat generation through the material microwaved, it is able to generate heat from inside to outside. This makes microwave heating, an efficent heating process.

However, microwave-assisted torrefaction has not been used to torrefy food waste. The time of torrefaction using a microwave oven is very long due to the slow rise in temperature. This extended duration increases the amount of energy used making it less efficient. A microwave absorbent is important to reduce the time of torrefaction. Charcoal would be an attractive absorbent of microwaves.

1.3 Objectives

The specific objectives of this research are:

1. To modify the microwave oven to support torrefaction process.
2. To torrefy kitchen waste at different charcoal content and mixture, ie., Layered and homogenous.
3. To determine the efficiency and economic analysis of the microwave-assisted torrefaction system.

1.4 Scope of Research

The scope of the research is restricted within the 2 common problems microwave assisted torrefation faces. This includes solving the failure of microwave-assisted torrefaction system due to overheating and increasing the system's efficiency by reducing the time taken to torrefy food waste. Other aspects like heat rejection system and pollutant management were not inlcuded in this research.

This research is limited to only one type of food waste, which are leftover chicken bones from KFC Restaurant, Nibong Tebal. Various food waste were not mixed for this research to obtain a more consistent data, for ease of interpretation.

Only proximate analysis is performed on the food waste due to its convenience and also equipments which are readily available for such test in the School of Mechanical Engineering, Universiti Sains Malaysia.

Asbestos is used as an insulating material in this research. Abestos is used because it is cheaper, more readily available and easier to be handled and it was abundantly available in the School of Mechanical Engineering.

1.5 Thesis Organization

This thesis is divided into 5 chapters. They are introduction, literature review, methodology, results and discussion and fnally, conclusion and future work.

Chapter 1, introduction is further divided into research background, problem statement, objectives and the scope of research. Research background briefly describes the potential of microwave-assisted torrefaction to manage the ever growing challenge of waste management and pollution. Problem statement addresses the 2 major challenges microwave-assisted torrefaction system faces to be a domestic product. Objectives list down the goals that this research aims to achieve and scope of research discusses the limits and boundaries of this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Municipal Solid Waste (MSW)

Change in lifestyle and drastic urbanization worlwide generate large quantities of municipal solid waste, making it a potential threat to the ecosytem (Karak et al., 2012, Hoornweg and Bhada-Tata, 2012). Most of the MSW are sent to landfills to be disposed (Anthraper et al., 2018). The generation of MSW has experienced a sharp increase in the last decade. It has increased from 0.5 kg per person per day to 1.7 kg per person per day (Ramayah et al., 2012). From 1.4 billion metric tonnes of MSW generated every year worldwide, the waste generation is expected to increase to 2.3 billion metric tonnes by the year 2025 (Hoornweg and Bhada-Tata, 2012). MSW must be effectively managed, because if otherwise it may cause serveral health and environmental problems (Tan et al., 2014). As such, a more organized method needs to be made to manage MSW in a more sustainable manner so, waste can be processed into energy and valuable products (Tan et al., 2014, Rizwan et al., 2018).

There are several indicators of urbanization that has been found to be linked with the rate of MSW generation (Ho et al., 2017). Furthermore, MSW generation is affected by socioeconomic factors including education, occupation and familiy composition (Bandara et al., 2007). Volume of waste generated is found to have a correlation with gross domestic product (GDP) per capita (Lee et al., 2016). The amount of MSW generated has a relation with population size meanwhile composition of MSW and waste generation has been attached primarily to GDP per income level (Cohen, 2017). Average local income increase directly changes the compositio and the volume of MSW (Ogwueleka, 2013). Increased food waste content is a result of recent economic development (Wang and Wang, 2013).

2.2 Composition of Municipal Solid Waste (MSW)

MSW an be classified into different categories. It inlcudes biodegradable waste, inert waste, composite waste and waste plastics, recyclable materials, toxic waste and domestic hazardous waste(Pham et al., 2015, Baniasadi et al., 2016). Accoridng to the Inter-governmental Panel on Climate Change (IPCC), food waste constitutes of the biggest portion of MSW (25-70%) with the remaining consisting of plastic, metal, glass, textiles, wood, rubber, leather, paper and others (Pham et al., 2015, CHANGE-IPCC, 2007, Albores et al., 2016).

