CHAPTER 1

INTRODUCTION

1.1 Solid Waste Management

According to Thailand's Energy Situation in 2009, Thailand had energy expenses of 47 billion US dollars (Damen, 2010). Industry and transport sectors consumed about 70% of total energy demand and only 5% agriculture (Energy Statistic of Thailand, 2012), as shown in Figure 1.1. Development on alternative energy would be needed. It will reduce import of oil and other energy resources. Renewable energy especially solar energy, wind energy, small hydro energy, biogas, biomass, and municipal solid waste would be crucial as future fuel expected to significantly substitute oil, coal, and natural gas for power generation.

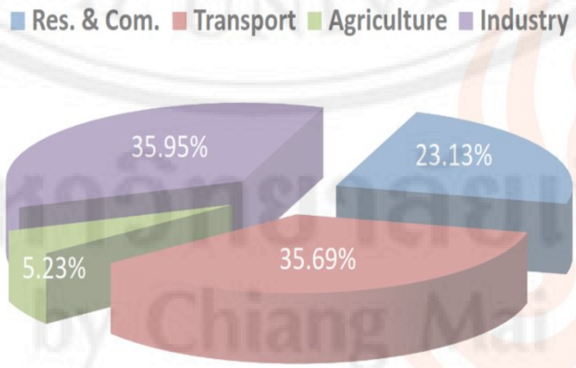


Figure 1.1 Energy demand in Thailand

(Source; Thailand Ministry of Energy, 2012)

In Thailand, Ministry of Energy established the alternative energy development plan in the 10 years (AEDP 2012-2021), as shown in Figure 1.2. The objectives of the ADEP are; (Source; Thailand Ministry of Energy, 2012)

- To capably develop renewable energy as one of the country major energy sources in sustainable replacing of fossil fuel and oil import for the future.
- To strengthen the country energy security.
- To create using renewable energy at community level as of integrated green community.
- To support the domestic renewable energy technology production industry.
- To research, develop and promote Thailand renewable energy technology for competitive capability in the international market.

This included alternative and renewable energy from waste and current situation of waste generation would be concerned. Therefore, waste to energy is an attractive option for energy generation in the future.

Increased generation of waste is a global environmental issue. Wastes are generated on a daily basis. Total solid wastes production in low, middle, and high-income countries were approximately 0.4–0.6, 0.5-1.0, and 1.1–5.0 kg/person/day, respectively. The World Bank estimated that the quantities of municipal solid waste (MSW) from urban areas of Asia would rise from 760,000 tons/day in 1999 to 1800 million tons/day in 2025. MSW includes wastes produced from commercial, omestic, industrial, institutional, demolition, construction and municipal services (Chandrappa et al., 2012)

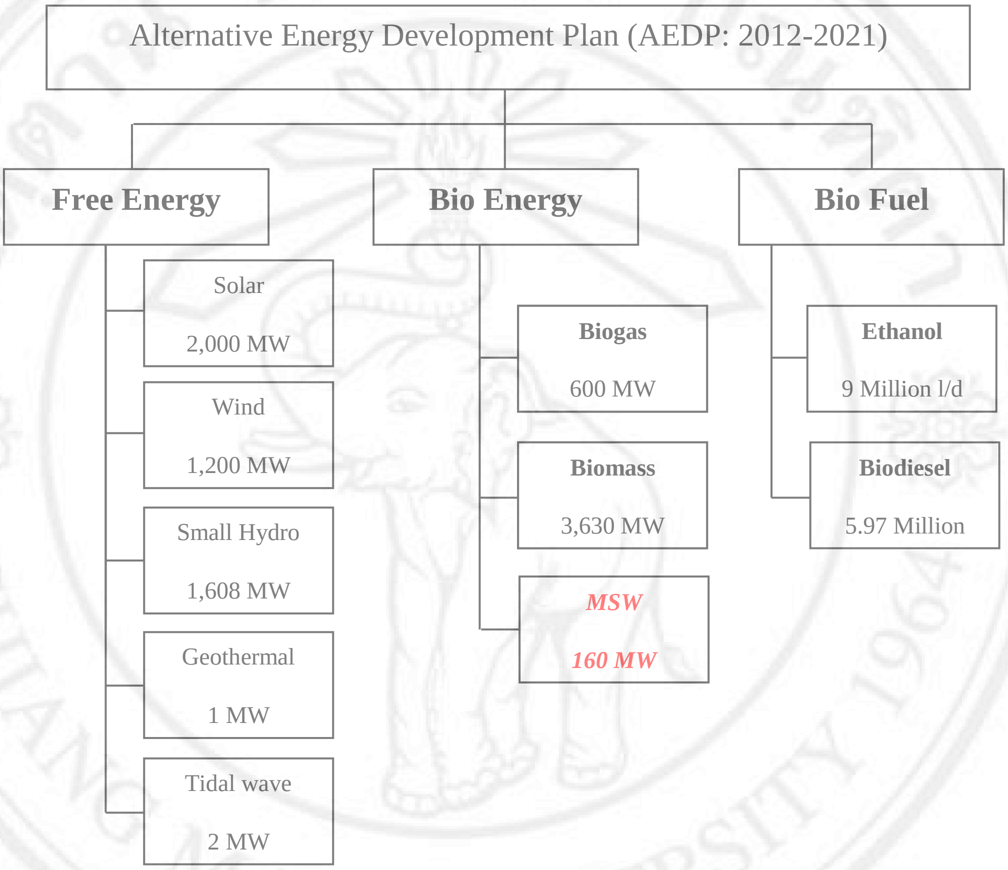


Figure 1.2 Alternative Energy Development Plan of Thailand Government, target 25% of RE in total energy consumption by 2021.

In Thailand, total MSW generation is over 35,000 tons/day and 12.78 million tons/year in 2007. Nevertheless, annual MSW generation in 2010 was reached to 15.11 million tons of which 12.69 million tons (84%) is collected. Waste production nationwide is estimated to reach almost 16 million tons/year with annual growth rate is 1.5% per year in 2011. (Tippayawong and Kinorn, 2007; Jacob et al., 2012). The most compositions of MSW in Thailand are biomass, plastics and papers (Pollution Control Department, 2006), as shown in Figure. 1.3.

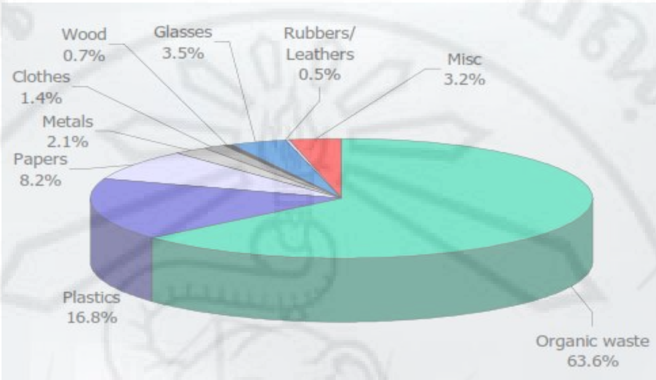


Figure 1.3 Compositions of municipal solid waste in Thailand

(Source; Pollution Control Department, 2006)

In 2008 most of Thailand's MSW was disposed improperly. According to Thailand's Pollution Control Department's staff, Thailand's MSW was disposed in open dumps about 78%. Only about 11% of the MSW was recycled and about 11% was treated in other proper technology facilities (Cherdsatirkul, 2012). MSW management in Thailand is summarized in Table 1.1.

The need to manage MSW is well recognized. Solid waste management in Thailand has moved toward national environmental policies and plans. The policy is developed mainly for integrated solid waste and wastewater management. The national integrated waste management policy purposes to minimize waste generation by promoting 3Rs hierarchy including promotion of waste reduction and separation at source, waste materials recovery for composting, materials and energy uses (Sharp et al., 2012). Recently, technological strategies for disposal of solid wastes in Thailand can be classified as (i) land filling, (ii) recycling, (iii) incineration, and (iv) waste-to-energy (WTE) conversion, as shown in Figure 1.4.

Table 1.1 Thailand MSW by means of disposal method; (Source; Cherdsatirkul, 2012)

Thailand MSW management 2008	Annual waste (tons)	% of Total
Open dumps	11,751,950	78.2%
Recycle	1,650,000	11.0%
Sanitary land filling	1,420,000	9.4%
Incineration	142,350	0.9%
Windrow composting	36,500	0.2%
Anaerobic digestion	29,200	0.2%
Total	15,030,000	100%

Figure 1.4 Disposal of solid wastes in Thailand

(Source; Pollution Control Department, 2006)

Land filling is a site for the disposal of wastes by burial. It considered the simplest and cheapest of disposal methods. However, there are many impacts from landfill method, such as (i) methane emissions from anaerobic decomposition of biogenic carbon compounds, (ii) transportation CO_2 emission from land filling equipment, (iii) biogenic carbon stored in landfill site, and (iv) CO_2 emission avoided through land filling gas-to-energy project. Incineration is described as thermal treatment for reducing mass and volume of wastes. High temperature is employed for combustion process. There are two types of incineration, with and without energy recovery. Both types can reduce the volume of disposed waste by up to 90%. In the case of incineration with energy recovery, the energy can be recovered from the process. Recovering the energy value embedded in waste prior to final disposal is considered preferable to direct land filling assuming pollution control requirements and costs are adequately addressed. Typically, incineration without energy recovery or non-autogenic combustion is not a preferred option due to costs and pollution. Open burning of waste is particularly discouraged due to severe air pollution associated with low temperature combustion (Hoornweg and Bhada-Tata, 2012). Recycling is the sorting of the wastes to recover materials that are recyclable, fermentable, or combustible. The key advantages of recycling are reduced quantities of disposed waste and the return of materials to the economy. Related green house gas (GHG) emissions come from the carbon dioxide associated with electricity consumption for the operation of material recovery facilities. Informal recycling by waste pickers will have little GHG emissions, except for processing the materials for sale or reuse, which can be relatively high if improperly burned, such as metal recovery from e-waste (Hoornweg and Bhada-Tata, 2012). WTE conversion is the utilization of solid waste for generation of energy and electricity (Tippayawong and Kinorn, 2007). WTE technology was summarized in the next point.

