Jurnal
Teknologi

Full paper

A Review on Plasma Treatment for the Processing of Solid Waste

Norasyikin Ismail, Farid Nasir Ani*

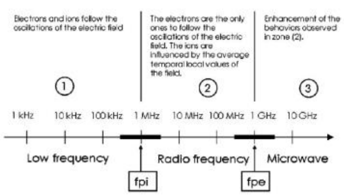
Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310, UTM Johor Bahru, Johor, Malaysia

*Corresponding author: farid@fkm.utm.my

Article history

Received : 15 August 2014
Received in revised form :
15 October 2014
Accepted :15 November 2014

Graphical abstract



Abstract

A staggering amount of solid municipal waste (MSW) is produced by one person daily in both developed and developing countries. However, by taking advantage of the situation, these solid waste could be converted into syngas; which are known to be potentially able to replace or mixed with natural gas for industrial and everyday energy applications. As well, existing treatment and processing of biomass and solid fuels such as coals has been widely used in industrial scale to generate electricity. This paper reviews the previous studies on plasma treatment for the processing of solid waste, which would be helpful in the production of syngas. Plasma technology is one of the efforts to practice sustainable cleaner technology for the industrial world. The types of plasma technology reviewed are thermal plasma, microwaves plasma, and radio frequency plasma. Other than processing and treatment of solid waste, plasma technology could also be applied in other area such as environmentally, decontamination of chemical and biological warfare agents and nanotechnology. As well, plasma technology could help in creating a greener world by lowering the greenhouse gas emissions from heavy industries. It is hoped that this review could put a light on the future direction of MSW management situation in Malaysia.

Keywords: Plasma treatment; plasma processing; solid waste; syngas

■1.0 INTRODUCTION

Enormous amount of solid wastes generated daily from MSW, industrial sector, agricultural sector and forest sector globally. In Malaysia itself, solid waste is expected to upswing to 31,000 tonnes by the year 2020 [1]. These wastes can be converted into syngas which is potentially able to replace natural gas for industrial and energy application. Various thermal processes, such as pyrolysis, vitrification, gasification, and incineration, can be used for treating these hazardous wastes. The objective of the treatment is to breakdown the organic fraction and converts the inorganic fraction so that it could be reused or disposed properly as an inert silicate slag [2-4].

Alternatively, combustion of solid wastes could be used to process organic wastes, enabling energy recovery [5]. However this is only applicable to wastes that do not contain hazardous or toxic substances. In which case, the plasma treatment could be used to treat these toxic wastes and benefit from their recoverable energy content. As well, the plasma is a safer and more ecofriendly option. This is because, the plasma arcs have high temperature, and consequently this will reduce any potential for undesirable byproducts to be generated. This is observable in the syngas produced.

Fridman defined plasma as an ionized gas, a distinct fourth state of matter [6]. "Ionized" means that at least one electron is not bound to an atom or molecule, converting the atoms or molecules into positively charged ions. When the temperature increases, molecules become more energetic and transform into matter in the sequence of: solid, liquid, gas, and finally plasma. This explain the positively charged ions named the "fourth state of matter". Ionization can be induced by other means, such as strong electromagnetic field applied with a laser or microwave generator, and is accompanied by the dissociation of molecular bonds, if present [7]. In this research, three types of plasma gasification is being reviewed which are thermal plasma, microwaves plasma, and radio frequency (RF) plasma in term of their system, energy-efficiency, environmental-friendly, and cost efficiency trait.

Generators of thermal plasma (plasma torches) operate simultaneously as a plasmachemical and a thermal apparatus. The electrical energy of the torches goes into the plasma which transfers its energy to the substances to be treated, thus triggering a dual simultaneous reaction process in the plasmachemical reactor. Here, the organic compounds are thermally decomposed into their constituent elements (syngas with more complete conversion of carbon into gas phase than in incinerators), and the inorganic materials are melted and converted into a dense, inert, non-leachable vitrified slag, that does not require controlled disposal [8]. Therefore, it can be viewed as a totally closed treatment system.

For gasification technology, supplying the steam should be done to generate syngas containing H_2 and CO. Using the arc plasma torch reduces the life expectancy of the electrodes because arc electrodes are vulnerable to moisture. Kanilo *et al*. claimed that microwave plasma technology provides a better method for gasification because it is more resistant to moisture [9].

Meanwhile, Uhm *et al*. stated that using microwaves as an energy source for plasma generation can form a plasma flame [10]. Using pure steam, plasma flame can generate a gasification reaction at a temperature several thousand degrees Celsius above the operation temperature of a conventional gasification.

■2.0 PLASMA TREATMENT FOR THE PROCESSING OF SOLID WASTE

Moreau *et al.* stated that plasmas are classified as "thermal" or "non-thermal", and this is based on their relative temperatures of electrons, ions and neutrals. For a start, thermal plasmas reach thermal equilibrium when the electrons and the heavy particles reach similar temperature. In contrast, non-thermal plasmas have much lower-temperature ions and neutrals, which is commonly at the room temperature. The electrons of non-thermal plasmas are much hotter than thermal plasmas [11]. The behaviour of the electrons and the ions in a plasma source are the result of the excitation frequency. Figure 1 shows the range for fpe (frequency of the electrons in the plasma) and fpi (ions frequency) in cold plasmas (e.g. glow discharges).

