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The Effect of Flame Temperature, Nozzle Position and Swirl Gas on Microwave Plasma Flame

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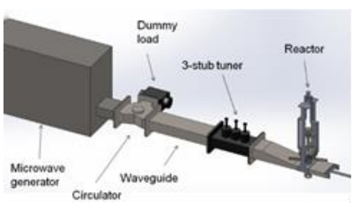
Graphical abstract



Abstract

In this study, a microwave plasma generator was used to develop a plasma flame. The effects of microwave plasma on flame temperature, nozzle position and swirl gas were investigated. A microwave generator with 1kW power was used to generate a single mode microwave in the wave guide and passes through a flame burner. The study show that the flame temperature increased when the microwave power was increased. This is due to 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. Compressed air was used as swirl gas to create a swirling effect that stabilized the plasma flame. The swirl gas does not shield the quartz reactor from the flame but enlarging the size of the flame. This is due to swirl gas which contains oxygen acts as oxidant which supplies oxygen to the combustion process.

Keywords: Plasma flame; microwave plasma; swirl gas

1.0 INTRODUCTION

According to Fridman, plasma is an ionized gas, a distinct fourth state of matter [1]. Ionized means that at least one electron is not bound to an atom or molecule, converting the atoms or molecules into positively charged ions. As the temperature increases, molecules become more energetic and transform into matter in the sequence of, solid, liquid, gas, and finally plasma, which explains the positively charged ions named the fourth state of matter. Ionization can be induced by other means, such as strong electromagnetic fields applied with a laser or microwave generator, and is accompanied by the dissociation of molecular bonds, if present [2]. Plasma technology can be applied to the treatment of solid waste. 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 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. Three types of plasma could be considered for the treatment of Malaysian solid wastes, that are the thermal plasma, microwave plasma, and radio-frequency (RF) plasma [3].

Microwave induced plasma consumes less power than conventional electrical arc plasma and capable of turning municipal waste into useful materials and energy such as syngas and slag [4]. Thermal plasmas such as DC plasma torch are not effective in terms of energy consumption as high energy is needed to maintain the high temperature induced by thermal plasma. In addition, arc based thermal plasmas is limited by the electrode lifespan as electrode can be corroded in the process; thus, increasing the operational cost and maintenance cost. On the other hand, microwave plasma can operate without electrode and the lower temperature of non-thermal plasma results in lower energy consumption in sustaining the discharge. These are supported by Kim *et al.* regarding to the advantages of microwave plasma over other plasmas [5]. Radio Frequency (RF) plasma is also a type of non-thermal plasma but the overall efficiency of RF plasma is reduced by the inductive coupling of RF power and the component costs. If compared to microwave plasma, RF plasma has lower power efficiency and requires more energy to generate plasma. Subsequently, excess energy needs to be dissipated by cooling system. Moreover, Kawase *et al.* stated that microwave plasma torch unit can be formed as a small-sized unit which offer flexibility in designing compact system [6].

A complete microwave plasma test rig consist of microwave generator, waveguide, 3-stub tuner, directional circulator and reactor. Magnetrons or microwave generators are used to generate 2.45GHz microwave frequency which are generally same as the typical home microwave ovens [7]. Directional circulator is needed in the microwave plasma system for transmitting unidirectional microwave. The circulator is diverting reflected power in the system to a dummy load for dissipation in order to protect magnetron [5]. A microwave impenetrable waveguide can be used to transmit the microwave to the reactor or chamber. The typical waveguides are rectangular waveguide and tapered waveguide. A tapered waveguide is capable of increasing the intensity of electromagnetic field in the quartz tube which enhances the formation of microwave plasma [8]. 3-stub tuner is used to maximize the electric field induced by the microwave radiation in the quartz tube [9].

The intensity of electric field located one quarter wavelength from the end of waveguide is the strongest [7, 9]. Hence, the reactor is placed at this position so that the flame and gas are exposed to the highest intensity of electric field and plasma is more likely to form. On the other hand, higher power input creates more reactive species such as ions and radicals which can enhance the plasma gasification process [5]. Besides, the plasma generated inside the quartz reactor can be stabilized by injecting swirl gas which shields the quartz reactor from the high temperature plasma [8].