Topographical site, standard of living, life smartness and the population of city affects the compostion of MSW (Zuberi and Ali, 2015). MSW from poor and medium-income nations contains higher organic//biodegrable which is used for gasification, compositing and landfilling. Size, mositure and density are important physical compositions of MSW. Smaller organic waste can decompose at a faster rate and the opposite is true as well. High density waste are more eco-friendly because they decompose faster compared to less dense waste. This signifies the high combustibility like platics, cardboard, paper. Anaerobic digestion, bio-digester gas and landfill gas are more suitable for waste with high moisture content (Zuberi and Ali, 2015). Large portions of kitchen waste, leftovers and food waste from residential areas, restaurants, factory lunch-rooms, cafeterias and markets are classified as organic fraction of municipal solid waste (OFMSW) because of their high biodegradability and moisture (Beylot et al., 2013, Alibardi and Cossu, 2015).

2.3 Municipal Solid Waste (MSW) in Malaysia

Combination of Peninsular and East Malaysia makes up a total land area of 328550 km^2. Malaysia has a population around 27 million with a population density of 79.87 km^2. The sources of MSW generation inlcudes households, commercial activities and activites which are similar to those of households and commercial entreprises. To name a few are wastes from offices, institutions, schools, shops, supermarkets, hotels and services such as street cleaning and maintenance of recreational areas which falls under the municipal's responsibilty (Ngoc and Schnitzer, 2009, Singh et al., 2011).

Between the years 2000 and 2015, the Malaysian population has risen to 30.65 million from 23.49 million (Fazeli et al., 2016). Along rapid population growth, MSW generation is also increasing. A study was conducted on MSW generation in Malaysia. Showed that total daily MSW generation was 29711 tonne per day in 2012 and these number is projected to hit 36155 tonne per day by 2020 (Tarmudi et al., 2009). The immense MSW generation rate has caused MSW disposal one of the main issues concerning environmental and sustainable development.

As stipulated in Section 72 of the Local Government Act 1976, the Ministry of Housing and Local Government under the purview of the local authority is to be in charge of the waste management in Malaysia (Manaf et al., 2009). In 1993, Malaysia made an attempt to integrate manangement to further facilitate handling of MSW by initaiting a privatization in which these were four concessionaires involved. These four concessionaires were Eastern Waste Management Sdn Bhd, Southern Waste Management Sdn Bhd, Northern Waste Industries Sdn Bhd, and Alam Flora Sdn Bhd. They were responsible of collecting and transporting waste from residential and commercial sites to final disposal centers. However, their incapabality of generating revenue and maintaining an efficent operation caused Northern Waste Industries Sdn Bhd and Eastern Waste Management to fail during their concession period, ending with the termination of their contract, leaving only the remaining two concessionaires to remain in operation (Fauziah and Agamuthu, 2012).

2.4 Common MSW disposal methods in Malaysia

Landfilling is a very common practice to dispose MSW. These landfill sites in Malaysia are mostly open dumping areas, posing serious environmental threats. These threats include large scale soil, water and air contamination. Another current practice exploits incineration technology. By theory, incineration is a form of controlled combustion of waste, which utilizes recovery heat to produce steam which produces electricity through steam turbine. Similar to landfilling, incineration poses environmental concern because emissions from incinerators can form a large variety of pollutants, including heavy metals, dioxins and furans which are also harmful to human health (Chen et al., 2016).

2.4.1 Landfilling

Lanfilling is a very old practie of MSW disposal in Malaysia, though its dependency is gradually being restricted due to acute land shortage, aesthetic factors along with the pollution caused by by odors and pests. Landfill is a piece of land, usually neglected, where waste is deposited (Singh et al., 2011) and permanently sealed after concentrating it for up to 20 years. Malaysia is currently experiencing problems associated with landfill pollution and wrong waste disposal practices because of the lack of emphasis on landfill manangement aspects. Landfill pollution is one of the main environmental problems experienced by many municipalities, besides water pollution and air pollution (Fauziah and Agamuthu, 2012). New problems have arised from sealed and active landfills as a result of water source pollution, forcing the government to form a special cabinet committee which functions to propose a more comprehensive waste mangement system in Malaysia, especially in regions of high density population (Chen et al., 2016).