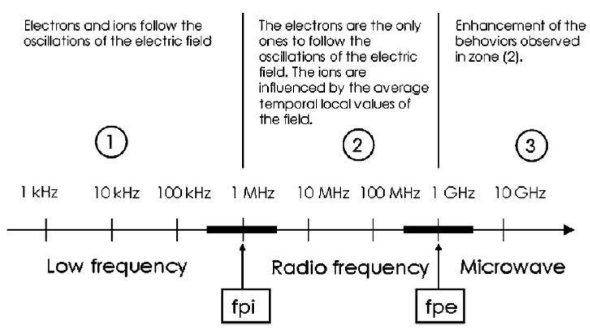


Figure 1 Electrons and ions frequencies in cold plasmas [12]

The atmospheric plasma sources can be grouped according to their excitation mode [12]. The three types of atmospheric plasma are:

- the DC (direct current) and low frequency discharges;
- the plasmas ignited by radio frequency waves
- the microwave discharges.

In this paper, previous research on plasma treatment for the processing of solid waste are reviewed. The three types of plasma gasification to be reviewed are thermal plasma, microwave plasma, and radio-frequency (RF) plasma. Most of the researcher used solid waste, wood, and coal as their input material. The percentage of component in syngas from different source will yield different component. The types of plasma method will also affect the syngas produced.

2.1 Thermal Plasma

In China, Qiu *et al.* investigated the gasification of coal under steam and air plasma conditions at atmospheric pressure in a tube-type setup. This is done with the aim of producing synthesis gas. Figure 2 shows the schematic drawing of the top part of the setup for coal gasification under plasma conditions. The content of H_2 and CO in gas rises with the increase the arc input power, and passes through a maximum with the increase of current in electromagnetic coil. Under the experimental conditions tested, the content of H_2 and CO in the gas could reach 75% in volume with CO_2 being less than 3.0 vol%. Arc input power, the electromagnetic coil current, and the coal-feeding rate are the process parameters that effect the gas composition. Here, the high input power arc helps the formation of H_2 and CO in the gas. The H_2 and CO content in gas will go through a peak according to the increase in the coil current or the feeding rate of the coal. The variation trend of the CO content in the gas is parallel to the variation of the intensities of CO+ ion and CH radical in the plasma, suggesting that CO+ ion and CH radical in the plasma are the precursors of CO in the synthesis gas [13].

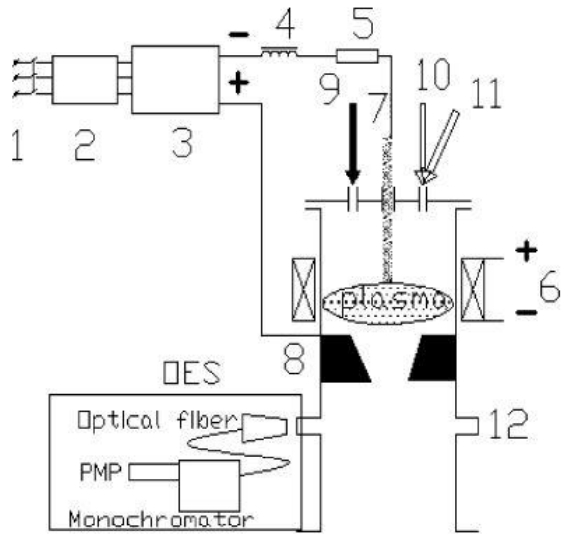


Figure 2 Schematic drawing of the top part of the setup for coal gasification under plasma conditions. (1) Three phase AC, (2) transformer, (3) rectifier, (4) inductance coil, (5) resistance, (6) electromagnetic coil, (7) cathode, (8) anode, (9) steam, (10) pulverized coal, (11) carrier gas (air), (12) view port [13]

Plasma pyrolysis of used tires will lead to the distribution of sulphur compounds in gas and char generated during the process. Sulphur transformation and distribution were investigated by Tang and Huang by analysing the gas and char at different conditions. Photometric method was used to analyse the sulphides in the gaseous product. It was found that hydrogen sulphide was the main compound containing sulphur. The parameters having influence on the distribution of total sulphur in products of thermal plasma pyrolysis are power input, feed rate, addition of water steam and addition of dolomite absorbent to the process. Increasing power input or feed rate tends to decrease the share of total sulphur in gas and increase the share of total sulphur in char correspondingly. The power input is ranging from 30.8 to 48.4 kV A [14].

Coal gasification in steam and air atmosphere under arc plasma conditions has been investigated by Galvita *et al.* using Podmoskovnyi brown coal, Kuuchekinski bituminous coal and Canadian petro coke. The gasification degree for coal to synthesis gas was 92.3%, 95.8 and 78.6% correspondingly. During the reduction phase of the cycle, the raw gas mixture of H_2 and CO reduces a $Fe_3O_4.CeO_2.ZrO_2$ sample, while during the oxidation phase steam re-oxidizes the iron and simultaneously hydrogen is being produced. Podmoskovnyi coal was investigated with the feed composition of 6.7 kg/h of coal, 2.4 kg/h of steam and 1.5 kg/h of nitrogen. The electric power applied to the reactor during an experiment was 62kW. For experiment with Kuuchekinski coal, the system was 4.0 kg/h of coal +1.9kg/h of steam and electric power of the reactor during the experiment was 25 kW. For experiment with Canadian petro coke, the system was 2.5

kg/h of coke +3.0kg/h of steam and electric power of the reactor during the experiment was 60.0kW. Galvita *et al.* claimed that combining these technologies are the suitable option for efficient stationary power generation. The simultaneous production of power and useful heat from a single plant is also a very useful option for improving the overall performance of the energy conversion system [15].