1.2 Waste-to-Energy Technology

WTE is an extremely attractive option. It refers to any waste treatment that generates energy in the form of electricity or heat from a waste source as well as energy byproducts, such as synthesis gas, liquid fuel and char. Presently, WTE technologies consist of many conversion methods, such as physical, biochemical and thermochemical. Physical conversion is a basic technology involving various processes to improve physical properties of waste. Hazardous waste, metal and other incombustible matters can be removed. The remaining combustible fraction of the waste is subsequently dried, size-reduced and compacted into fuel pellets. Refuse derived fuel (RDF) is the main product from the physical conversion process. RDF is combustible or, in other word, high calorific fraction recovered from MSW. There is another definition defined by ASTM standard (2006) that RDF is a shredded fuel derived from MSW which metal, glass and other inorganic materials have been removed and has particle size 95 %wt passes through a 2-in square mesh screen. MSW composition is varied from different sources, seasons and living behaviors. Raw MSW has high moisture content, low calorific value, wide range of particle size distribution and high ash content. These reasons make using raw MSW as fuel difficult and unattractive. RDF presents several advantages as a fuel over raw MSW. The main advantages are higher calorific value which also remains fairly constant, more uniformity of physical and chemical composition, ease of storage, handling and transportation, lower pollutant emissions and reduction of excess air requirement during combustion. (Nithikul et al., 2011). In low and middle-income countries, composition of the mechanically separated MSW consists of 30% paper, 50% biomass, and 20% plastic. It has low moisture content, improved calorific value, and uniform size (Chandrappa et al., 2012). Biochemical processing of waste is an anaerobic digestion, it is a technology appropriate to the solid waste with high organic content. Organic compounds can be separated and fed into the digestion tank where anaerobic fermentation takes place. As a result, methane gas is generated and can be collected for various kinds of application (Sharp et al., 2012). Thermochemical processing of waste can produce a high valued syngas, rich in H_2 and CO, CH_4. It is a technology of choice for utilization of waste. It includes combustion, pyrolysis and gasification conversion. Direct combustion of waste with energy recovery is the most common WTE implementation. Nevertheless, it normally gives low energy efficiency. Pyrolysis or gasification are a thermochemical process in an oxygen starved environment at relatively high temperatures (> 500ºC), transforming wastes into liquid and gaseous fuels as well as char. The product gas containing H_2 and CO is a key advantage that can be further used in a variety of applications such as combustion in a turbine or an engine, heat and power generation as well as use in fuel cells (Blanco et al., 2013).

In Thailand, the government is promoting community to collaborate in broaden production and use of WTE technologies. WTE implementation in Thailand was shown in Figure 1.5. The government promotes and supports WTE production from MSW in small communities, such as schools, temples, communities, local organizations. RDF management, production and utilization in local administrative organization were promoted. General purpose of WTE is to produce energy from

MSW by all types, especially the used of RDF to generate heat for power plants, including production of synthesis oil and gaseous fuel derived from thermochemical conversion of RDF (Haema, 2012). Thermochemical conversion is the technology that converts waste into higher grade fuel, such as synthesis gas, oil and char. It includes pyrolysis, gasification as well as plasmochemical conversion. Thermochemical conversion of RDF can be generated higher quality synthesis fuel and offers advantages over raw waste from higher yield and calorific value of product gas, higher H_2 generation, and lower pollutant emissions (Moustakas et al., 2005; Nithikul et.al, 2011). Therefore, it is an attractive option for WTE.

Figure 1.5 WTE implementation in Thailand

(Source; Jacob et al., 2012)

1.3 Plasmochemical Conversion

Faraday proposed to classify the matter in four states (Atav, 2013). The states of matter are solid, liquid, gaseous, and radiant. The last state of matter started with the studies of Heinrich Geissler (1814-1879). Heinrich discovered the new phenomena with matter in a different state. The new term of matter is radiant and coined by Faraday (Atav, 2013). Plasma is an ionized gas. It is the fourth state of matter. Four states of matter was shown in Figure 1.6.

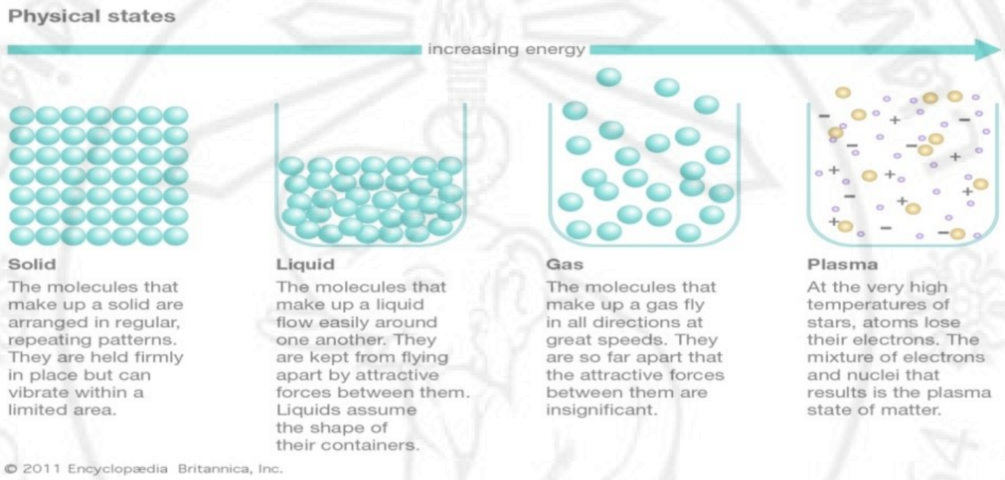


Figure 1.6 States of matter

(Source; http://www.britannica.com/EBchecked/media/148660/

States-of-matter,%202012)

Plasma can be generated by applying energy to gas electrons. Elastic collisions between electrons and heavy particles occur. Due to the large mass of heavy particles, the collided electrons rebound whereas the heavy particles remain static. Supposing that electrons get enough energy to produce inelastic exciting or even ionizing collisions, the gas is partially ionized and becomes plasma which supports energy propagation as shown in Figure 1.7. Plasma can be formed in natural like lightning and aurora (astronomy) as shown in Figure 1.8. Some common plasma are found in household, such as neon sign, fluorescent lamp, plasma ball, and plasma display etc., as shown in Figure 1.9. Plasma can be carried out at atmospheric or reduced pressure. Depending on electron density or temperature of plasma. These two parameters distinguish plasmas into different categories. It can be classified into the range of thermal and non-thermal plasma (Tendero et al., 2006). Plasmas can be used for a wide purposes, such as surface activation, oxidation, depositing of materials, (Buyle, 2009) as well as thermochemical processing etc.

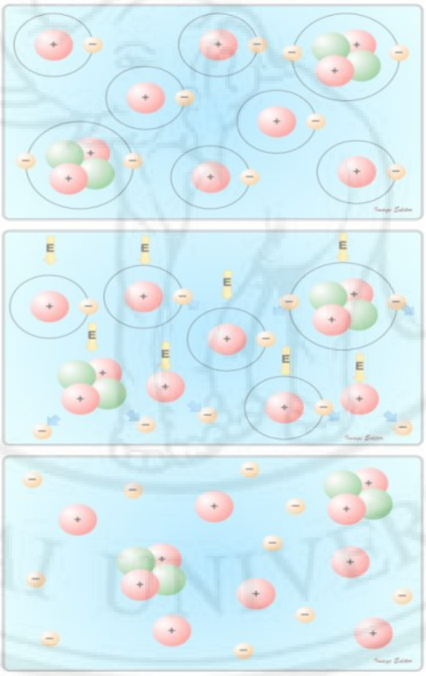


Figure 1.7 Plasma generation.

(Source; http://www.flickr.com/photos/11304375@N07/2821103686)

(a) (b)

Figure 1.8 Plasma in natural, (a) lightning, (b) aurora (astronomy)

(Source; (a) http://en.wikipedia.org/wiki/Plasma_physics

and (b) http://apod.nasa.gov/apod/ap071009.html)

(a) (b) (c)

Figure 1.9 Plasma in household, (a) neon signs, (b) fluorescent lamp, (c) plasma ball

(Source; (a) http://en.academic.ru/dic.nsf/enwiki/182381,

(b) http://www.advancedbuildings.org/fluorescent-bulbs.html

and (c) http://www.123rf.com/photo_343577_colorful-plasma-

lamp-experiment-on-a-black-background.html)

Plasmochemical conversion may be adopted. Depending on plasma temperature, it can be used for material processing, surface coating, as well as fuel synthesis (solid, liquid, and gaseous fuel). In the case of fuel synthesis, thermochemical conversion of hydrocarbon substrate is well known. It includes pyrolysis and gasification. Conventional pyrolysis or gasification needs external heat source such as burner or electrical heater to maintain reaction temperature. However, the needed power for external heat source can reduce system efficiency. Plasmochemical conversion or plasma processing method is a relatively new kind of thermochemical conversion. It offers advantages over conventional thermochemical processes from fast heating, ease to controls, low power consumption and environmentally friendly method to dispose of hydrocarbon substrate, converting it to commercially usable by-products (Moustakas et al., 2005). The process generates high product gas quality compared with conventional thermochemical conversion, such as incineration, pyrolysis and gasification. The thermal and chemical properties of plasma are synergized with the pyrolysis and gasification process, as shown in Figure 1.10. The process was claimed to interrupt the formation of dioxins and kills bacteria. It was reported that organic materials can be converted to gases at more than 99% conversion efficiency (Hu et al., 2012; Yoon et al., 2012; Li et al., 2005; Nema et al., 2002; Ahmed et al., 2009; Tang and Huang., 2005; Tsai et al., 2006). Plasmochemical conversion would be summarized in literature review.