2.4.2 Incinerators

Since 1996, small scale incinerators have been used in the resort islands of Labuan, Langkawi, Pangkor, and Tioman. Local authorites are responsible of the MSW management of these touristy islands. The local authority responsible of Tioman Island's collection, transportation and solid waste incineration is the Tioman Development Authority (TDA). It uses subcontracts to collect solid waste from village heads and committees within the island. In 2001, 3221 of MSW was incinerated using the island's two 3-t incinerators(Unit, 2004). Unfortunately, recently the usage of these incinerators have been discontinued due to the high operating costs during incineration of high moisture waste, which resulted in high fuel costs and poor technical expertise to maintain the incinerators. As a result, finding an incineration technology that is capable of incinerating high moisture waste accompanied by a low calorific value has proved to be a challenge (Sharifah et al., 2008).

2.5 Waste to energy (WtE) conversion technologies

The share of renewable energy, a carbon zero and clean discharge energy, is showing increase year by year in the world electricity production. Biomass conversion has seen rapid growth in the recent years (Cutz et al., 2016, Antonopoulos et al., 2014). This is the result of the growing concern of climate change, interest in low price energy, increase in safety supply and to reduce environmental impact (Cutz et al., 2016, Apergis and Payne, 2011). The growing price of non-renewable energy generation set to be the precursor for developing countries to focus in waste to energy, WtE (Korai et al., 2016, Chakraborty et al., 2013). One of the promising WtE conversion technolgies, especially in thermal conversion metthods are incineration, gasification and pyrolysis.

2.5.1 Incineration

Incineration is essentially a method where waste is disintegrated in a furnace by monitoring burning at high temperatures between 750°C and 1100°C (Tozlu et al., 2016, Kim et al., 2013). Incineration aims to degrade and destroy organic elements in MSW in the presence of oxygen to reduce weight and volume of MSW to form energy from the heat (Anderson et al., 2016, Kalogirou et al., 2012). Through incineration, reduction of almost 70% of the total waste mass and 90% of total volume (Tozlu et al., 2016, Kalogirou et al., 2012) or solid wastes up to 80-85% (Pham et al., 2015, Kalogirou et al., 2012) can be witnessed depending on the composition of degree of recovery of certain materials like metals present in the ash to be recycled (Kalogirou et al., 2012).

Pollutants such as Sulfur Oxides (SO_x), Nitrogen Oxides (NO_x), Carbon Oxides (CO_x), Polyaromatic Hydrocarbons (PAH) and heavy metals are generated during the practice of incineration. These pollutants are harmful and need to go through additional treatment using state of the art flue-gass cleaning system before emitting them into the atmosphere (Tozlu et al., 2016, Pham et al., 2015, Elsamadony and Tawfik, 2015, Organization, 2007). The main importance of incineration is to produce heat and steam from MSW. The nature of the energy manufactured, effectiveness of the processing system and the amount of thermal potential of the material collected are the important factors to determine WtE recovery. The energy efficiency of generating pure electricty, heat and cogeneration ranges from 20%, 80% and 20-30% respectively (Paleologos et al., 2016, Liu et al., 2015).

2.5.2 Gasification

Gasification is a thermochemical transformation of combustibles, which is MSW, into hydrocarbon gases (carbon monoxide (CO), carbon dioxide (CO_2) hydrogen (H_2), methane

(CH_4) and low molecular weight hydrocarbons), hydrocarbon liquids (oils) and char (carbon and black ash) (Rogoff and Screve, 2019) which react at temperatures as high as (800-1200°C), without the occurance of combustion in a controlled amount of oxygen and/or steam (Kalyani and Pandey, 2014). Besides CH_4, he reactor design and the operating conditions allows the generation of other higher hydrocarbons (HC). Green gaseous fuels produced from MSW is one sparingly and universally capable action to deal with the diffculties (Tozlu et al., 2016).