The plasma gasification process has been demonstrated in many of the most recent studies as one of the most effective and environmentally friendly methods for solid waste treatment and energy utilization. This method is applied by Mountouris *et al.* to the treatment of sewage sludge. Plasma gasification offers an attractive and environmentally sound option for the treatment and energy utilization of solid wastes. The study demonstrates the energy utilization potential of sewage sludge treatment using an integrated process involving plasma gasification, pre-drying and electric energy production. According to Mountouris *et al.*, application in the case study involving the sludge from the Psittalia sewage treatment plant indicates that the process is not only self-sufficient from an energy point of view, but it leads to net production of 2.85 MW electrical energy [16].

In Korea, Byun *et al.* had demonstrated the thermal plasma gasification/vitrification for municipal solid waste treatment. The gasification/vitrification unit, with a capacity of 10 tonnes/day, was developed using an integrated furnace equipped with two non-transferred thermal plasma torches. The thermal plasma process for the gasification/vitrification of MSW is an environmentally friendly process that can be used as an alternative to other MSW treatment technologies. The amounts of electricity and LPG consumed were 1.14 MWh/MSW-tonnes and 7.37 Nm^3/MSW-tonnes, respectively. Two non-transferred thermal plasma torches were installed into the integrated furnace at a 30° angle to induce a centrifugal force in the furnace. The power capacity of each plasma torch was 200 kW, with operational voltage and current of 571±30Vand 293±10 A, respectively [17].

Rutberg *et al.* studied about high temperature plasma gasification of wood for the production of a fuel gas (syngas) for combined heat and power production. Plasma has advantage over existing thermochemical processes which are in the high heating value gases, process control and the lower energy consumption per unit of output. From one kilogram of 20% moisture wood it is possible to obtain 4.6e4.8 MJ of electricity (net of electricity input) and 9.1e9.3 MJ of thermal energy when using wood with average elemental composition and with a LHV energy content of 13.9 MJ, when using a combined Brayton and Steam cycle generating plant. Rutberg et al. found out that gasification by the air plasma is the most simple and promising method for developing the technology of generating the syngas from wood and wood residuals [18].

Byun *et al.* has studied about hydrogen recovery from the thermal plasma gasification of solid waste. In the study, high purity H_2 was produced from the thermal plasma process of solid waste with water gas shift (WGS) and pressure swing adsorption (PSA) systems. Gases emitted from a gasification furnace equipped with a non-transferred thermal plasma torch were purified using a bag-filter and wet scrubber. Thereafter, the gases, which contained syngas (CO + H_2), were introduced into a H_2 recovery system, consisting largely of a WGS unit for the conversion of CO to H_2 and a PSA unit for the separation and purification of H_2 .The results from this study crucially show the feasibility of the production of high purity H_2 (>99.99%) from the thermal plasma gasification of waste [19].

According to Popov *et al.*, plasma gasification of waste is a method of energy saving. To prove that, several versions of the organizations of the process of plasma-chemical gasification with the use of air, carbon dioxide, steam and their mixtures as the plasma-forming gas are conducted. The most effectively use of plasma energy are the downdraft and twin-fire schemes of gasification because the mixture of pyrolysis products with plasma in a point of its inlet and long residence time of solid pyrolysis products in a high-temperature zone. The most suitable oxidizer for plasma gasification of wood waste is air as on 1 MJ of the input energy the chemical energy yield of synthesis gas increases on ~1.55 MJ. Application of plasma during gasification allows increasing the efficiency of the electric power generation and liquid fuel production from wood waste [20].

Lázár *et al.* runs an experiment of peat gasification in plasma reactor to verify the assessment of utilizable synthesis gas at high-temperature thermal treatment of the selected fuel commodity in terms of the energy recovery system in the cogeneration unit. A plasma reactor with 80 kVA dependent electric arc was used. The plasma arc was generated by nitrogen gas in a hollow graphite electrode. The results showed that the gasification is not economically profitable. Low percentage of combustible components of synthesis gas (H_2 and CO) and high content of nitrogen, used for generation of the plasma column of volume of 8.5 to 10 $Nl \cdot min^{-1}$, take significant share in low average value of lower calorific value of the obtained gaseous medium which is in range of 1.3 to 2.3 $MJ \cdot Nm^{-3}$ in this case [21]. Figure 3 shows an example of thermal plasma gasification system.

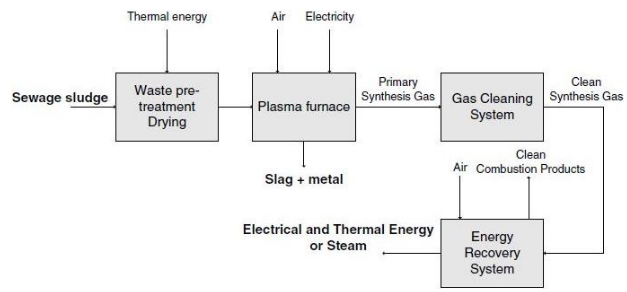


Figure 3 Block diagram of thermal plasma system [16]

2.2 Microwave Plasma

Microwaves plasma is a new technology for gasification of solid. Previous studies had proven that this method can save more energy than conventional method. A portable microwave torch using magnetrons operated at the 2.45 GHz has been developed by Uhm *et al.* in 2006. This electrode less torch can be used to various areas, including commercial, environmental and military applications. The microwave torch has been used to synthesize the carbon nanotubes providing the opportunity of a mass production of the nanotubes. The microwave plasma-torch can be made of the same magnetrons as the ones used in typical household microwave ovens. Therefore, the microwave plasma torch is simple, compact, and economical. Since all microwave power is either absorbed by the plasma or confined within a compact waveguide, there is no safety problem with radiated power [22].