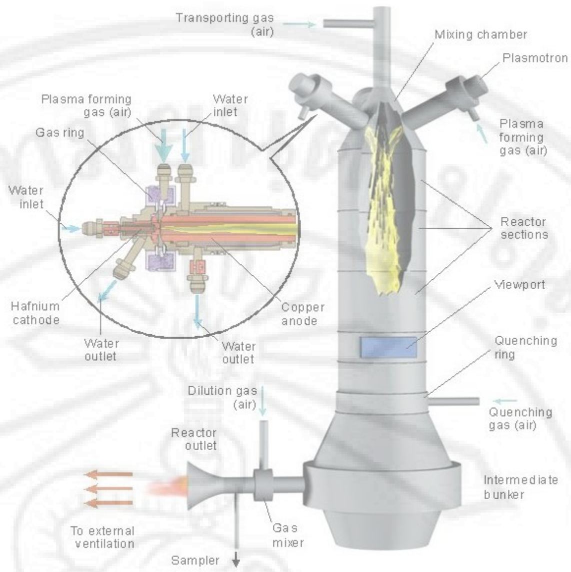


Figure 1.10 Plasma gasification system

(Source; http://www.httcanada.com/chemtoxrad.html)

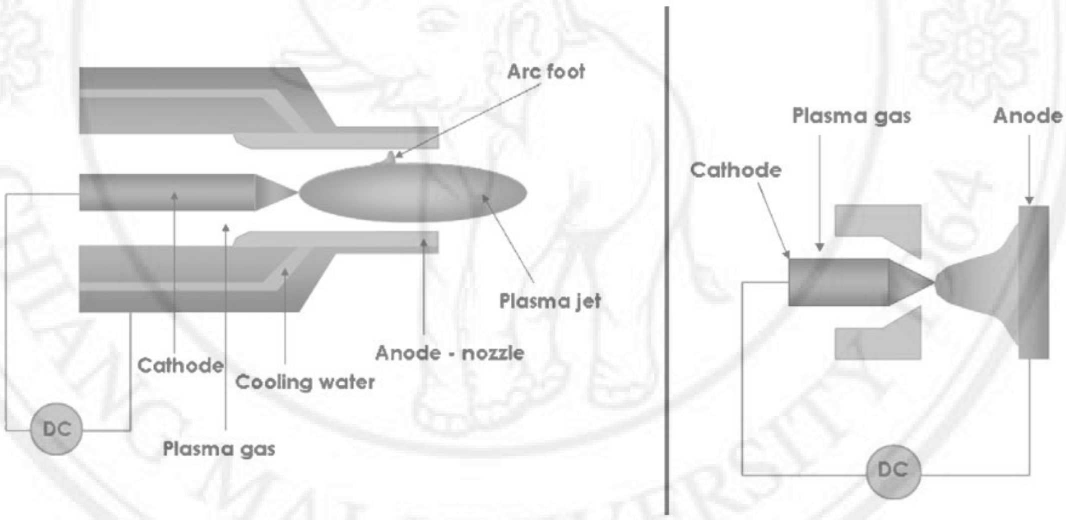
1.4 Literature Reviews

Plasmochemical methods include plasma gasification and pyrolysis. This section discusses plasma pyrolysis in the literature. The review can be divided into seven related areas as follows.

1.4.1 Plasma Sources

All types of plasma source have been developed using the same principle. Energy was applied to a gas in order to reorganize the structure of the gas species (atoms, molecules) and to produce excited ions. This energy can be thermal, electric current or electromagnetic radiations (Tendero et al., 2005). There are many types of plasma source, such as arc plasma, radio-frequency (RF) induction plasma, and microwave induction plasma etc.

Arc plasma are electrical discharge (AC or DC arc) plasma sources can be operated at atmospheric or reduced presser. The electrical power is supplied to a pair of electrode with the plasma gas being extracted as a jet through an opening in the electrode gap and out of the confines of the cathode and anode space (Nema et al., 2002; Tendero et al., 2006). The principle of arc plasma torches design was shown in Figure 1.11. It generate thermal-plasma, requires high electrical energy to keep high temperatures in the plasma discharge.



(a) (b)

Figure 1.11 The principle of arc plasma torches,

(a) non-transferred arc, (b) transferred arc

(Source; Tendero et al., 2006).

Many researchers are active in the development of plasma systems using arc plasma technology for pyrolysis and gasification. For example, Janajreh et al., (2013) investigated the plasma gasification of waste. Their plasma system consisted of a non-transferred DC arc plasma torch, electrical power supplies, insulated reaction chamber, feeder, slag handling equipment, syngas treatment system, monitoring and control system, as shown in Figure 1.12. Reaction chamber is connected to a plasma torch that supplies the energy for the gasification reactions. Plasma decomposes feedstock and reduces inorganic compound and ash portion to a molten slag in reaction chamber. The slag is collected at the bottom of the reactor. Product gas contain CO, H_2 and traces of pollutant gases.

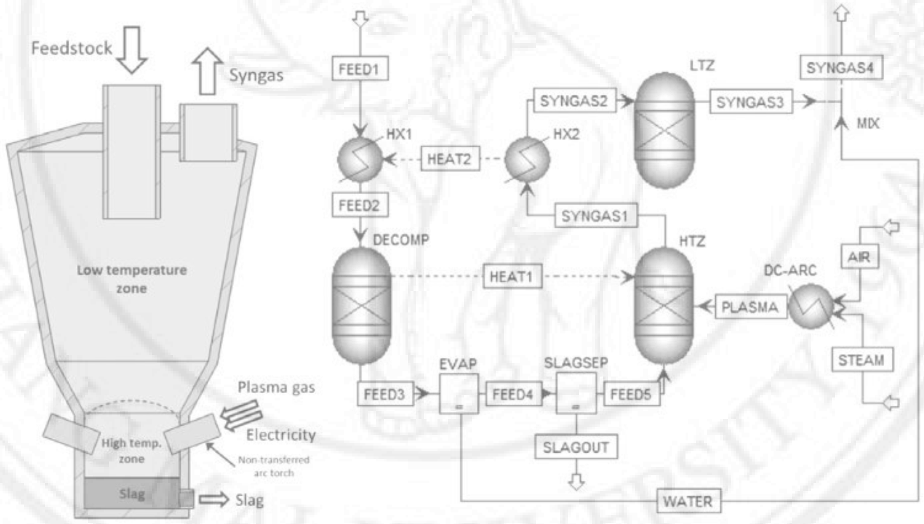


Figure 1.12 Schematic diagram of Arc plasma gasification system

(Source; Janajreh et al., 2013)

In 2002, Nema et al. used the arc plasma torch to treat hazardous medical waste. The arc plasma torch is used as external heat source. The torch consisted of a water cooled tungsten tip with an auxiliary copper anode. The anode cup is placed in front of the cathode. Both electrodes are surrounded by a magnetic field coil, which produces an axial magnetic field parallel to both the anode and cathode axes. The power supply for plasma pyrolysis experiments is 50 kW (DC) with open circuit voltage of 400 V, arc voltage of 125 V and maximum arc current of 400 A. It has a high voltage of 3.5 kV and high frequency of 4 MHz. The spectroscopic temperature measurement is used. Temperature close to the cathode, anode tip, and waste are around 20,000 K, 7000 K, and 1500 K, respectively. Nitrogen is used as plasma gas. The flow of plasma gas is controlled using rotameters. The plasma pyrolysis system consisted of two process chambers. Hospital wastes are fed into primary chamber which arc plasma torch was installed. Product gas came out from primary chamber contain hydrocarbons, CO and H_2. Then, primary gases are passed through a temperature zone about 1050 ^oC and burned with some excess quantity of air and they are converted into CO and H_2O in the secondary chamber. The arc plasma pyrolysis system schematic was shown in Figure 1.13. Whereas, the high energy requirement of electrical arc plasma torch reduce the process efficiency. However, depending on power supply, plasma temperature, operation cost, as well as feedstock. In case of high temperature needed, such as plasma gasification coal, used tire and oil, arc plasma is available. Whereas, initials temperature of arc plasma (3000 to 10,000K) is too high for plasmochemical conversion of biomass (Tang and Huang, 2004 and 2005; Konno et al., 2011). The used of arc plasma, high energy supply was required and its electrode has limited lifetime.

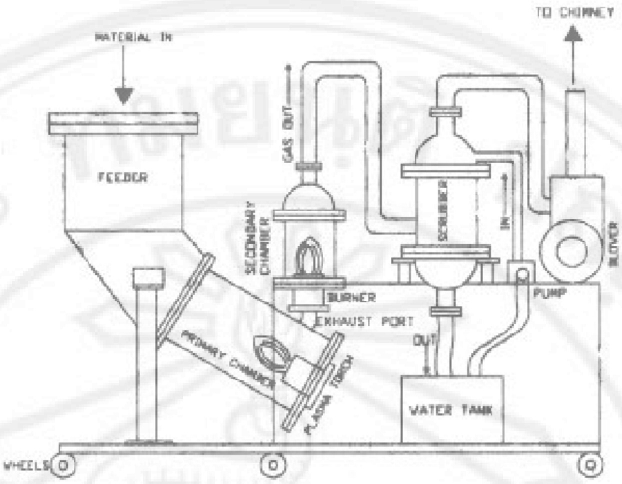


Figure 1.13 Schematic diagram of Arc plasma pyrolysis system

(Source; Nema et al., 2002)

Radio-frequency induction plasma or RF plasma is the use of a radio frequency magnetic field to transfer energy by means of electromagnetic induction to the plasma gas. The current is flows in the RF coil induces magnetic field in the plasma zone. The electric field accelerates the electrons in plasma gas and maintains the discharge. The frequency of the RF is higher than 1 MHz. This frequency level implies that electrons follow the electric field oscillations and neither ions nor electrons can reach the torch wall. The plasma is formed in a tube which made of quartz, ceramic, silicon or nitride. Cooling system can be added, depending on the working power. A higher working power is regulated with lower torch diameter and lower RF frequency (Tendero et al., 2006). The principle of RF plasma torches design was shown in Figure 1.14.

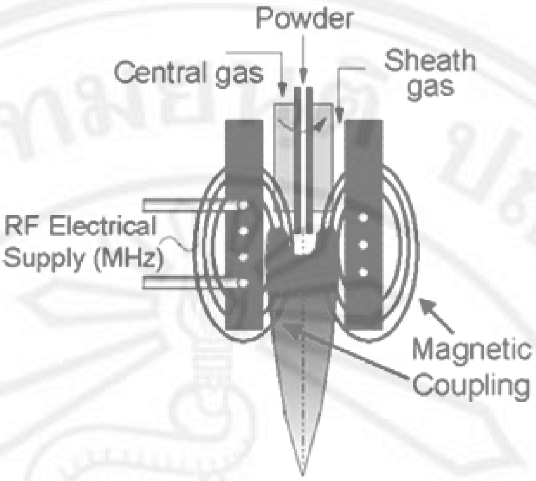


Figure 1.14 Principle of RF plasma torches

(Source; Tendero et al., 2006).

