EXPERIMENTAL INVESTIGATION OF IN-SITU OXIDATION OF SOOT

By

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

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Approved by,

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(Dr Zainal Ambri Abdul Karim)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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MOHAMED HAZIQ BIN HARON

ABSTRACT

The formation of soot is common in diesel engine, and it causes environmental pollution as well as decreasing the engine performance and causes cost of maintenance to rise. However, soot can be eliminated by trapping it using soot trap element within the exhaust and burning it off to soot oxidation temperature which is around 600°C. The soot trap element is to be permanently installed at the exhaust system of the diesel engine as current off the shelf product uses filters that needs to be replaced after certain time.

To reach the high soot oxidation temperature, this research is focusing on using microwave in order to reach the soot oxidation temperature. Experiment matrix for this research has been developed, and the maximum time of exposure of the soot that is trapped within the filter element is 600 seconds. The source of soot is from the diesel engine and the soot trap is initially filled with soot as well to ensure that it is full of soot. The amount of NOx, CO, CO_2 and O_2 as well as the opacity of the smoke are recorded at the initial and end of the experiment by using the Anycar AutoChek gas & smoke analyzer. The decreased amount of NOx, increased amount of CO_2 and a less opaque smoke emitted indicates that the soot combustion has occurred within the soot trap. The microwave generator used in this experiment can reach up to 3 kW, but it is decided to use 3 different levels of microwave energy to the soot which is at 0.5 kW, 1.0 kW & 1.5 kW. A relationship between level or intensity of the electromagnetic wave and smoke opacity, NO_x and CO_2 has been discovered from the results. The result has shown that the level of electromagnetic wave are increased, the amount of smoke and NO_x reduction while CO_2 increment are more. In-situ oxidation are very useful and has a bright future in after treatment of exhaust emissions as it ensure the vehicle to comply with the regulations in standard of gas & smoke emission and also provides a safer environment to the society as well as to the future generations.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Soot is basically one of the components that is polluting the air. Soot is made up from carbon particles due to incomplete combustion of hydrocarbons, woods etc. Soot is released to the air in two forms; extremely small particles or liquid droplets. As per Figure 1, size of soot is very small, 2.5 picometers in diameter or smaller. Due to its small size, soot can penetrate deep into the lungs and bloodstream and it is linked to serious health effects such as premature death, heart attacks, acute bronchitis and aggravated among children (Weidman and Marshall, 2012).

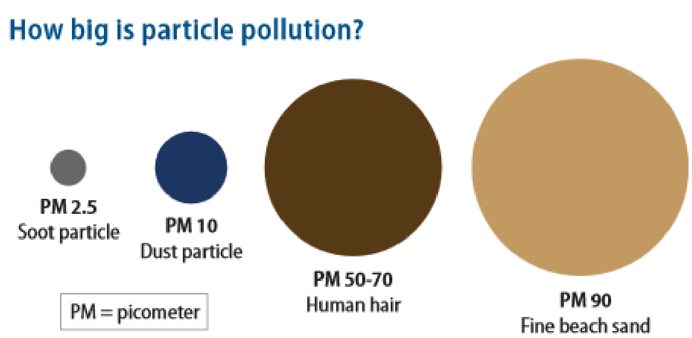

Figure 1: Size of Soot Particles (Weidman and Marshall, 2012)

Soot can be found as a byproduct of diesel engine emitted from the exhaust. The advantages of diesel engine comparing to gasoline engine is that it has better fuel economy and less carbon dioxide production per kilometer driven. However, soot are emitted by diesel engine due to the low efficiency of catalyst in removing the three main exhaust pollutants (hydrocarbons, CO & NOx) due to larger amounts of oxygen in diesel exhaust gas (Simonsen, 2008). A gasoline engine on the other hand has a so-called three-way catalyst which is way more efficient in removing the pollutants compared to a diesel engine.

Due to the pollution caused by soot, several emission standards have been introduced throughout the world in order to contain the pollutant emission into air. Such standards are listed below:

1. European emission standards (EURO)
2. United States emission standards governed by Environmental Protection Agency (EPA)
3. Japanese Air Pollution Control Act

Most of the countries in the world adopted EURO standards as the benchmark for pollutant emission standards. According to Agren (2013), current EURO standard which is EURO VI which will apply from 31 December 2013, is on par with United States emission standards where the limit value for NOx is 400 milligrams per kilowatt hour (mg/kWh), a remarkable 80% less value compared to EURO V and the particulate matter (PM) limit is 10 mg/kWh, 66% reduction compared to EURO V and the value can be seen in Figure 2 below.