Sekiguchi and Orimo had examined the gasification of polyethylene (PE) pellet using atmospheric argon-steam plasma generated by microwave discharge and the feasibility of the process. The experiment was conducted with 2.45 GHz microwave power supply giving a power of 600 W. The experimental results showed that additional steam to argon plasma promoted the weight decrease of PE and enhanced the production of H_2, CO, CO_2 and CH_4. From the results, Sekiguchi and Orimo claimed that microwave steam plasma has a potential to convert plastic to CO and H_2 effectively [23].

A method for sewage sludge treatment based on subjecting the wet sludge to high temperature thermal treatment in a microwave was investigated by Mene´ndez *et al.* Under the appropriate operating conditions, drying, pyrolysis and gasification of the sewage sludge take place, giving rise to a gas with a high CO and H_2 content and oil with a low Polycyclic Aromatic Hydrocarbons (PAH) content. The microwave-induced drying, pyrolysis and gasification (MWDPG) of wet sewage sludge at high temperatures produces a solid residue of a very low micro- and mesopore volume. This residue may partially vitrify if a sufficiently high temperature is reached during the process. The MWDPG of the sewage sludge was carried out in a one process, using a single-mode microwave cavity oven. This oven works at a frequency of 2450 MHz and the power delivered can be regulated up to 2000 W [24].

A study conducted by Chen *et al.* indicated that the reduction kinetic condition of the direct solid-phase reduction of metal oxide powder containing coal by microwave heating is better than that by the conventional heating process. The research showed that the gas ionization during carbothermal reduction accelerates the carbon gasification reaction and interface chemical reaction, and it also improves the kinetic conditions of carbothermal reduction. Gases produced in the carbothermal reduction in solid phase between metal oxides and coals may be ionized in microwave field, which can accelerate the process of carbon gasification and improve the kinetic conditions of carbothermal reduction. Thus, gas ionization attaches great significance to the carbothermal reduction in microwave field [25].

Kabalan *et al.* conducted a research on real-time optimisation of a microwave plasma gasification system in 2011. A microwave plasma gasifier has been designed to produce syngas from waste. The controllable parameters in the experiment are the microwave power applied, the reflected power from the microwave plasma jet, the tuner arm position, the gas flow and pressure, and the temperature inside the gasifier. The plasma flame was generated using 1.1 kW, 2.45 GHz microwave power supply. Argon gas was passing through the nozzle inside the chamber during the gasification. The result showed the benefit of using the control system to optimise the gasification procedure and compared the results with and without the control system [26].

In 2012, Yoon and Lee had successfully produce syngas from coal through microwave plasma gasification. The parameters in the study were types of coals, O_2/fuel ratio, steam/fuel ratio, and coal particle sizes. The plasma was generated by using a 2kW microwave plasma unit. Nitrogen was used as a plasma forming gas. CH_4 was not observed in a syngas, which is typical of high temperature plasma gasification. The H_2, CO_2 contents tend to increase and CO content in the product gas decreased with increasing steam/fuel ratio. This was similar to the tendency in conventional gasification. The microwave spectrum is usually defined as electromagnetic energy ranging from approximately 1 GHz to 100 GHz in frequency [27].

Hong *et al.* in early 2012 investigate the plasma gasification of brown coal with ash and moisture content of 38.12% using 4kW microwave plasma torch system. The experiment use pure steam torch plasma generated by 2.45 GHz microwave energy. Coal powders with an average particle size of 70 µm were injected to the steam torch. From the experimental data showing the relative concentrations of synthesized gas species versus the ratio of coal to steam for brown coal at the microwave power of 4 kW, the relative concentrations of synthesized gases at a ratio of 1.36 of coal to steam was 48% of hydrogen, 23% of carbon monoxide, 25% of carbon dioxide and 4% of methane. The further increase of coal to steam ratio did not much reduce carbon dioxide concentration. This research proved that a low-grade coal can also be well gasified in steam plasma torch [28].

Ann *et al.* studied the effect of flame temperature, nozzle position and swirl gas on microwave plasma flame. In this study, a microwave plasma generator was used to develop a plasma flame. 1kW power microwave generator was used to generate a single mode microwave in the wave guide and passes through a flame burner. When the microwave power was increased, the flame temperature also increased. This is because of absorption of energy from the microwave. The optimum position of the quartz nozzle when generating plasma was located one quarter of wavelength away from the end of the waveguide. This was the optimum location of the nozzle because the intensity of electric field was the strongest at this point. The vertical position of the quartz nozzle does not affect the plasma formation. Ann *et al.* used compressed air as a swirl gas to create a swirling effect that stabilized the plasma flame [29].

Shin *et al.* also studied on coal gasification by using pure steam microwave plasma torch. The power for the microwave generator use in this research was 5 kW. Shenhua coal was used in the experiment. Coal powders with an average particle size of 70 µm were injected to the steam torch. The relative concentrations of synthesis gases were 52% of hydrogen, 23% of carbon monoxide and 25% of carbon dioxide at a ratio of 0.55 of steam to coal [30].