RF system can generate non-thermal and thermal plasma depending on working power. RF plasma is used in a various purposes. Many researchers used RF plasma as the external heat source for plasmochemical conversion. Tang and Huang, (2005) presented a RF plasma pyrolysis of biomass. Their plasma device consisted of a capacitive coupled, RF (13.56 MHz) generator with a maximum power output of 2000 W, a matching network, and a cylindrical quartz reactor tube with an inner diameter of 16 mm and a length of 500 mm. Two cylindrical copper electrodes with each 25 mm wide and spaced 30 mm apart are installed surround reactor tube. Electrodes transmitted power from the RF power source to the gas that flows through the tube. The reactor operated at pressures between 3 to 8 kPa. Nitrogen (N_2) with flow rate 0.5 lpm is used to purge oxygen in the system and serve as a carrier gas to generate the plasma. Feedstock are fed into the plasma reactor on the top of quartz tube with feed rate of 0.3 g/min. Product gases are evacuated from the reactor by means of a variable speed rotary vacuum pump. Gaseous products are analyzed using a gas chromatography (GC) system. Their RF plasma discharge length is 9 to 14 cm, and the gas temperature are in the range of 1173 to 1773 K. The yield of product gas is averaged 66 wt % of the biomass feed at an input power of 1800 W and an operating pressure of 5 kPa. The total content of CO and H_2 are averaged 76 vol % on a nitrogen-free basis. The RF plasma pyrolysis of biomass system schematic was shown in Figure 1.15.

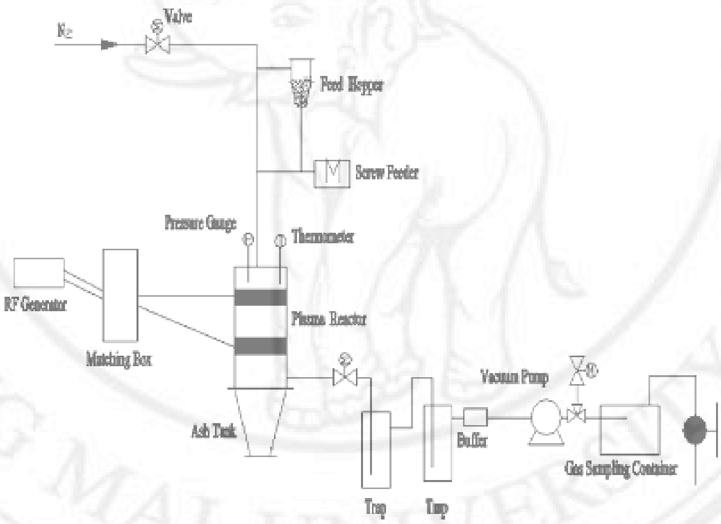


Figure 1.15 Schematic diagram of RF plasma pyrolysis system

(Source; Tang and Huang, 2005)

Tu et al., (2008) presented pyrolysis of rice straw using RF plasma. Their RF plasma reactor consisted of a 13.56 MHz RF generator with a maximum power of 2000 W, an auto matching equipment. The reaction tube made of quartz with an outer diameter of 50 mm, a wall thickness of 2 mm, and a length of 500 mm. Two electrodes made of copper arc with each length of 320 mm are fixed and covered around the outside of the quartz tube with a gap between two electrodes. Nitrogen (N_2) is used as working gas, it passed through drying tube and controlled via a mass flow controller with flow rate of 200 ml/min. Feedstock are fed by a continuous feeder with two valves open and closed exchanged to hold the vacuum in the plasma reactor. Thermocouples (type K) is used to measure the temperatures of the RF plasma reactor. Reaction temperatures are controlled from 300 to 950 K with the input power of 137 to 591 W under the absolute pressure of 1/760 atm (1 torr). The length of plasma reaction zone is about 320 mm. Plasma temperature are in the range of 607 to 954 K. The schematic diagram of the RF plasma pyrolysis of rice straw was shown in Figure 1.16.

Microwave plasma is non-thermal and can be generated using a 2.45 GHz magnetron from commercial microwave oven. It is simple, economical, easy to control and requires low power (Tendero et al., 2005; Chaichumporn et al., 2011; Uhm et al., 2006). Microwave plasma is designed for wide purpose, such as plasma coating, plasma torch, plasma synthesis, and plasmochemical conversion etc. For example, Karches et al., (2001) presented a circulating fluidized bed microwave plasma reactor, as shown in Figure 1.17. Their microwave plasma reactor consists of a quartz tube with internal diameter of 4 cm and length 50 cm. It is surrounded by four ring shaped slotted antennas with length of 6 cm for the coupling of microwave energy. The tube is replaced one a vertical steel tube, where the particles are fluidized and entrained with a high gas flow rate. Axial temperature are continuously measured with thermocouples. Pressure profiles are also continuously measured above the glass tube with pressure sensors. Argon is used as plasma gas. It is stable, long lived ions stabilize, enlarge the electron density, forms negative ions and reduces the number of electrons in the plasma. They found that microwave power is only absorbed by the plasma gas electrons and reflected power should be as small as possible for an energy efficient process. Power absorption is an indicator for the plasma strength and stability. Internal heat transfer in the reactor is not sufficient to provide a uniform temperature and to avoid hot spots. The maximum temperature was found at the axial position of the coupling slots with net microwave power of 400 W. It is approximately 423 K.

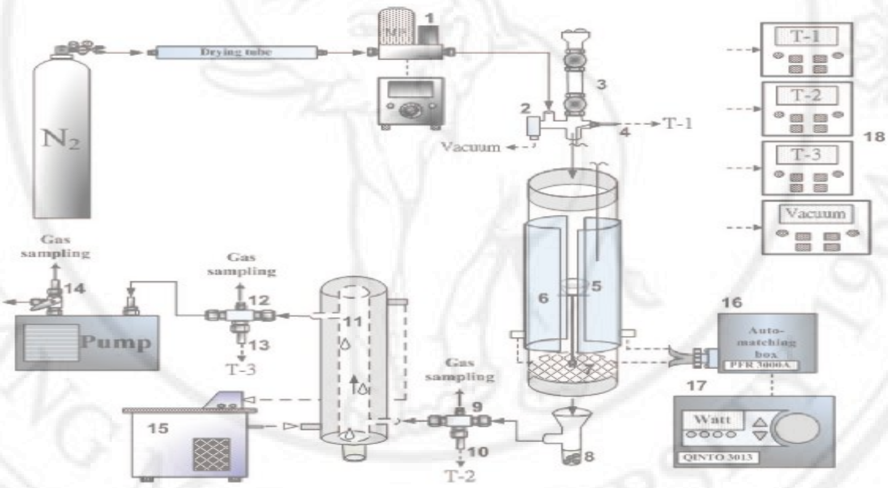


Figure 1.16 Schematic diagram of RF plasma thermolysis system,

(1) mass flow controller, (2) vacuum meter, (3) continuous feeding apparatus,

(4, 10, and 13) thermocouples, (5) crucible and its support, (6) copper electrode,

(7) stainless steel net, (8) solid product storage, (9,12, and 14) gas product samplers,

(11) condenser and liquid product collector, (15) circulating thermostat,

(16) auto-matching box , (17) RF plasma power supply, (18) digital monitors

(Source; Tu et al., 2008)

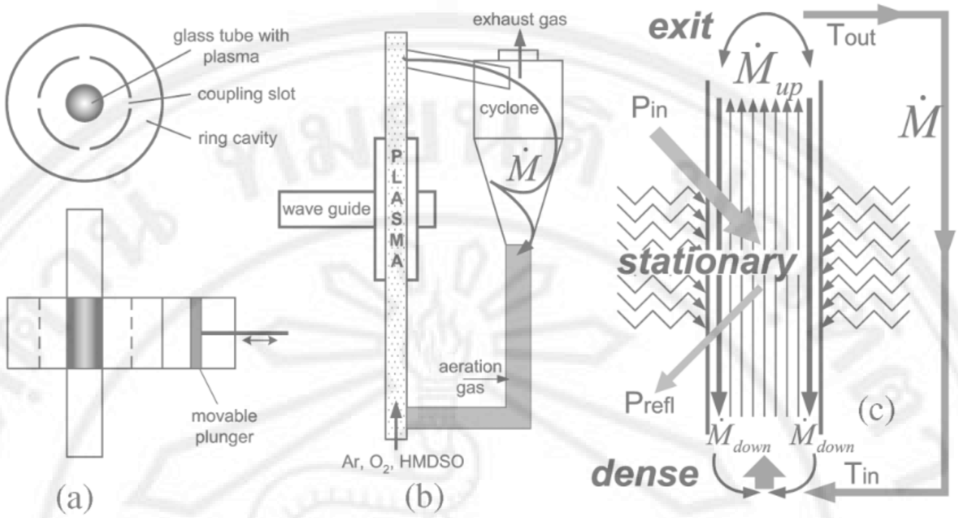


Figure 1.17 Schematic diagram of a circulating fluidized bed microwave plasma reactor (CFB), (a) MW source, (b) CFB, (c) solid flow scheme (Source; Karches et al., 2001)

Many researchers present plasma pyrolysis and gasification using another types of plasma source. Some studies presented microwave assisted pyrolysis using microwave irradiation power to heat feedstock. Wang et al., (2012) studied the microwave induced torrefaction of rice husk and sugarcane residues. The study utilized microwave irradiation to mild pyrolysis by varying different parameters, including microwave power level, processing time, water content, and particle size of biomass. Microwave source in this study was a single focused microwave device. A schematic diagram of the system was shown in Figure 1.18. The magnetron with maximum power 2 kW and 2.45 GHz frequency was applied inside the microwave generator. Microwave device was connected to the cooling system to prevent overheating during the experiment. Microwave energy was guided to reaction chamber using wave guide. A 3-stub tuner was used to regulate the incident angle of microwave to make sure that the peak of microwave was in the center of reaction zone. A short circuit was set to adjust the wavelength phase of microwave at the end of waveguide. The quartz reaction tube with length of 40 cm, outer diameter of 5 cm and the quartz sample holder with length of 3 cm, outer diameter of 4 cm were installed inside the reaction chamber. The reaction temperature was measured by a thermocouple that placed at the bottom of the sample holder. The dried and sieved feedstock of in the range of 7 to10 g was placed in the sample holder. Nitrogen was used as a carrier gas. It was injected into the system with a flow rate of 50 ml/min and controlled by flow meter to purged an oxygen for 30 min before experiment. After processed, microwave power was shut down. However, carrier gas kept purging until solid residues are cooled down to 80 ^{o}C before removing to desiccators. They found that mass yield and energy yield of rice husk and sugarcane residues are reduced with increasing of process time at certain microwave power levels. The mass yields of rice husk with microwave power of 250 W and process time of 8, 10, 12, and 30 min are 39.71%, 38.18%, 37.28%, 33.62%, and 33.37%, and the energy yields are 46.00%, 45.36%, 44.99%, 42.25%, and 39.55%, respectively. The mass yields of sugarcane residues for 4, 5, 6, and 15 min are 67.16%, 59.49%, 32.90%, and 25.47%, and the energy yields are 79.42%, 74.06%, 47.98%, and 39.87%, respectively. They suggested that microwave power and processing time should be the primary parameters affecting the performance of microwave induced torrefaction. The water content of biomass would not affect the reaction as much as other parameters at moderate microwave power.