Nowadays, gasification appeals as an attractive alternative to the well-established thermal treatment systems to recover renewable energy from municipal solid wastes (Wu et al., 2016). Syngas, product of gasification is characterized by improved calorific value, cleaned and can be used depending its favorite. Gasification generates bottom ash which is comparable to incineration and needs to be removed and precisely preserved (Shareefdeen et al., 2015).

Raw materials used in gasification are usually coal, petroleum-based materials, and organic based materials. These raw materials are dryed before using them. The materials in the reactor in are exposed to high pressure and heat to provide energy to produce heat while reacting in an aerobic or anaerobic condition (Rogoff and Screve, 2019). Syngas produced during gasification contain high concentrations of hydrogen and carbon monoxide and are burned in an isolated container to generate electricity (Klinghoffer and Castaldi, 2013).

2.5.3 Pyrolysis

Pyrolysis can be described as a destructive distillation process (Bajpai, 2015) where thermal decomposition takes place takes place in the absence of oxygen within the range 300-1300°C (Chhabra et al., 2016). Conventional pyrolysis (500-900 K), fast pyrolysis (850-1250K), and flash pyrolysis (1050-1300K) (Tozlu et al., 2016, Gedam and Regupathi, 2012) are the three common type of pyrolysis. Two sets of thermal degradation inlcudes major decomposition of MSW and formation of low molecular weight gases and char from volatile materials. The products of this reaction includes gaseous product, pyrolytic liquid, and char with ash as an undesirable residue (Rahman, 2013).

The feedstock, heating rate, temperature range and typre of reactor used affects the compositipn of MSW and the yield product of pyrolysis (Chen et al., 2015a). An example would be the product spreading pattern change when pyrolysis temperature varies. Lower pyrolysis temperatures usually produce more liquid product whereas higher pyrolyis temperature yields gaseous yields respectively. The speed of the process and heat transfer rate also influences the product distribution (Agll et al., 2014).

There are numerous drawbacks when converting MSW into energy via pyrolysis process. They include air pollution caused by HCl, H_2S, NH_3, SO_x, NO_x, bad odor, and exhaust gas emissions (Chen et al., 2015a). To reduce the problems, pyrolysis service are always finished along emission control strategies. Efforts to improve quality of the gas, liquid and char products must be developed to make MSW pyrolysis a more benefial process for environment (Gedam and Regupathi, 2012). In terms of waste reduction and carbon recovery, pyrolysis seems to a justifiable solution for cost profitable and reduction of environmental pollution. The biggest edge of practicing pyrolysis is that it is suitable for carbonaceous waste like chicken bones to produce liquid oil as the main product with 38MJ/kg of high calorific value (Chhabra et al., 2016, Velghe et al., 2011, Nizami et al., 2017), reducing the volume of residual to be landfilled and condensate recovery (Grycová et al., 2016, Doucet et al., 2014).

High quality crude oil, having the potential to replace fuel and refine oil as a chemical feedstock are generated through pyrolysis to obtain valuable industrial chemicals, including aromatics and phenols. MSW can be pyrolysed to produce valuable pyrolytic oils. Liquid yields produced from the pyrolysis of MSW are chemically very complex, containing a considerate amount of water (Chen et al., 2016, Ding et al., 2016).

Pyrolysis is gaining popularity as a newly distributed MSW treatment practice and also an effective waste to energy (WtE) converter. Common pyrolysis reactors includes fixed-bed, fluidized-bed, rotary kin, and tubular reactors. The latter 2 are conveniences at large scale operation. Uniform products besides heat or power must be established, to allow the formulation the expansion, as shown in Eq. 1, and use of single stage pyrolysis technology (Chen et al., 2015a).