2.0 EXPERIMENTAL

2.1 Designs of End Waveguide and Reactor

This rig was setup to create a plasma flame from microwave generator. The microwave transmission system consist of microwave generator, directional circulator, rectangular waveguide, and 3-stub tuner. At the end of the waveguide, a reactor with gas system were design to let the rig complete. Five main functional parts were designed with Solid Works and then fabricated after validation and approvals. The five parts were tapered end waveguide, adjustable support rig, movable plunger, gas mixer and quartz reactor. Figure 1 shows the designs of the test rig components while Figure 2 shows the full assembly of the microwave plasma test rig.

The tapered end waveguide was designed to enclose the microwave, trapping the microwave within. The tapered part was capable of intensifying the microwave while the hole was for the entry of the reactor and nozzle. Besides, the adjustable support rig was designed to hold and support the gas mixer and quartz reactor. The movable plunger was designed to enclose the microwave within the tapered end waveguide. The movable plunger can be moved horizontally and was used to control and adjust the microwave resonance cavity formed inside the tapered end waveguide. The purpose was to intensify the electric field within the quartz nozzle in order to increase the tendency to form plasma within the reactor. On the other hand, the gas mixer was designed to mix the fuel gas and air through swirling inside the mixer while the quartz reactor was where the gas mixture ignited and plasma generated. The reactor and nozzle were made of quartz which microwave can penetrate and transfer energy to the gas mixture and flame, inducing plasma.

Parts of test rig were validated by using Matlab and Fluent before the designs were being sent for fabrication. Matlab was used to validate the propagation of microwave inside the waveguide while Fluent was used to validate the gas mixing and gas swirling inside the gas mixer and quartz reactor. Matlab was used to determine the minimum width that the waveguide should have so that the microwave can propagate. The wavelength of the microwave within the waveguide or waveguide wavelength must lower than the cut-off wavelength and the frequency of the microwave within the waveguide or waveguide frequency must higher than the cut-off frequency in order to propagate and transfer energy within the waveguide.

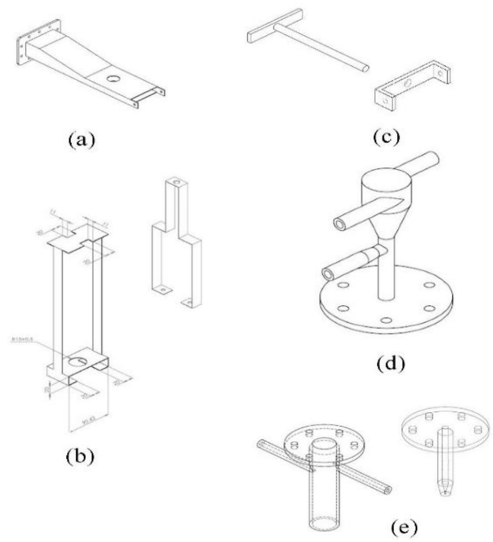


Figure 1 Design of (a) tapered end waveguide, (b) adjustable support rig, (c) movable plunger, (d) gas mixer and (e) quartz reactor

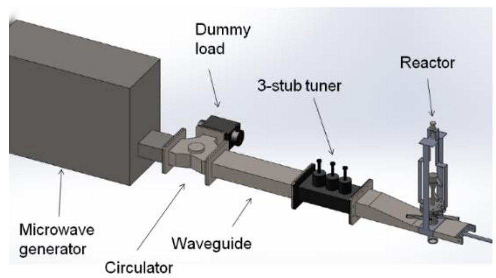


Figure 2 Full assembly of microwave plasma test rig

Cut-off wavelength was determined using the following Equation (1);

$$\lambda_c = \frac{2}{\sqrt[2]{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}} \quad (1)$$

where λ_c, a, b, m and n are cut-off wavelength, waveguide width, waveguide height and eigenvalues respectively.

Wavelength of microwave in open air was calculated using the following Equation (2);

$$\lambda_o = \frac{c}{f} \quad (2)$$

where λ_o, c and f are the wavelength of microwave in open air, speed of light and frequency of microwave respectively.

So, waveguide wavelength was calculated like Equation (3);

$$\lambda_g = \frac{\lambda_o}{\sqrt[2]{1 - \left(\frac{\lambda_o}{\lambda_c}\right)^2}} \quad (3)$$

where λ_g is the waveguide wavelength.