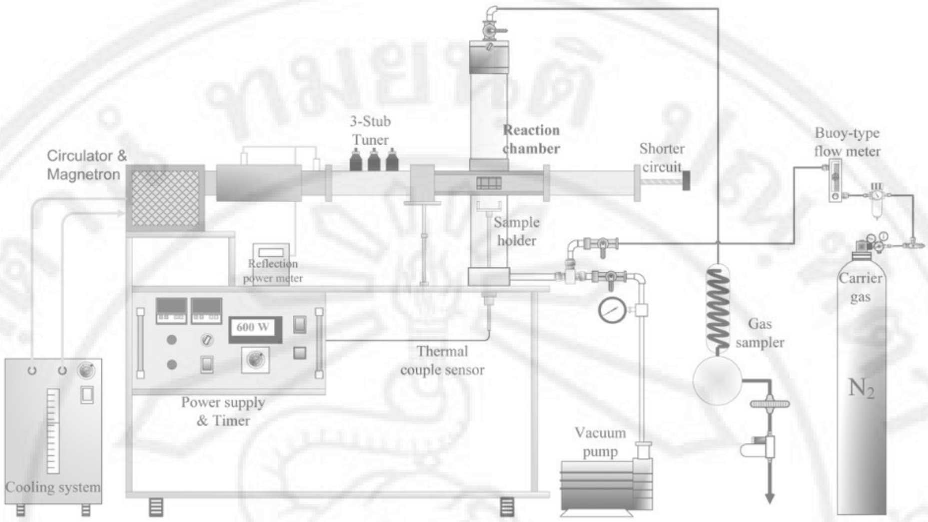


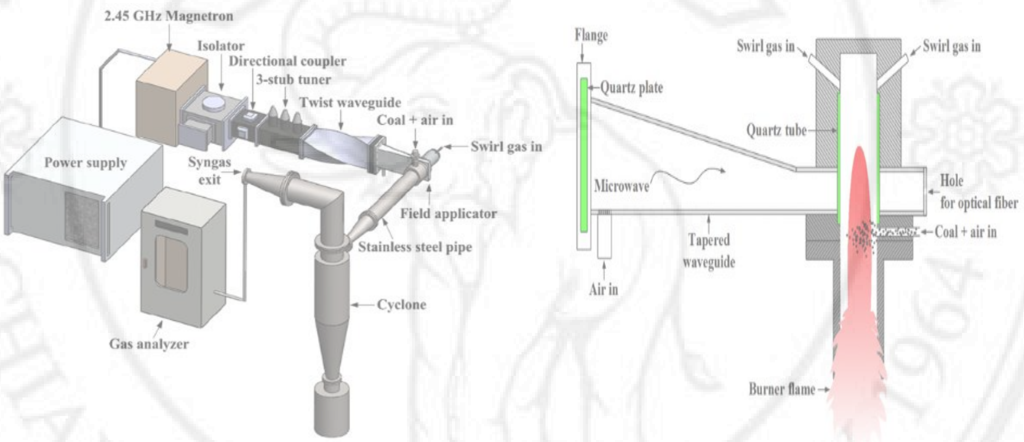
Figure 1.18 Schematic diagram of a microwave induced torrefaction of rice husk and sugarcane residues

(Source; Wang et al., 2012)

However, microwave pyrolysis system of Wang et al., (2012) did not generate the plasma. They used microwave power as heating source. There are a few studies of plasmochemical using microwave plasma. For example, Hong et al., (2012) investigated the production of syngas from microwave plasma gasification of brown coal. Their atmospheric pressure pure steam torch plasma consisted of microwave generator with power of 4 kW and frequency of 2.45 GHz, WR-340 waveguide components with isolator, directional coupler, 3-stub tuner, reactor tube, and a coal feeder, as shown in Figure 1.19 (a). The WR-340 waveguide was tapered to a shorted cross section to increase the electric field intensity in the discharge tube. A quartz plate was installed at the end of the tapered waveguide to prevent the 3-stub tuner and magnetron from injected air, as shown in Figure 1.19 (b). A quartz tube with an outer diameter of 30 mm and thickness of 1.5 mm was inserted perpendicularly to the wide wall of the waveguide. It was located at a 1/4 wavelength away from the end of the waveguide, where the electric field was peaked. Microwave power was applied directly into reactor tube. The electric field in the quartz tube and reflected microwave power can be adjusted with the 3-stub tuner. The plasma was started by a the ignition system. It formed at a tip of tungsten wire which was installed into the quartz tube. Plasma inside the quartz tube was stabilized by injecting a swirling gas. The gas fed into the discharge tube on sideways via four small holes. Injected gas was created a vortex flow in the tube. It stabilized plasma flame in the center of the tube and prevented the tube wall from the heat. Air, O_2, and a mixture of air and O_2 were used as a plasma gas. Powdered brown coal with the average particle size of about 70 µm was used as a feedstock. From the experimental data, they found that the relative concentrations of product gas at a ratio of coal to steam of 1.36 is 48% of H_2, 23% of CO, 25% of CO2 and 4% of CH4. They explained that H_2 was generated from the moisture content in the coal. The further increasing of coal to steam ratio is not much reduced CO_2 concentration.

Kim et al., (2010) developed microwave plasma system for fuel reforming of methane, iso-octane and gasoline. Their microwave plasma system was powered by a low cost commercial magnetron with power of 250 W and frequency of 2.45 GHz. The microwave power was applied to the nozzle via a coaxial cable. Microwave from the resonator was coupled to the circulator with Type-N connector and forward power was connected to the nozzle. The internal geometry of the nozzle is especially optimized for plasma ignition by delivering high electric field at the nozzle tip. The reflected power from the nozzle was passed through the circulator and it was delivered to a dummy load for dissipation. They used Ar as a dilution gas to avoid excessive heat release from the oxidation reaction and to protect the nozzle and electrode. Flow rates of Ar, CH_4 and O_2 were controlled by the mass flow controllers. The cylindrical shape reactor with inner diameter of 80 mm and length of 150 mm was made of quartz. The two aluminum covers were installed at the top and bottom of the reactor and the nozzle was attached to the top cover. Feedstock fed through the nozzle with the tube which installed at the bottom cover, as shown in Figure 1.20. They explained that the reason of not to feed raw materials together with carrier gas was to prevented the nozzle from choking which can be caused by carbon deposition. Their reactor is different from others in which a feedstock and carrier gas is supplied together into the plasma torch. This system is a non-premixed type configuration. In this study, the torch was generated plasma flame with approximately length and diameter of 1.5 cm and 0.5 cm, respectively. For liquid feedstock reforming, they attached evaporating device into the system. Liquid feedstock was fed by a syringe pump at a fixed flow rate and passed through a tube which was heated by a heating tape at temperature around 250 ^{o}C. Argon with flow rate of 0.2 lpm was mixed with feedstock vapor to carry evaporated feedstock to the plasma flame. From experimental results of methane reforming, they found that the more applied input power is resulted in more production of H_2 and CO. This result indicated that their plasma reforming of methane is not conducted completely in low applied input power. Moreover, they explained that more power input is used for the partial oxidation to convert methane to H_2 and CO. From experimental results of iso-octane and gasoline reforming, they found that the more power input is also raised the production level of

H_2 and CO. However, iso-octane and gasoline reforming are produced CO more than twice of that produced from methane reforming for the same mass of feedstock injected although no significant difference has been observed for H_2 production. The maximum efficiency of the system is 3.12% that obtained with iso-octane reforming for power consumption of 28.8 W, O/C ratio of 1, and feedstock supply rate of 0.1 g/min.



(a) (b)

Figure 1.19 Syngas production from gasification of brown coal in a microwave torch plasma

(a) Schematic of microwave plasma gasification system,

(b) Cross sectional view of microwave plasma torch and coal injection part in detail

(Source; Hong et al., 2012)

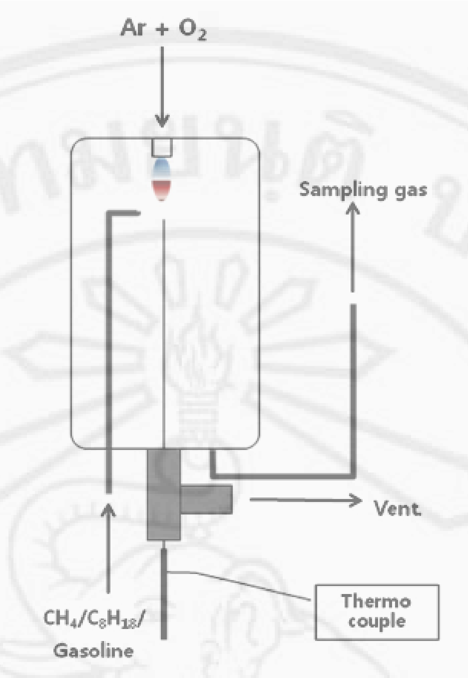


Figure 1.20 Schematic diagram of microwave plasma reforming reactor

with non-premixed configuration

(Source; Kim et al., 2010)

However, there are only a few studies of plasmochemical conversion of solid waste using microwave plasma. For example, Lupa et al., (2013) presented a microwave induced plasma (MIP) reactor using for plasma pyrolysis of waste and biomass. It consist of a welded steel box and a 2.45 GHz, 2 kW microwave plasma jet. Operating pressure in the reactor was maintained at approximately 200 mbar. Nitrogen was used as the carrier gas, its flow rate was maintained at 1 lpm. They found that, product gas is showed a large increase in gas mass with the addition of oxygen. Heating value of synthesis gas was determined in the range about 11 to 17 MJ/Nm^3. Product gas is consisted predominantly of CO in the range about 46 to 61%,