Yoon and Lee repeated the microwave plasma gasification in 2012, this time using 5 kW microwave plasma power. Two kinds of coal and one kind of charcoal were used in this experiment. Steam and air acted as the plasma-forming gases. When using pure steam as the plasma-forming gas, the syngas produced H_2 content was mostly more than 60%, but the carbon conversion and cold gas efficiency were low. When air was used as the plasma-forming gas, the syngas produced was low in H_2 content and high CO and CO_2. On the other hand, the carbon conversion and cold gas efficiency were higher than when steam was used as the plasma forming gas. When the steam and air were mixed together, the maximum cold gas efficiency was shown when the O_2/fuel ratio was 0.272. The carbon conversion and cold gas efficiency of charcoal with high fixed carbon and carbon contents were lower than the values obtained with the coals used in this study [31].

Shen *et al.* studied about methane coupling in microwave plasma under atmospheric pressure based on the thermodynamics of chemical reaction. The acetylene yield of methane coupling in microwave plasma was much higher than the maximum thermodynamic yield of acetylene. This occurrence was cause by the non-expansion work in the microwave plasma system. The experimental set-up consisted of a microwave generator, a circulator, a high-power variable attenuator, a directional coupler, and a power meter (YM2463), a rectangular waveguide resonator, and a quartz reaction tube that was filled with CH_4 and H_2. The microwave power supply was 800 W at 2450 MHz With the aid of microwave energy; methane was discharged to form plasma. When ratio of methane to hydrogen decreased, methane conversion and C_2 hydrocarbon yield increase, while the yield of carbon deposit decreases. With the increase of CH_4 flow rate, methane conversion, C_2 hydrocarbon yield, and the yield of carbon deposit decrease, while the selectivity to acetylene increases slowly. With the increase of microwave power, methane conversion and C_2 hydrocarbon yield increase. Under CH_4 flow rate of 500 mL/min, the $n(CH_4)/n(H_2)$ ratio of 1/4 and the microwave power of 800W, methane conversion was 88.1% and acetylene yield was 66.0% [32].

Asad *et al.* had tested coaxial injection microwave excited plasma torch, operating at atmospheric pressure to treat greased metallic surfaces. Optical emission spectroscopy was used for the treatment conditions. Argon was used as the plasma gas, with argon or oxygen in the periphery. The sample was weight before and after treatment to see if the treating process is successful.

Initial period of treatment yielded etching of the grease, but, later on, the grease stabilized forming polymeric films, independent of the gas present in the periphery. The etching behavior was explained by different mechanisms involved in the plasma grease surface and sub-surface interactions. The main problem that was encountered was the role of temperature as the system is highly dynamic and the plasma substrate interaction is quite localized, the notion of temperature is more or less ambiguous. Applied grease layers were not completely removed using the plasma but it can be useful in removing the superficial layers of a highly resistant lubricant. Atmospheric pressure microwave plasma torch can be efficiently used in removing thin lubricant layers, especially in the final phase of surface cleaning treatment on a production line [33].

Bang *et al.* had synthesized metal nitride nanoparticles, such as titanium nitride (TiN), vanadium nitride (VN), and silicon nitride (Si_3N_4) by an atmospheric microwave plasma torch. The reactants in gas-phase are fragmented to atoms or molecules and then the fragmented species create particles in micro or nano size. X-ray diffraction, field-emission scanning electron microscope, and field-emission transmission electron microscopy have been employed to investigate powder diffractions, surface morphologies, particle sizes, etc. The particle sizes of as-produced samples are approximately 10–25 nm, revealing well-ordered individual layers with high crystallinity. The microwave plasma generated from the injection of N^2 gas provides nitrogen rich radicals and ions to enhance the reaction rate, ratio, etc. [34].

Jašek *et al*. synthesized a well aligned multi-walled carbon nanotubes (CNTs) at atmospheric pressure. Microwave plasma torch on silicon substrates with silicon oxide buffer layer and catalyst over layer in the mixture of argon, hydrogen and methane were used in this study. The catalysts used were iron/nickel. The optimum substrate temperature for the deposition on Si/SiO2/Fe substrates was about 970 K. At optimized conditions using the SiO2/Fe double layer on the silicon substrate, the synthesized CNTs exhibited very good vertical alignment, a length up to 50 µm and narrow diameter distribution around 15 nm. Fast substrate heating and simultaneously high concentrations of reactive carbon species in the discharge were probably advantageous for the deposition process. The substrates with Ni catalysts needed lower temperature for the CNT deposition and the quality of the deposit was always lower [35].

Ray and Hieftje investigated a modulated tandem source for generating atomic and molecular mass spectra in a rapid, sequential manner. The source consist a microwave plasma torch and an atmospheric-sampling glow discharge. Microwave plasma torch was used to produce atomic ions while the atmospheric-sampling glow discharge, produce molecular fragmentation mass spectra. The mass spectra of several volatile organic compounds representative of both atomic and molecular modes of operation are presented, and the latter directly compared to mass spectra produced by an electron-impact ionization source. Unique aspects of the experimental construction and performance of this pair are considered [36].