$$C_xH_yO_z + Heat \rightarrow Char + Liquid + Gas + H_2O \quad (1)$$

2.6 Torrefaction

Torrefaction is described a mild pyrolysis of biomass where biomass is thermally pretreated within the range of 200-300°C in an inert environment under atmospheric pressure (Chen et al., 2015c). Torrefaction decomposes cellulose, lignin and hemicellulose in lignocellulosic biomass (Chen et al., 2012, Rousset et al., 2011) and lipid, carbohydrate and protein in algal biomass whereas moisture and volatiles in biomass are removed (Chen et al., 2015b, Kumar et al., 2017). The solid as a product of torrefaction has better fuel quality because of its reduced atomic hydrogen to carbon ratio and oxygen to carbon ratio, higher calorific value (Basu et al., 2014, Chen et al., 2015b), improved grindability and enhanced hydrophobicity (Arias et al., 2008, Commandre and Leboeuf, 2015). Biomass waste that is undergone densification can lower storage and transportation costs (Chai and Saffron, 2016, Couhert et al., 2009). The advantages of using torrefaction as means of biomass conversion and utilization have gained popularity in recent years (Chen et al., 2015c, Rizzo et al., 2013).

There are two types of heating mechanism for biomass torrefaction, which is tube furnace torrefaction, which is the conventional torrefaction, and microwave torrefaction (Gronnow et al., 2013).

2.7 Principles of microwave irradiation

Energy waves from the electromagnetic spectrum with frequencies of 0.3 to 300GHz, and wavelengths from 1m to 1 mm are called microwaves (Haque, 1999). Microwaves are transmitted to specific frequencies to allow absorbtion of energy of waves for the material intened for heating (Puligundla et al., 2016). Microwaves cause electric fields to fluctuate resulting the dipoles in polar liquids to constantly realign (Collins et al., 1991). Microwaves also cause the migration of ions due to electromagnetic field. The constantly changing dipoles and migration of ions produces internal friction, dispersing heat causing te material to be heated (Collins et al., 1991, Haque, 1999, Puligundla et al., 2016). Consequently, heating depends on the ability of the materials to absorb and store energy and also to disperse this stored energy to heat up by microwave. This ability is also known as dielectric constant and dielectric loss repsectively (Collins et al., 1991, Haque, 1999) whereas the materials with this ability are called 'dielectrics' or 'lossy dielectric'. The extent these materials can be heated depends on the ratio of dielectric loss to dielectric cosntant (Haque, 1999).

2.8 Microwave-assisted torrefaction

Natarajan et al., (2018) employed microwave torrefaction on *Prosopis juliflora* and studied the effects of the particle size and microwave power on the torrefaction. It was concluded that at 418W microwave power and 1.9 mm particle size, maximum energy recovery was possible. Huang et al., (2012) used rice straw and pennisetum as feedstocks for microwave torrefaction with different power levels and concluded that energy density of torrefied biomass was 14% higher than raw biomass. Wang et al., (2012) performed microwave torredaction on rice husk and sugarcane residues as feedstocks and found that microwave torrefaction lowered the O/C ratio of rice husk more than conventional torrefaction. Emadi et al., (2017) linear low density polyethylene (LLPDE) as a binder along with microwave heating to torrefy wheat and barley straw pellets. They concluded that adding LLPDE from 1 wt% to 10wt% resulted in an increase in higher heating value and a decrease in the ash contents of the two pellets. Microwave heating is a potential route to torrefy biomass and upgrade fuel. Bermúdez et al., (2015) scaled up the microwave heating process and studied the difference in energy expenditure of microwave heating as a function of the scale used. They found that the specific energy cosumption decreased by 90-95% when the sample was increased from 5 to 100g, was consistent after 200g. Huang et al., (2017) stated that biochar production by microwave torreffaction of leucaena was promising if it was deployed in an industrial scale.

2.9 Carbon as a microwave absorbent

Carbon materials which includes carbon, charcoal and activated carbon being very good absorbents of microwaves can get heated easily by microwaves. Furthermore, carbon materials has the potential to be used as a microwave receptor to heat up materials which are microwave transparent. Hence, the use of carbon materials as microwave receptors has been shown in soil remediation processes, pyrolysis of biomass and organic wastes and catalytic heterogenous reactions, etc (Menéndez et al., 2010). Currently, a new concept of pyrolysis using microwave absorbents is under development. These absorbents significantly improved the rate of heating. Relatively minimal energy input via microwave irradiation is needed to heat the absorbent. When the solid residue is dropped on the heated absorbent, the temperature in the reactor is at a steady state. Here, two heating mechanisms are employed simultaneously to heat up the biomass which is microwave irradiation and conduction due to the high temperature absorbents. The biomass is heated up less than a second to reaction temperature, allowing continuous or semi-continuous feeding of biomass to the reactor (Borges et al., 2014). These findings suggest that microwave-assisted pyrolysis with intially being a slow or intermediate rate pyrolysis, can now be a fast microwave-assisted pyrolysis, allowing to achieve higher product yield and quality at the same time (Borges et al., 2014).