CO_2 about 26 to 28%, and H_2O about 2 to 23%, in total accounting for more than 90% of the detected gas mass. They concluded that, low capital costs and proven microwave technology demonstrate as a plausible energy from waste treatment method. Sekiguchi et al., (2004) investigated gasification of polyethylene using steam plasma generated by microwave discharge, as shown in Figure 1.21. Their reactor consisted of a 600 W microwave generator with frequency of 2.45 GHz. A reactor tube made of quartz with inner diameter of 8 mm was inserted perpendicular in the microwave waveguide at zone of concentrated electromagnetic field. The end of the tube was inserted in a stainless reactor. Commercial PE pellet was used as a model of plastics waste. The sample of PE mass of 1 g was placed in the crucible. The crucible was installed at 45 mm below the waveguide in the stainless reactor. Argon with flow rate of 3.5 lpm was used as carrier gas. Steam with content of 20 mol% was heated and added into the carrier gas. The plasma processing time was carried out for the range of 1 to 5 min each experiment. Product gas was collected in a gas sampling bag after treatment. After each experimental run, microwave power was shut down at a certain time elapsed. Rather, Ar and steam are still supplied until approximately 5 min to adjust almost the same volume in the gas sampling bag. They found that, added steam is changed the plasma color from blue–white to reddish. The generation of white smoke is observed in both the experiments with and without steam. The smoke is condensed as oily droplet on the wall of the gas sampling bag. Product gas are CO, CO_2, CH_4, and H_2. They found that, the additional steam enhanced the production of H_2 and CH_4. CO is a major content of gas product. H_2 would be produced at least in the same amount as CO considering. H_2 is only released from steam with CO formation reaction.

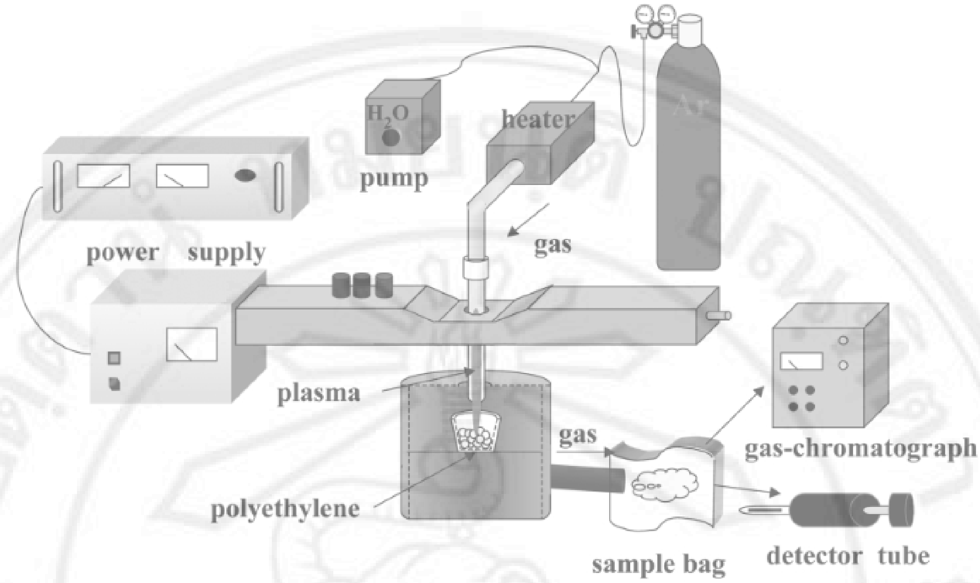


Figure 1.21 Schematic diagram of microwave plasma steam gasification of polyethylene

(Source; Sekiguchi et al., 2004)

In comparison with other plasma sources, plasmochemical conversion of hydrocarbon substrate using microwave plasma has many advantages. For example, Konno et al., (2011) investigated the comparison of cellulose decomposition by microwave plasma and radio frequency plasma. They suggested that the temperature of thermal plasma is too high for conversion biomass. The temperature of cold or non-thermal plasma that lower under 3000 K is expected to be sufficient for biomass plasmochemical conversion. Non-thermal plasma can be generated with microwave or radio frequency. They investigated cellulose decomposition by using radio frequency plasma and microwave plasma reactor as shown Figure 1.22 (a) and (b), respectively. Their RF plasma reactor was consisted of a low pressure flow quartz reaction tube with internal diameter of 12 mm and length of 600 mm, a radio frequency (RF) generator with frequency of 13.56 GHz and a pair of copper ring electrodes. The electrodes were placed around the reactor tube with space of 17 mm. Moreover, their microwave plasma reactor was constructed of a bigger quartz reaction tube with internal diameter of 25 mm and length of 800 mm, rectangular wave guide, a microwave generator with frequency of 2.45 GHz, and cooling system. Both reactor were operated with equal power input of 300 W. The reduced operating pressure was 1.3 kPa for RF reactor and 4.0 kPa for microwave reactor. Argon was used as a carrier gas and was fed with flow rate of 0.45 mmol/min and 0.89 mmol/min for RF and microwave plasma, respectively. Cellulose with weight of 1.0 and 1.5 g were investigated with reaction time of 1 to 30 min and 0.5 to 10 min by RF plasma and microwave plasma reactor, respectively. From experimental results, they found that the main composition of gaseous products obtained from both reactor are H_2 and CO, and the others are a few of CO_2, CH_4, C_2H_2 and C_2H_4. The amount of H_2 and CO are increased with an increasing reaction time and indicated a maximum value at 10 min for microwave plasma and at 30 min for RF plasma. The amount of H_2 and CO obtained from microwave plasma is about 18 mmol/g and 24 mmol/g, and that obtained from RF plasma is about 9 mmol/g and 14 mmol/g, respectively. Microwave plasma is highly convert cellulose to gaseous products at short time in comparison with RF plasma, irrespective of the reaction time. Moreover, the maximum yield of gaseous products by microwave plasma is about 85 wt% at 10 min that higher than by RF plasma at 30 min by about 23 wt%. In addition, a large amount of C element is remains in the residue. Those results, they suggested that microwave plasma is suitable for cellulose decomposition. It highly convert C, H and O element to H_2 and CO and has higher energy efficiency than radio frequency

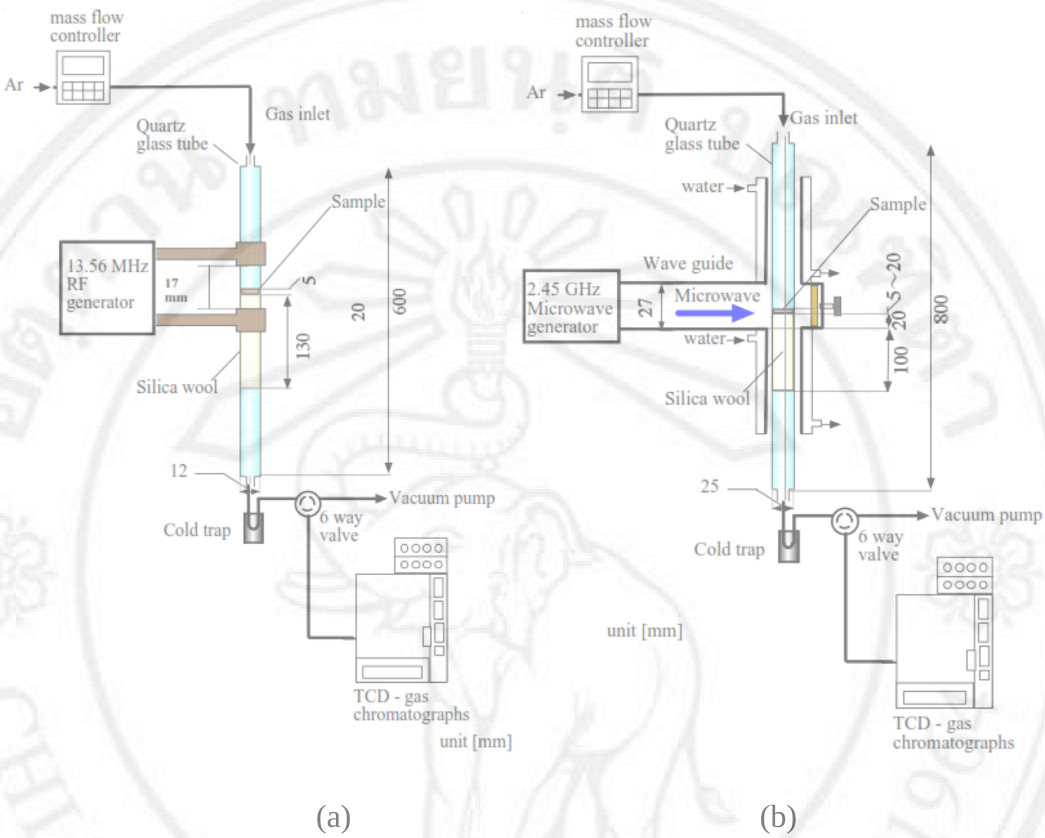


Figure 1.22 Schematic diagram of cellulose decomposition by radio frequency plasma and microwave plasma, (a) RF plasma reactor, (b) microwave plasma reactor (Source; Konno et al., 2011)

1.4.2 Raw Material of Plasmochemical Conversion Process

Hydrocarbon substrate can be converted into solid, liquid and gaseous products by thermochemical methods such as pyrolysis, gasification as well as plasmochemical conversion. Many researchers presented plasmochemical conversion of coal, biomass, waste and RDF. For examples, Lin et al., (1999) presented a laboratory scaled fixed bed reactor for pyrolysis of RDF. The samples used were separated and prepared from MSW. The samples preparing process consisted of four major subsystems, (i) bag ripping, (ii) magnetic sorting, (iii) shedding, and (iv) rotary trammel screening. Lupa et al., (2012) presented a microwave-induced plasma reactor using for plasma pyrolysis of waste and biomass. Three samples of pelletized waste wood from different sources were used as feedstock. Chang et al., (1996) investigated pyrolysis of used tires using thermal plasma. Nema et al., (2002) used the arc plasma torch to treat hazardous medical waste. Janajreh et al., (2013) investigated the plasma gasification of waste in comparison with conventional air gasification. Many types of waste were used as feedstock, such as tire, wood, and MSW. The feedstock of plasmochemical conversion process in literature were summarized in Table 1.2.