As the speed of light, c and the frequency of microwave, f in open air are constant, the value of the wavelength of microwave in open air is constant as well which is

$$\lambda_o = 0.122449 \text{ m}$$

For microwave to propagate inside the waveguide $\lambda_c > \lambda_g$

$$\frac{2}{\sqrt{\left(\frac{m}{a}\right)^2+\left(\frac{n}{b}\right)^2}} > \frac{\lambda_o}{\sqrt{1-\left(\frac{\lambda_o}{\lambda_c}\right)^2}} \quad (4)$$

For the simplest form of wave to pass through, m=1; n=0

$$\lambda_c = 2a \quad (5)$$

$$a > \frac{\lambda_o}{\sqrt{2}} \quad (6)$$

Hence, the minimum width of waveguide to enable the microwave to pass through is

$$a > 0.0866 \text{ m}$$

To sum up, the width of the waveguide must be more than 0.0866 m or 8.66 cm so that the propagation of microwave inside the waveguide is feasible. Figure 3 shows the graphs of cut-off wavelength, waveguide wavelength, cut-off frequency and waveguide frequency against waveguide width. The design of waveguide is feasible when cut-off wavelength is more than waveguide wavelength and cut-off frequency is less than waveguide frequency. Apparently, the width of the waveguide has to be more than 0.0866 m; however, for better manufacturability and cost saving, 9 cm of waveguide width was chosen.

According to the formula, the waveguide wavelength, λ_g which is the wavelength of the microwave within the waveguide which has the width of 9 cm is 16.71 cm. Meanwhile, the frequency of the microwave within the waveguide is 1.795GHz. The cut-off wavelength and cut-off frequency are 18 cm and 1.667GHz respectively. In conclusion, it is feasible to design a waveguide with the width of 9 cm which enables the propagation of the microwave within the waveguide.

Figure 4(a) shows the simulation of velocity profile of gas mixing within the gas mixer while Figure 4(b) shows the simulation of pressure profile of gas mixing with venturi effect within the gas mixer and Figure 4(c) shows the simulation of velocity profile of air within the quartz reactor by using Fluent. All the simulations show that the designs of the gas mixer and quartz nozzle are feasible in mixing the fuel with air, the venturi effect which drew the waste gas to mix with the gas mixture and gas swirling within the quartz nozzle.

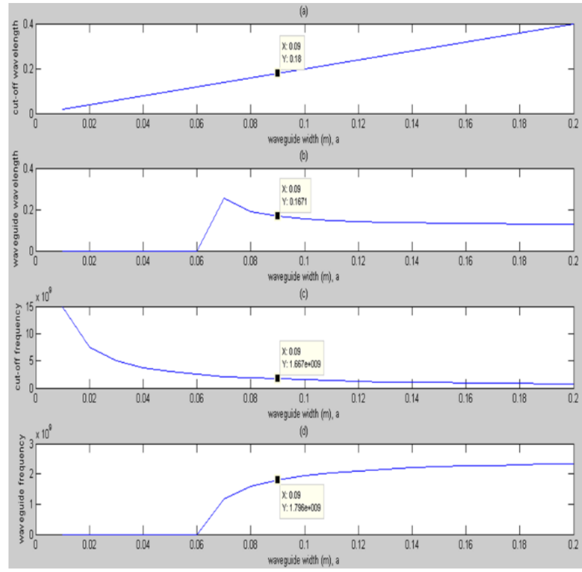


Figure 3 Graphs of (a) cut-off wavelength versus waveguide width, (b) waveguide wavelength versus waveguide width, (c) cut-off frequency versus waveguide width and (d) waveguide frequency versus waveguide width

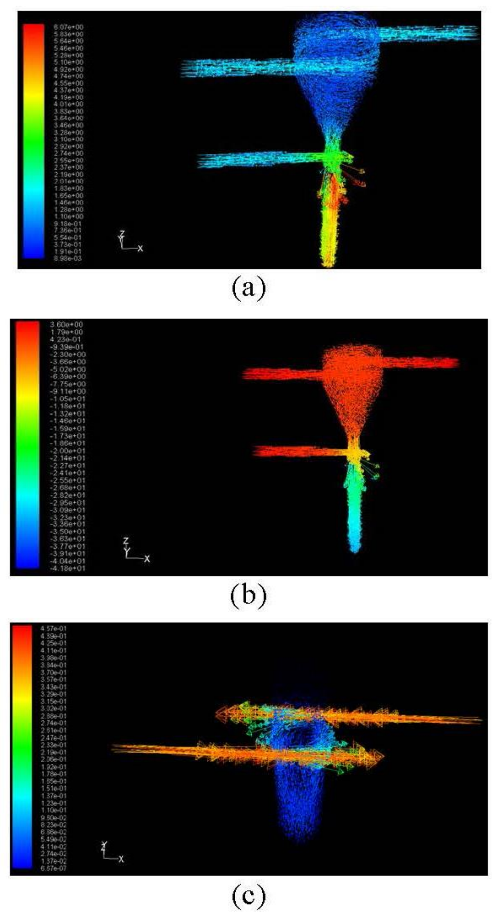


Figure 4 Simulation of (a) velocity profile of gas mixing within the gas mixer, (b) Pressure profile of gas mixing within the gas mixer and (c) Velocity profile of gas swirling inside the quartz reactor