CHAPTER 3

METHODOLOGY

3.1 Introduction

Microwave-assisted torrefaction is used to remove moisture and volatiles along with chemical transformation of the remaining components to produce a brittle carbonaceous coal like solid torrefied product, which has increased fraction of fixed carbon. Microwave radiation, a high-frequency electromagnetic radiation as used in heating application, termed as dielectric heating. Charged particles in the material to be heated interacts with the microwave radiation causing them to heat up. In this project, the microwave oven used is Samsung ME711K Microwave Oven with a maximum cooking power of 800W. The material torrefied was chicken bones, that were leftovers in a KFC Restaurant located in Nibong Tebal. The maximum torrefaction temperature set was 300°C . The time of of the whole process were set to 2 hours and the products of this microwave-asisisted torrefaction were assesed of their higher heating value and composition. The higher heating value of these materials were tested using Yoshida Seisakusho, 1013-B bomb calorimeter. The solid yield, energy density, energy yield and it's constituent components were calculated. Furthermore, the economic analyis and the system's efficiency were then calculated to evaluate the system.

3.2 Materials

The material selected for this experiment were leftover chicken bones and charcoal. The chicken bones are the material aimed to be torrefied meanwhile charcoal acts a microwave absorbent which is responsible in aiding the torrefaction process.

3.2.1 Food Waste

Chicken bones were selected as the material to be torrefied. With the aim of this project to make microwave-assisted torrefaction system as a household product, it was necessary to keep as much conditions similar to those faced if it were used in a domestic level. Chicken bones are very common food waste, especially from fast food restaurants. Chicken bones in this project were obtained from KFC Restaurant located in Nibong Tebal.

3.2.2 Charcoal

Charcoal is not the product of torrefaction, but its role is as a aid to torrefaction. Carbon is a good microwave absorbent (Menéndez et al., 2010). With charcoal being the most abundant and cheapest form of carbon, it was a reasonable decision to use charcoal for a project which is aimed to create a domestic product. Due to charcoal's microwave absorbent property, it heats up very fast, allowing torrefaction temperature to be reached at a faster rate. Thus, the total time taken to torrefy food waste can be reduced, reducing the operational time of the microwave oven and as a result reducing the cost of torrefying food waste.

3.3 Microwave-assisted Torrefaction System

The torrefaction system's design revolves around a microwave oven. It was modified to suit the needs of this project. The following is the setup of the microwave-assisted torrefaction system used with labels.