Table 1.2 Previous Work on Plasma Assisted Conversion of Solid Fuel

Reference	Method	Raw material
Wang et al., (2012)	Microwave plasma	rice husk
Wang et al., (2012)	Microwave plasma	cane residue
Tang and Huang., (2005)	RF Plasma	sawdust
Tang and Huang., (2004)	DC arc discharge plasma	used tires
Zhao et al., (2012)	Microwave induced pyrolysis	wheat straw
Shie et al., (2010)	Arc plasma torch	rice straw
Kanilo et al., (2003)	Microwave plasma	coal
Lupa et al., (2013)	Microwave plasma	waste
Janajreh et al., (2013)	Arc plasma torch	MSW

1.4.3 Plasmochemical Conversion Product

The products of thermochemical process, such as pyrolysis, gasification and plasmochemical are solid, liquid and gaseous. The interesting combustible gaseous products are CO, CH_4 and H_2. Solid and liquid product is char and tar, respectively. Many researchers presented plasmochemical conversion of hydrocarbon substrate. For examples Lupa et al., (2012) presented a microwave-induced plasma reactor using for plasma pyrolysis of waste and biomass. The product gas, methane and toluene were found to be the most abundant hydrocarbons. The average mass reduction of the samples was 79.6%. Lupa et al., (2013), investigated the effect of elemental composition of the feedstock and reaction time on syngas evolution. The commercial and industrial wastes were used as feedstock. Gas evolution was found to peak at approximately 200 s of reaction time. The heating value was determined to range from 11.4 to 17.4 MJ/m^3. Gaseous product of plasmochemical conversion process were summarized in Table 1.3.

1.4.4 Effect of Elemental Composition

Raw material properties such as elemental composition is the main variable that effected on plasmochemical products evolution. There are some researchers investigated the effect raw material properties, such as Lupa et al., (2013) investigated the effect of elemental composition of the feedstock and reaction time on syngas evolution using microwave induced plasma pyrolysis of commercial and industrial waste (C&IW). They found that feedstock with high oxygen composition increased the heavier gas species in product gas composition, such as CO, CO2, and H_2O, as a result of oxidation.

Table 1.3 Gaseous Product from Plasmochemical Conversion Process

Reference	Source	Feedstock	Product gas content (%mol)				LHV
			H_2	CO	CH_4	CO_2	(MJ/m^3)
Kanilo et al., (2003)	MWP	coal	2.4	8.1	1.2	9.6	1.7
Zhao et al., (2012)	MWP	wheat straw	22.1	34.7	7.9	33.8	9.6
Sekiguchi et al., (2004)	MWP	PE	14.0	26.0	6.0	12.0	6.9
Lupa et al., (2012)	MWP	waste wood	0.0	56.9	0.5	33.8	7.3
Kowalska et al., (2008)	Gliding Arc	waste oil	0.0	0.5	0.0	2.0	0.1
Tang L. et al., (2005)	RF	sawdust	8.5	11.0	1.5	4.0	2.8
Janajreh I. et al., (2013)	Arc	MSW	43.5	34.5	0.01	0.03	9.0

1.4.5 Effect of Moisture Content

In the case of moisture, Hong et al., (2012) investigated the production of syngas from microwave plasma gasification of brown coal. From the experimental data, they found that the relative concentrations of product gas at a ratio of coal to steam of 1.36 is 48% of H_2. They explained that H_2 is generated from the moisture content in the coal.

1.4.6 Microwave Modeling

Computer programs are used to calculate energy, electromagnetic and electric fields in microwave system. Microwave system factors are the placement inside cavity, the cavity size, microwave power and frequency (Rattanadecho, 2011). The electromagnetic can be used to help stabilized plasma in the microwave plasma system. Therefore, to design microwave plasma reactor, electromagnetic field strength should be calculated at the reaction zone. The electromagnetic field is solved according to Maxwell's theory (Rattanadecho, 2011). In the case of domestic microwave oven, there are several studies in literature comparing the Maxwell’s and Lambert’s law equations in predicting electromagnetic field during microwave power supplied. Lambert’s law is not appropriate for microwave power processing, its simplified numerical results were comparable with the experimental methods. However, Maxwell’s equations are more accurate than Lambert’s law in calculating power dissipation in a food material (Pitchai et al., 2012) and generally used to calculate electromagnetic field strength in microwave system. Many researcher investigated numerical modeling using Maxwell’s equations, such as Pitchai et al., (2012). They presented the coupled electromagnetic and heat transfer model for microwave heating in domestic ovens. They investigated the effects of various electromagnetic and computational parameters. The conformal finite difference time domain based (FDTD) numerical method is used to solve electromagnetic Maxwell's equations. Their geometric model is developed for a domestic microwave oven with power of 700 W. The geometric model consisted of oven cavity, magnetron, turntable, waveguide, crevices and a metal bump. The microwave feed port is located on top of one side of the microwave oven cavity, as shown in Figure 1.23. Simulation variables are the number of iterations to reach steady state, cell size, heating time step, magnetron frequency, electric field strength, electromagnetic mode and power input. The simulation was performed with 2.45 GHz microwave frequency. They suggested that electromagnetic simulation in a dielectric material typically requires about 8 to 10 cells per wavelength. For example, the wavelength of microwaves in material is 13 mm therefore the cell size should be less than 1.3 mm. In their study, cell size in the air domain is set at 5 mm. Material domain, the effect of cell size along the x, y and z direction in the range of 1 to 6 mm depending on power absorption. The meshing scheme used for 2-dimensional direction in x–y (top view) and y–z (side view) planes was shown in Figure 1.24. From simulation results, they found that the temperature in material is increased with increasing electric field that stabilized with increasing microwave frequency at any point in the domain as shown in Figure 1.25.

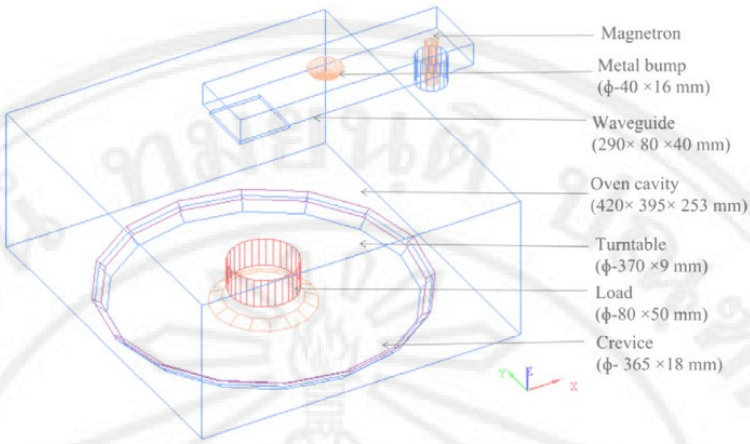


Figure 1.23 Geometric model of 700 W rated power microwave oven cavity

with magnetron as coaxial microwave feed source,

(Source; Pitchai et al., 2012)

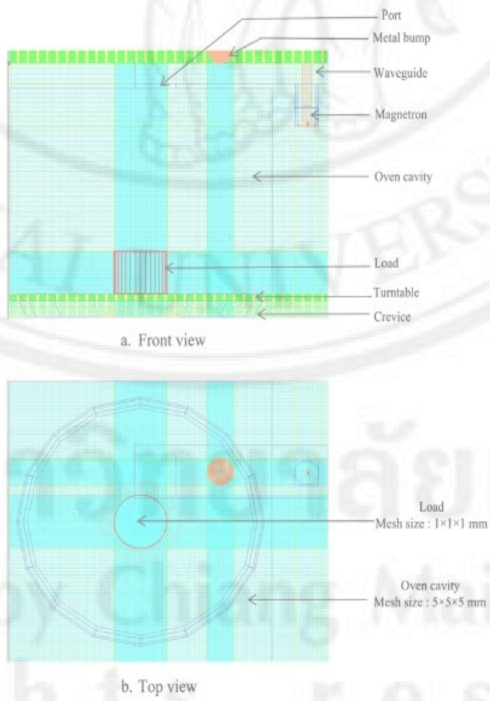


Figure 1.24 Meshing scheme in the computational domain,

(Source; Pitchai et al., 2012)

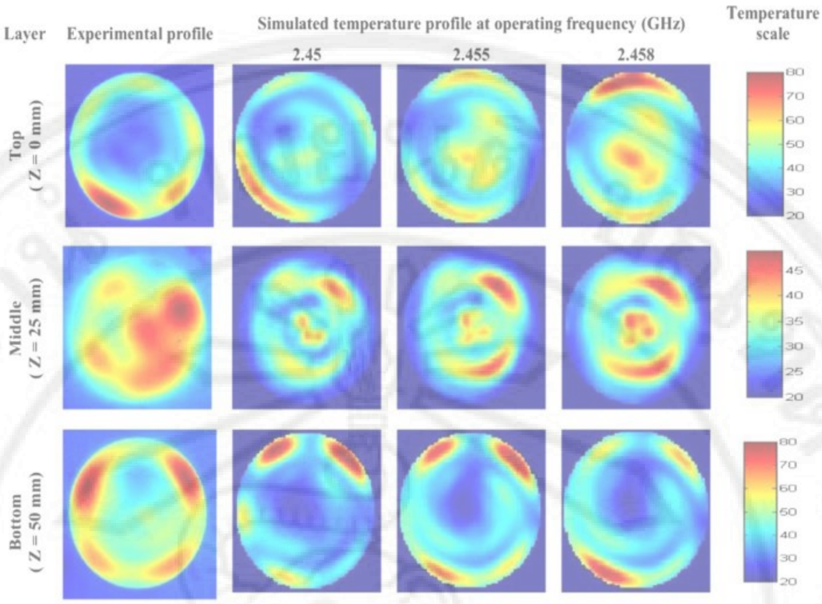


Figure 1.25 Effect of microwave frequency on temperature in material that resulted from electromagnetic field,

(Source; Pitchai et al., 2012)

Ciacci et al., (2010) investigated a 2-dimensional mathematical model for the microwave induced pyrolysis of a wood block. A quasi-steady approximation was used for the electromagnetic field. A planar field was created for a variety of microwave applicator configurations such as waveguides and cavities to investigate the coupling between the electromagnetic and thermal fields. The Maxwell equations govern the electric and magnetic fields. Plane-polarized radiation were two states (i) transverse electric mode (TE) and (ii) transverse magnetic mode (TM). The solution of the system was numerically computed using a finite difference time domain. Their simulation result was shown in Figure 1.26.