2.2 Experimental Setup

Microwave plasma generation started with the microwave generator which generates microwave with 2.45GHz. A circulator was installed in between the reactor and microwave generator so that the reflector power in the system was diverted into a dummy load. The dummy load was dissipating the reflected power into the water. In this research, the circulator was connected to a rectangular waveguide that used to guide the microwave into the reactor which made of quartz. A 3-stub tuner which used to maximize the electric field in the reactor was installed in the middle of the waveguide. There were two types of gases being used, liquefied petroleum gas (LPG) and air which consists of 79% nitrogen and 21% of oxygen. The mass flow rate of each type of gas was controlled by flow meter and the gases were premixed inside the gas mixer. The gas mixture passed through a quartz nozzle inside the quartz reactor. As microwave penetrated the quartz tube, charge carriers were generated rapidly in the gas mixture due to the electromagnetic field of the microwave and plasma was formed subsequently. A thermocouple was placed under the quartz reactor to get the reading of the flame temperature. The experiment was conducted to investigate the effect of microwave on flame temperature, effect of quartz nozzle position and swirl gas in plasma generation. The experiment was conducted with the distance between the quartz nozzle and the end waveguide set to 3 cm, 4 cm, 5 cm, 6 cm and 7 cm according to Figure 5. The experiment was repeated by setting the quartz nozzle vertical position according to Figure 6.

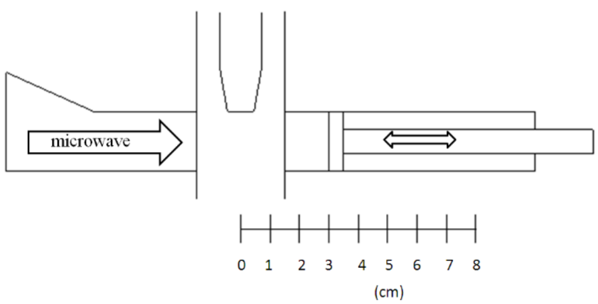


Figure 5 Adjustment of distance between quartz nozzle and plunger

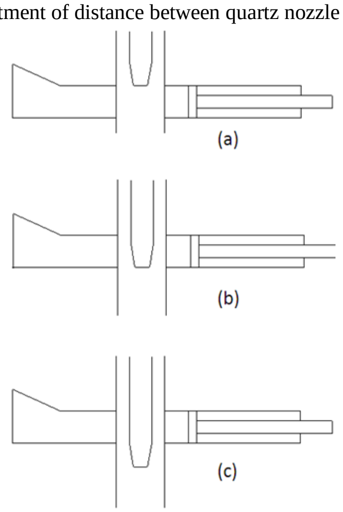


Figure 6 Nozzle position (a) above waveguide, (b) within waveguide, (c) below waveguide

3.0 RESULTS AND DISCUSSION

Figure 7 shows the graph of temperature increment of flame against the distance between quartz nozzle and plunger while Figure 8 shows the effect of microwave and swirl gas on the flame. The temperature of the flame without turning on the microwave generator was approximately 810^{o}C ± 10^{o}C. The flame temperature was increased when the microwave generator was turned on. As microwave penetrated the quartz tube, the energy from microwave was transferred to the flame. Charge carriers were generated in the gas mixture due to the electromagnetic field of the microwave. The flame temperature peaked when the distance between the quartz nozzle and plunger is 4 cm. The intensity of electric field located one quarter wavelength from the end was most powerful. More charge carriers were created due to stronger intensity of electromagnetic field was induced. Hence, the temperature reading of the flame was the highest when the quartz nozzle was located 4 cm away from the plunger.