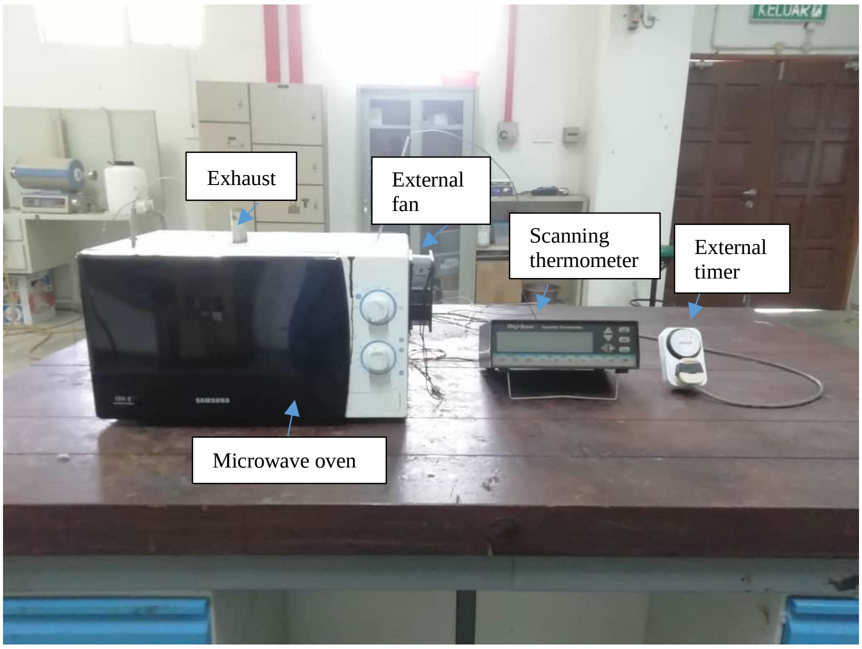

Figure 3.1 Microwave-assisted torrefaction system

The design and fabrication of the system is further discussed in the following sections.

3.3.1 Domestic Microwave Oven

The microwave oven used for this project was Samsung ME711K Solo Microwave Oven with Ceramic Enamel. The microwave's cavity dimension measures at (W×H×D) 330mm×211mm×309mm with a capacity of 20 Litres. The technical specfications of the mirowave oven is listed in Table 3.1.

Power Supply	240V/50Hz
Input Power	1150W
Energy Output	800W
Outer Dimension (W×H×D)	489mm x 275mm x 320mm
Cavity Dimension (W×H×D)	330mm x 211mm x 309mm
Cavity Volume	20 Litres
Net Weight	10.5kg
Max Cooking Time	35 minutes
Heat Source	Solo
Power Level	7
Control Method	Mechanical
Door Opening Type	Push Button Type

Microwave Distribution	Turntable
Cavity Interior	Ceramic Enamel

Table 3.1Samsung ME711K Solo Microwave Oven Specifications

3.3.2 Torrefaction Reactor

The torrefaction reactor consists of glass container and an aluminium exhaust. This is a pass down item where previous final year project (FYP) students with a relatable topic purchased the glassware and fabricated the exhaust.

Figure 3.2 Glass pot and exhaust

3.3.2(a) Glass pot

A microwavable glassware is necessary to conduct this experiment. The most important parameter to classify it as a microwavable container concerns with the tangent loss. A low dielectric constant absorbs less microwave allowing more of them to penetrate through the reactor to the food waste. Borosilicate glass, a common material for microwavable glassware has a dielectric constant as low as 3.0, making it transparent to microwaves to let microwaves to pass through the walls of the reactor without absorbing them.

3.3.2(b) Exhaust

Torrefaction causes the release of moisuture and volatiles. Therefore, an exhaust was need to release them away from the system. A simple exhaust was used to channel these unwanted products out of the microwave-cavity. The exhaust in Figure 1.2 was the work of previous students. It is a lid made out of aluminium with a dimension of 20 cm and has a hollow cylindrical leading away frm the reactor.

3.3.3 Insulation

Thermal cracking occurs in glass when there is temperature difference between 60°C - 80°C with the inner and outer surface (Yang et al., 2018). Thermal cracking is a very likely to occur during opening of microwave oven’s door. Cold atmosphere air with an ambient temperature of 27°C will rush into to cool down the outer surface of the glass reactor while the torrefied material with a temperature of 300°C continues to heat up the inner surface of the glass reactor, creating a temperature difference of 273°C in opposing walls of the glass. With this high temperature difference, thermal cracking is a very likely occurance.

Another need of insulation of reactor is to seal the heat in the reactor in the reactor itself and dispose it through the exhaust. This is to prevent heat from the reactor to reach the electric and electronic components. Most electrical and electronic items are soldered at 180°C for tin or lead eutectic solders and more than 217°C for lead-free solder alloys (K. Netting, 2012). With a temperature of 300°C in the reactor, is very likely for the electric and electronic components to experince failure if heat is not blocked away from them.

Asbestos was used as an insulating material. Abestos has a low thermal conductivity of 0.08 and a dielectric constant of 4.8 making it a good insulator and a good microwave transparent material respectively. It was also easily attainable making it a convenient insualting material to be used. Asbesots was wrapped around the reactor to a thickness of 2cm.