Leštinská *et al*. had developed and tested a new method for temperature measurements of near equilibrium (near-LTE) air plasmas at atmospheric pressure. It is suitable for plasmas at relatively low gas temperature (800–1700 K) with no appropriate radiation for direct spectroscopic temperature measurements. Air plasma jet is used as an excitation source for N_2. The lateral and axial gas temperature profiles of the microwave plasma jet were measured at various powers and flow rates. The temperatures measured by the corona probe were slightly higher than the thermocouple. This is because thermocouple radiative losses have to be taken into account. After considering these losses, the temperatures measured by the thermocouple and the corona probe are much better. In summary, the presented non-equilibrium corona discharge temperature probe, unlike thermocouples, can be considered a reliable method for the near-equilibrium plasma temperature determination, even for plasma with no radiation applicable [37].

Hong *et al.* developed a microwave plasma torch operated in a closed and isolated environment operating at a low pressure. This may provide an opportunity for the mass production of chemically active radicals for various chemical and biological processes. It is found that the plasma profile at a low pressure is asymmetric with higher density on the incoming side of the microwaves. This behavior of the torch inhibits high-power operation of the microwave plasma torch at a low pressure. However, the asymmetry of the plasma profile disappears under a high gas flow rate. It was also found that a microwave plasma torch used at a low pressure can efficiently produce an abundance of chemical radicals. Nevertheless, the microwave plasma torch operated at a low pressure was shown to be capable of efficiently producing an abundance of chemical radicals that can be used in material processing and surface cleaning processes [38].

Kim *et al.* had developed a microwave plasma system for fuel reforming. The system was tested for three different hydrocarbon fuels. The microwave power was delivered to the nozzle from the magnetron via a coaxial cable, which offers tremendous flexibility for system design and applications. A non-premixed configuration was achieved by delivering a separate stream of fuel to the plasma plume, which is composed of diluted oxygen only. The feasibility of syngas production capability of the microwave plasma system was demonstrated and the reforming characteristics of methane, iso-octane and gasoline were compared. The effects of input power, injected fuel amount, total flow rate and O/C ratio were evaluated. The production rates of both hydrogen and carbon monoxide were proportional to the input power and the inverse of the total flow rate. As a result, the maximum efficiency of 3.12% was obtained with iso-octane for power consumption of 28.8W, O/C ratio of 1, and 0.1 g/min of fuel supply. Liquid fuels produced more syn-gas and showed better efficiency than methane for the same input powers and O/C ratios [39].

Kongkrapan *et al.* developed a microwave plasma reactor for conversion of waste papers to generate fuel gas in March 2013. The variables for the experiments are air flow rates, syngas yield production and composition. At constant power of 800 W, average gas produce and maximum carbon conversion achieved were 2.10 m^3/kg and 59%. Total content of CO and H_2 produce on a nitrogen free basis was 31-43%. At this percentage, the gas can be used as synthetic gas. Figure 4 shows the schematic of the microwave plasma reactor setup for gasification of waste papers [40].

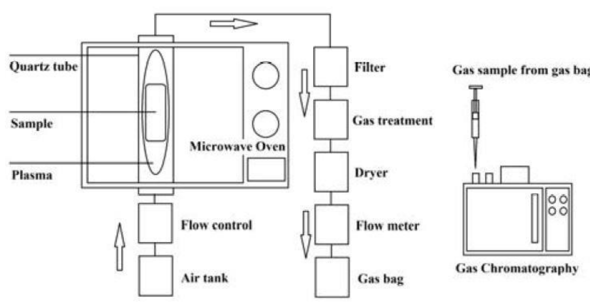


Figure 4 Schematic of the microwave plasma reactor setup for gasification of waste papers [40]

2.3 Radio-Frequency (RF) Plasma

Tang and Huang in 2005 have developed coupled RF plasma technology to overcome the problem of current DC thermal plasma processes. A laboratory-scale capacitively coupled RF plasma pyrolysis reactor working in reduced pressure has been developed. Experiments have been performed to examine the characteristics of this RF plasma reactor and the products of biomass gasification. It was found that the electrode geometry, input power and reactor pressure were the key parameters affecting the plasma characteristics such as plasma length, temperature, and energy transfer efficiency. Biomass gasification using input power 1600–2000 W and reactor pressure 3000–8000 Pa produced a combustible gas consisted of H_2, CO, CH_4, CO_2 and light hydrocarbons as well as a pyrolytic char. On average, the gas yield can reach 66 wt% of the biomass feed. An energy balance analysis on the RF plasma pyrolysis system was also given. From these experiments, it was concluded that the conversion of the biomass feed to gaseous products were enhanced by higher input power, operating pressure, and shorter electrode distance; using double sets of electrodes was advantageous compared to one set of electrodes. The energy balance analysis on the RF plasma reactor indicated that further improvement of energy efficiency is needed [41].

Later in 2009, Tang and Huang run a research also on capacitively coupled RF plasma reactor but this time in pyrolysis treatment of waste tire powder. It was found that using a RF input power between 1600 and 2000 W and a reactor pressure between 3000 and 8000 Pa (absolute pressure), a reactive plasma environment with a gas temperature between 1200 and 1800 K can be reached in this lab scale reactor. Under these conditions, pyrolysis of tire powder gave two product streams: a combustible gas and a pyrolytic char. The major components of the gas product are H_2, CO, CH_4, and CO_2. Experiments on this reactor have shown that: (1) the solid conversion ranges from 40% to 78.4% over the range of conditions considered; (2) the gaseous product contains a large percentage of H_2 and CO and small percentage of methane and other light hydrocarbons; (3) the solid conversion and the H_2 concentration are enhanced by higher power and pressure; and (4) the pyrolytic char contains about 85%carbon, and may be used as semi-reinforcing carbon black. Radio frequency (RF) is a rate of oscillation in the range of about 3 kHz to 300 GHz, which corresponds to the frequency of radio waves, and the alternating currents which carry radio signals. Figure 5 shows a RF plasma gasification system [42].