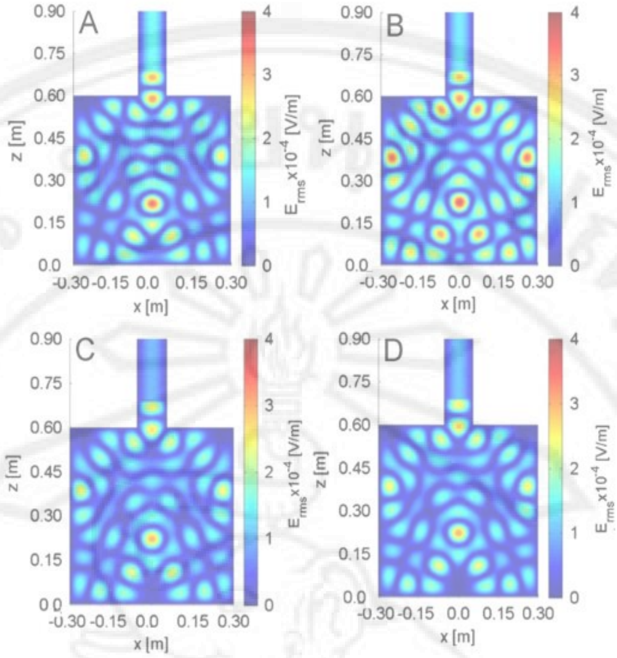


Figure 1.26 Predicted color maps of the root mean square of the electric field at steady conditions in the cavity, (A) without the sample, (B) with the wood sample, (C) with a char sample at a temperature of 800 K and (D) with a char sample at a temperature of 1000 K, (Source; Ciacci et al., 2010)

1.4.7 Thermodynamic Equilibrium Modeling

The thermodynamic models are investigated in various processes, such as pyrolysis, gasification (Syed et al., 2012; Barman et al., 2012; Ngo et al., 2011) as well as plasmochemical conversion. Thermodynamic equilibrium models have many advantages such as to design reactor, to select raw materials and operation condition (Wongsiriamnuay, 2012). Thermodynamic analysis of plasmochemical technology includes prediction of the synthesis gas production, energy and exergy calculations. Plasmochemical model is developed in the same principal with traditional pyrolysis or gasification model. Thermodynamic equilibrium, mass and energy balance are required for the optimization of process. General thermodynamic equilibrium reaction that used for plasmochemical modeling are endothermic, (such as heterogeneous water gas shift reaction, boudouard equilibrium, and methane decomposition) and exothermic reaction, (such as hydrogenating gasification, and water gas shift reaction) respectively (Mountouris et al., 2006). However, there are few studies in thermodynamic modeling of plasmochemical conversion process. For example, Mountouris et al., (2006) developed equilibrium model for solid waste plasma gasification. They focused on plasma gasification of the organic fraction of the solid waste. They explained that thermochemical conversion process took place inside the plasma reactor can be described by the term of gasification. They described waste material by its ultimate analysis as $C_XH_YO_z$. Their model development based on thermodynamic equilibrium and various chemical reactions in the case of some remaining solid carbon in the gasification products. System equilibrium analysis is described by independent chemical reaction, energy balance and partial mass balance equations. Plasma gasification reaction which used in their model is written as equation (1.1).

$$CH_xO_y + wH_2O + mO_2 + 3.76mN_2 = n_1H_2 + n_2CO + n_3CO_2 + n_4H_2O + n_5CH_4 + n_6N_2 + n_7C \quad (1.1)$$

The equilibrium is calculated for the composition of H_2, CO, CO_2, H_2O, CH_4, O and C (solid carbon residue). Three independent chemical reactions that they selected for the equilibrium calculations are methane decomposition, water gas shift and primary water gas shift. Three partial mass balances for carbon, hydrogen and oxygen are considered. Energy balance are calculated from specific heat and enthalpy changes of the gas products that are a function of the gasification temperature and the equilibrium constants of the chemical reactions. From modeling results, they explained that their equilibrium model is not achieved when the gasification temperature is below 800 ^{o}C, while it is ok at higher temperatures. In addition, Wongsiriamnauy, (2012) suggested that the low residence time is not long enough to meet the equilibrium state. The error between the models and the experiments come from the overestimation of H_2 and CO and underestimation of CO_2 and CH_4.

1.4.8 Summary

Many researchers are active in the development of plasma technology for plasmochemical conversion of hydrocarbon substrates such as, biomass (Lupa et al., 2012), waste (Janajreh et al., 2013), used tires (Chang et al., 1996), hospital waste (Nema et al., 2002), and RDF (Lin et al., 1999). General purpose of plasmochemical conversion process is to produce high grade fuel such as synthesis gas, synthesis oil as well as char from hydrocarbon wastes. Plasmochemical process is the new technology for WTE. Plasmochemical processing of waste can produce a high valued syngas, rich in H_2 and CO, CH_4. RDF is the main product from the physical conversion of MSW. It presents several advantages as a fuel over raw MSW. The main advantages are higher calorific value which also remains fairly constant, more uniformity of physical and chemical composition, ease of storage, handling and transportation, lower pollutant emissions and reduction of excess air requirement during combustion (Nithikul et al., 2011). Therefore, plasmochemical conversion of RDF is an alternative attractive for WTE.

There are many types of plasma source for plasmochemical conversion process, such as arc plasma (Janajreh et al., 2013; Nema et al., 2002), radio-frequency (RF) induction plasma (Tang and Huang, 2005; Tu et al., 2008), and microwave induction plasma (Hong et al., 2012; Kim et al., 2010; Lupa et al., 2013; Sekiguchi et al., 2004; Konno et al., 2011) etc. Some researchers suggested that temperature of thermal plasma obtained from arc plasma is too high to be unfit for the conversion biomass (Tang and Huang., 2005; Konno et al., 2011). The temperature of cold or non-thermal plasma that lower under 3000 K is expected to be sufficient for biomass plasmochemical conversion. Non-thermal plasma can be generated with microwave or radio frequency. Some researcher such as Konno et al., (2011) suggested that microwave plasma can highly convert biomass to gaseous products at short time in comparison with RF plasma, irrespective of the reaction time. Moreover, the maximum yield of gaseous products by microwave plasma is higher than by RF plasma. As well as, microwave plasma can be generated using a 2.45 GHz magnetron from commercial microwave oven. It is simple, economical, easy to control and requires low power (Tendero et al., 2005; Chaichumporn et al., 2011; Uhm et al., 2006). Therefore, this thesis would employ microwave plasma as plasma source for plasmochemical conversion of solid waste.

Thermochemical conversion is a technology of choice for utilization of RDF. It includes combustion, gasification, and pyrolysis. Direct combustion of waste with energy recovery is the most common WTE implementation. Nevertheless, it normally gives low energy efficiency. Pyrolysis/gasification is a thermochemical process in an oxygen starved environment at relatively high temperatures (> 500ºC), transforming wastes into liquid and gaseous fuels as well as char. The product gas containing H_2

and CO is a key advantage that can be further used in a variety of applications such as combustion in a turbine or an engine, heat and power generation as well as use in fuel cells (Blanco et al., 2013) . Plasmochemical or plasma processing method is relatively new. It offers advantages over conventional thermochemical processes from fast heating, ease to controls and low power consumption. The thermal and chemical properties of plasma are synergized with the pyrolysis and gasification process. The process was claimed to interrupt the formation of dioxins and kills bacteria. It was reported that organic materials can be converted to gases at more than 99% conversion efficiency (Hu et al., 2012; Yoon et al., 2012; Li et al., 2005; Nema et al., 2002; Ahmed et al., 2009; Tang and Huang., 2005; Tsai et al., 2006).

However, there are few studies on plasmochemical process to generate fuel gas and char. Literature on plasmochemical conversion of RDF using microwave-induced plasma was rare. In this study, three majors combustible fraction of MSW were investigated, both as single component and in the form of RDF. Microwave oven was modified for used as the direct-contact plasma pyrolysis reactor (Khongkrapan et al., 2013). The plasma generated was contacted directly to the feedstock and converted it into the fuel gas and char. Investigation on effect of carrier gas flow rate on the plasma characteristics, such as plasma temperature, discharge length, and power density were carried out. Evolution and composition of fuel gas obtained from plasma pyrolysis of each feedstock were also investigated. Elemental analyses of raw materials and chars were also carried out. Product gas yield, char yield, carbon conversion efficiency, and calorific value were calculated and compared with literature.

1.5 Research Objectives

1.5.1 To design, construct and test a laboratory scaled, microwave plasma reactor for plasmochemical conversion of solid waste

1.5.2 To experimentally investigate factors that affect gaseous fuel production from plasmochemical conversion of solid waste

1.5.3 To numerically model gaseous fuel production from plasmochemical conversion of solid waste

1.6 Potential Benefits

1.6.1 A useful laboratory scaled microwave plasma system obtained can be used for further research into plasmochemical conversion.

1.6.2 Explanation on effect of substrate type and carrier gas flow rate on yield and compositions of fuel gas are obtained.

1.6.3 Further knowledge in control parameters that affect plasmochemical conversion.

1.7 Scope of the Study

1.7.1 Microwave plasma reactor was constructed in laboratory scale with 800 W, 2.45 GHz microwave generator.

1.7.2 Sample wastes used as feedstock were paper, plastic, biomass and RDF.

1.7.3 The maximum mass of feedstock is about 8 g.

1.7.4 Carrier gas flow rates were between 0.50-1.25 lpm.

1.8 Outlines of the Thesis

This thesis has five chapters. Chapter 1 is an introduction that contains the statement and significance of problem, objective, benefit and scope of this study. Chapter 2 contains the principle and theories of feedstock and plasma processing that used in this research. Chapter 3 is the methodology of this research, design and construction of plasma reactor, feedstock preparation, experimental set up, data collection and thermodynamics equilibrium modeling. Chapter 4 is the discussion of the experimental results of plasmochemical conversion of solid waste and thermodynamics equilibrium modeling. Chapter 5 presents conclusion and suggestion of this research.