Figure 3.3 Insulated reactor

3.3.4 External Timer

The torrefaction was set to run for 2 hours while the original setup of the microwave oven to run only for 35 minutes. So modifictions were done to allow the microwave oven to run continuously for 2 hours. The timer in the microwave oven was by passed to allow the microwave oven to run immediately after the switch was turned without relying on the timer. Secondly, an external timer was fixed to limit the microwave oven to operate for 2 hours only.

Figure 3.4 External timer

3.3.5 External fan

The microwave comes with an internal fan which sucks in cool atmosphere air and blows it directly onto the magnetron. This cooling method alone will not suffice to support the extended operation period of the microwave oven and the relatively high temperature of torrefaction to cool the system. Therefore an external fan which sucks in hot air from the region of microwave oven which places the magnetron together with electric and electronic components to release it out of the microwave oven. This is to further enhance the ventilation of the region and thus preventing congestion of hot air within the region mentioned. The fan used was a Kyoto Cooling Power which has its own wiring to independently turn it off and on it as required in this project. The technical specifications of the fan is in Table 2.

Model Number	KT-1238HB
Power Supply	240V AC/ 50Hz
Current Input	0.14 A
Power Input	21 Watts
Fan Speed	2500 rpm
Rate of Air Flow	138 cfm

Table 3.2 Technial specification of Kyoto Cooling Power fan

3.3.6 Thermocouples

4 K-type thermocouples were utilised in this experiment. Type K was used because it has a wide temperature range (-270 to 1260°C). Thermocouple 1 was used to measure

temperature in the reactor. This is to obtain heating curve of the material to be torrefied. Thermocouple 2 was used to measure temperature on the outer surface of the insulation. This is to measure the effect of insulation on the system. Thermocouple 3 was used to measure the temperature in the cavity. Finally, Thermocouple 4 was used to measure temperature of magnetron to study the behavior of the magnetron.

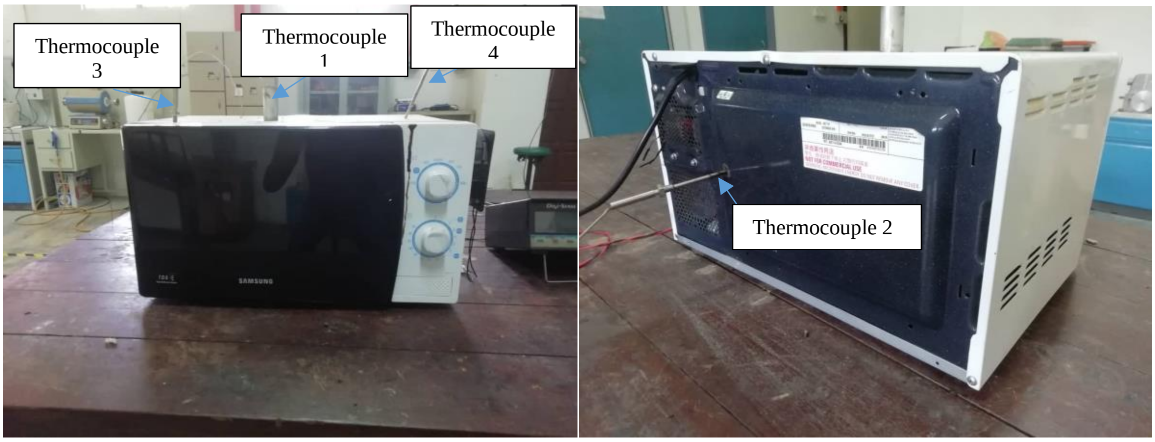

Figure 3.5 Thermocouple positon

3.3.7 Minor Modifications

The turntable was removed because movement of the aluminium lid paired with the microwave from magnetrons produce unstable readings in the thermocouple. For the sake of the experiment, the turntable was removed.

This microwave oven model comes with perforations to allow light from the bulb located in the electric and electronic region. This poses a problem because it allows heat to enter the electric and eletronic region. Besides, soot from the microwave oven travels through the perforations and into this region, which has the potential to damage the components in the region. Therefore, a silica sealent was used to seal away these perforations.