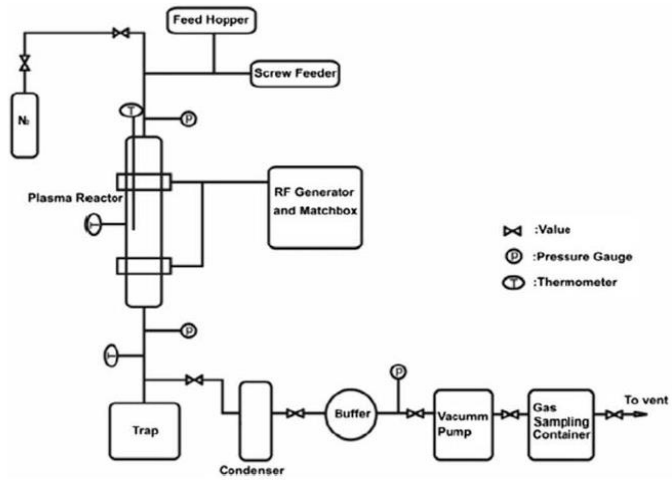


Figure 5 RF plasma system [42]

3.0 SUMMARY

3.1 Method, Solid Types, and Gas Percentage

Table 1 shows the comparison of syngas composition in different types of plasma method and solid used [17, 28, 42-45]. From the table, plasma method is proven to produce syngas with higher percentage of H_2 compared to conventional method. Composition of natural gas (NG) and Liquefied Petroleum Gas (LPG) are also included in the table to compare with syngas produced from plasma method. Natural gas is higher in hydrocarbon especially methane but the syngas is higher in hydrogen with a slight trace of hydrocarbon. LPG is totally different than other gases because it only contains propane and butane.

Table 1 Method, solid types, and gas percentage (vol%) [17, 28, 42-45]

Method	Thermal Plasma	Microwave Plasma	RF Plasma	Conventional	Natural Gas [44]	Liquefied Petroleum Gas (LPG) [45]
Solid Type	Municipal Solid Waste [17]	Coal [28]	Waste Tires [42]	Biomass [43]		
			Gas Percentage (vol%)			
CO	40.0	23.0	21.8	34.19	-	-
CO_2	12.3	25.0	14.9	19.68	1.0-2.0	-
H_2	40.3	48.0	48.5	21.83	-	-
N_2	7.4	-	-	21.20	1.0-5.0	-
CH_4	-	4.0	14.8	3.10	>85.0	-
C_2H_6	-	-	-	-	3.0-8.0	-
C_3H_8	-	-	-	-	1.0-2.0	30.0
C_4H_{10}	-	-	-	-	<1.0	70.0

3.2 Higher Heating Value of Gas

The heating value or calorific value is the energy content of a biomass fuel. It is one of the most important characteristic parameters for design calculations and numerical simulations of thermal systems. Rather it is a direct combustion [46] or co-firing with other fuels [46-48] it is still a significant parameter. The heating value of a fuel is divided into two, the higher heating value (HHV) or gross calorific value and the lower heating value (LHV) or net calorific value. The HHV refers to the heat released from the fuel combustion with the original and generated water in a condensed state, while the LHV is based on gaseous water as the product [49]. Higher heating value of gas is calculated using the data of gas composition in Table 1.

Table 2 shows the higher heating value of gas that has been calculated. The calculations use 100 mole of gas as a basis. The equation to calculate the HHV of syngas is as Equation (1);

$$HHV=\sum x_i(HHV)_i \quad (1)$$

Where (HHV)i is the heating value of the *i*th combustible substance and x_i is the mole or mass fractions of the fuel components [50]. Table 3 shows the comparison of various plasma method and conventional method.

Table 2 Higher heating value of gas [17, 28, 42-45]

Method	Thermal Plasma	MW Plasma	RF Plasma	Conven-tional	NG [44]	LPG [45]
Solid Type	MSW [17]	Coal [28]	Waste Tires [42]	Biomass [43]		
	Higher Heating Value of Gas					
kJ/mol	228.4	237.9	332.1	186.8	915.1	2681.0
kJ/kg	11,710.4	12,485.8	20,736.2	7,435.9	53,333.8	49,729.2
kJ/Nm^3	7,374.0	5,927.5	10,891.6	5,519.7	40,242.6	117,781.8

Table 3 Summary of plasma and conventional method [16, 28, 41, 43]

Method	Thermal Plasma [16]	Microwave Plasma [28]	Radio Frequency (RF) Plasma [41]	Conventional [43]
Solid	Sewage Sludge	Brown Coal	Biomass	Coal and Biomass
Gasifier	Plasma Furnace with DC arc	Stainless steel pipe	Plasma reactor with capacitively coupled RF plasma	Fluidized bed
Solid Conversion (%)	86.8	65.0-99.0 (according to particle size/150-45μm)	32.5-88.4	78.2-93.0
Energy Required per 1 kg (kW)	0.0054	1.2	1.6-2	Not mention by authors but high energy may be used
Temperature (K)	1273	2000-6500	1173-1773	1220-1300
Pressure (kPa)	Not mention by authors but high pressure to heat up gasifier	101.3	3-8	Not mention by authors but high pressure to heat up gasifier
Advantages		-Fast gasification -High solid conversion -Operates at atmospheric pressure		
Disadvantage	-Slow heating of furnace -Erosion of electrode	-High temperature	-Formation of char -Very low pressure	-Slow reaction -Slow heating