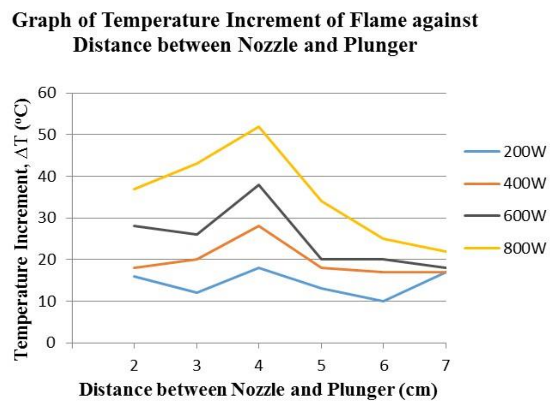


Figure 7 Graph of temperature increment of flame against the distance between quartz nozzle and plunger

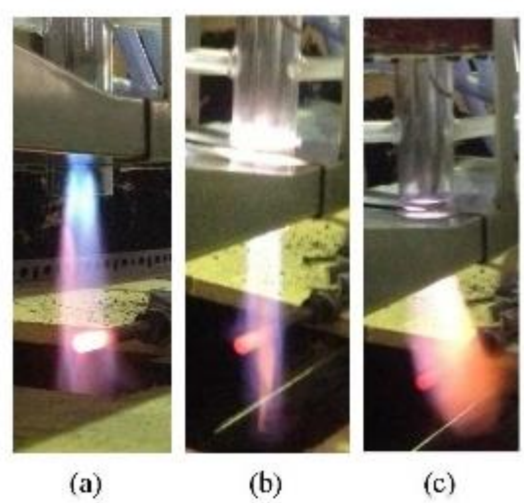


Figure 8 Flame (a) without plasma generation, (b) with plasma generation and (c) with plasma generation and swirl gas

Based on the observation made, the test rig showed the sign of plasma when the quartz nozzle was 5 cm away from the plunger; however, plasma was not seen when the quartz nozzle was 2 cm and 8 cm away from the plunger. The intensity of electric field induced by microwave peaked when the quartz nozzle was adjusted one quarter wavelength away from the end. As position of quartz nozzle at 5 cm was nearer to the location where the electric field peaked, the plasma was more likely to form. On the other hand, the intensity of electric field located 2 cm and 8 cm away from the end was weaker; hence, less charge carriers were created and plasma was not generated when the quartz nozzle was placed at these locations. The results showed no different when the vertical position of the nozzle was changed. This showed that the vertical position of the quartz nozzle did not help in intensifying the electric field. Furthermore, the results showed no different when the microwave power increased from 500W to 1000W. Even though the intensity of electric field located 2 cm and 8 cm away from the end became stronger when the microwave power increased, the intensification was still cannot match the intensity of electric field located 5 cm away from the plunger. On the other hand, the plasma was also generated for the case with swirl gas when quartz nozzle was located 5 cm away from the plunger. The flame generated at the presence of swirl gas was larger in size through observation. The air used as the swirl gas consisted oxygen which can be involved in the combustion of fuel. Thus, the air acted as oxidant as the same time, assisting the formation of flame. Consequently, flame with larger size was created. However, the purpose of the swirl gas was to shield the quartz reactor from the flame. The swirl gas that used air did not shield the quartz reactor but enlarge the flame that could damage the quartz reactor instead.

The temperature of the flame is expected to exceed 1000°C; however, the highest temperature reading obtained was only 860°C. In addition, the temperature increment of the flame after turning on the microwave generator is less than 100°C regardless the position of the quartz nozzle. These phenomena were caused by microwave leakage where microwave propagated and escaped from the rig. As more portion of the microwave was not absorbed by the flame and the total energy absorbed by the flame reduced, the temperature of the flame did not reach 1000°C.

■4.0 CONCLUSION

In conclusion, generation of plasma with 2.45GHz microwave was feasible with microwave generator, directional circulator, dummy load, waveguide, 3-stub tuner and reactor. The process started with the microwave generator which generated 2.45GHz microwave, and then the waveguide transmitted the microwave. Meanwhile, directional circulator diverted the reflected microwave into dummy load where the excess microwave was absorbed by water. The 3-stub tuner adjusted and tuned the microwave within the waveguide. Finally, the microwave induced plasma was formed inside the reactor where the gas passed through.

Microwave was capable of increasing the temperature of the flame and generating plasma inside the quartz reactor. Electric field induced by microwave can be also be intensified by increasing the microwave power. Thus, the temperature increment of the flame increased when microwave with higher power was used. The effect of the microwave was significant when the quartz nozzle was located one quarter wavelength away from the end of waveguide which was adjusted by the plunger. Besides, plasma was also formed when the quartz nozzle was located at this position; however, plasma was not formed when the quartz nozzle was located at 2 cm and 8 cm away from the end of waveguide because the lower intensity of electric field was formed at these locations. The formation of plasma is successfully carried out regardless of the quartz nozzle vertical position and presence of swirl gas.

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