■4.0 OTHER APPLICATIONS OF PLASMA TECHNOLOGY

In the recent years, issues relating to serious climate change have been discussed more than ever amongst the experts, particularly the environmentalist. One of the main issues discussed is the impact of the release of greenhouse gas emission in large scale to the atmosphere. There are also large issues in solid waste management all over the world, especially on such countries that does depend on heavy industrial production such as India, Japan, China and India. Poor surveillance and violation of existing laws, rules and regulations in some of the countries will result a tragic incident such as happened in Bhopal in 1984. The government of Madhya Pradesh confirmed a total of 3,787 deaths related to the gas release. Others estimate 8,000 died within two weeks and another 8,000 or more have since died from gas-related diseases.

A government affidavit in 2006 stated the leak caused 558,125 injuries including 38,478 temporary partial injuries and approximately 3,900 severely and permanently disabling injuries. In June 2010, seven ex-employees, including the former UCIL chairman, were convicted in Bhopal of causing death by negligence and sentenced to two years imprisonment and a fine of about $2,000 each, the maximum punishment allowed by Indian law. An eighth former employee was also convicted, but died before the judgment was passed. There are also the issues of controlling nuclear waste. Lake Karachay, Chelyabinsk, Russia, close to the modern border with Kazakhstan, is located within the Mayak Production Association, one of the country's largest and leakiest nuclear facilities. In their long decades of obscurity, the nuclear engineers at Mayak spent their time mainly having nuclear meltdowns and dumping radioactive waste into the river. The watered-down waste was a cocktail of radioactive elements, including long-lived fission products such as Strontium-90 and Cesium-137–each with a half-life of approximately thirty years.

Plasma technology is one of the efforts to practice cleaner technology in industry world. Other than processing and treatment of solid waste, plasma technology can be applied in other area. The rapid growth of plasma technology is reflected in applications that are today already making our daily lives more convenient and healthier. The unobtrusive way in which our lives and environment are being enriched with products that benefit from plasma processes or, indeed, owe their very existence to such processes, goes hand in hand with a characteristic trait of plasma technology: Sustainable use of raw materials and energy, leading to products that are durable and of lasting value. For example, in environmental applications, decontamination of chemical and biological warfare agents and nanotechnology. Besides, plasma technology can also be apply in surface coating, and has the potential to be applied in various industries such as fuel cell technology. This technique has the potential to be developed into small rapid testing unit for various kinds of materials but not limited to biomass. Products can find versatile application as fuels, energy, power generation, composite materials, and others. For big scale industries, plasma technology can be applied in gasification, biotechnology, chemicals, power generation, treatment, waste destruction, and solid waste management.

The manufacture of steel involves many energy intensive processes that consume raw or recycled materials, such as iron ore and scrap metal, from around the world. Raw materials with intrinsic carbon contents (e.g., iron carbide, carbon electrodes, charge carbon, or limestone), the primary resources for steel production, can have material significance in the calculation of climate impacts. Virtually all of the greenhouse gas emissions associated with steel production, however, consists of the carbon dioxide emissions related to energy consumption; the primary focus of climate related impacts in the steel industry are those associated with carbon-related energy sources. Energy consumption in steel production represents about 2.5% of domestic energy use and about 8% of all U.S. manufacturing energy use. About half of the steel industry's energy is derived from coal and a large portion of this is consumed during the reduction of iron ore to pig iron. Pulsed plasmas present to be alternative features for the steel industries. One reason for this is the large variety of possible pulses, which solve plasma-chemical problems, which allow tailor-made solutions to be found. Today's largest and most powerful industrial plasma plants, operating at a few tens of megawatts, are ones that run on a continuous basis. The plasma-melting plants, which are used primarily to melt steel scrap and to re-melt alloyed steels and high melting-point metals such as titanium, tantalum, molybdenum, or niobium, will slowly take over the use of traditional methods in steel productions.

5.0 CONCLUSION

The world is in a frustrating situation, in their near-futile search for new sources of energy; in the meantime facing an ongoing environmental degradation. Plasma treatment and processing of waste can be the solution to these problems. As plasma gasification is a potential substitute for conventional gas processing and treatment. Also, it has many advantages such as operating under atmospheric pressure, require short time to elevate to higher temperature, and help saving the energy. As shown in the discussion above, plasma technology has been proven to be one of the most successful efforts in practicing cleaner technology in industry world. Other than processing and treatment of solid waste, plasma technology can also be applied in other area such as environmental applications, decontamination of chemical and biological warfare agents and nanotechnology. Plasma technology will help the world to become greener by lowering the greenhouse gas emissions from heavy industries. Plasma gasification technology is commercially proven and viable, while also meeting all current regulatory requirements. Plasma gasification is positioned to take hold as a practical, economical and environmentally responsible alternative to conventional forms of waste disposal and power generation.

Acknowledgement

The authors would like to thank Ministry of Higher Education, Malaysia and UTM for Research University Grant (Vote No: 4F135) for funding this research activity.

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