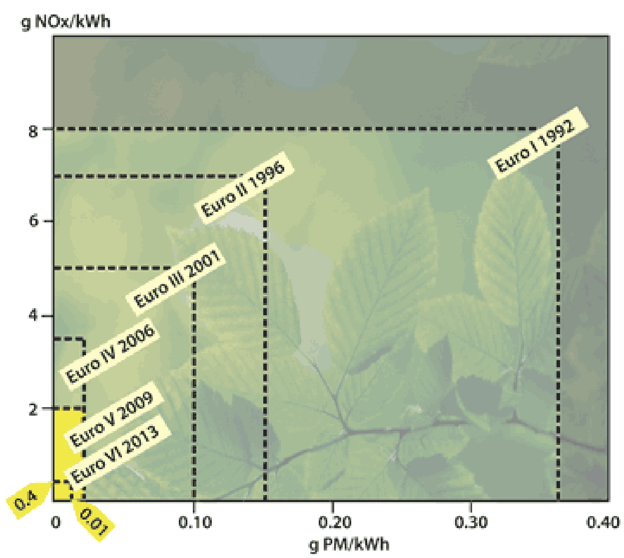

Figure 2: Development of European emission limits for NOx and PM from heavy duty vehicles (Agren, 2009)

In order to comply with these regulations, one of the methods to reduce the soot emission through the exhaust is by using diesel particulate filters (DPF). A DPF is a device fitted to an exhaust of a diesel engine vehicle and filters most particulate matters from the exhaust gas & a typical DPF are shown in Figure 3. It filters the solid particles and lets the gases escape through the exhaust. Regular maintenance is required for DPF and the process of regeneration is done during the maintenance. Regeneration is a process where particles trapped within the DPF is burned off at high temperature at least 600 °C and leaving behind very small residues.

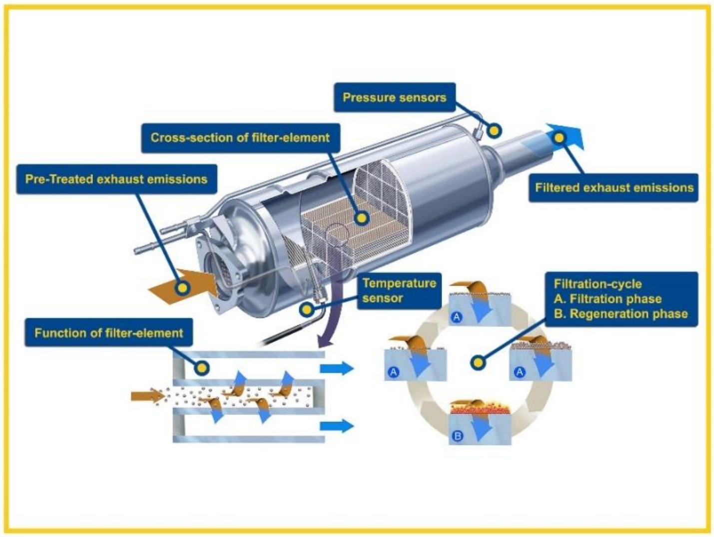

Figure 3: Typical soot trap and regeneration cycle of a diesel particulate filter (Marshall, 2014)

One of the methods to burn the trapped soot at temperature of at least 600 °C is by using microwave. Microwave is part of the waves, with frequencies from 300 MHz to 300 GHz and wavelength of 1 to 1000 mm. Microwaves, emitted through magnetron and the material exposed to microwaves absorb the waves and excites the free electrons available in the material, causing it to move rapidly and therefore heating itself up (Yoshikawa, Ishizuka & Taniguchi, 2006). No fire is required in microwave heating and rapid heating can be done using microwave compared to conventional heating.

1.2 PROBLEM STATEMENT

Soot, a combustion product of diesel fuel is subjected to environmental pollution regulation. After-treatment of soot emission can be employed by trapping the soot using filter in the exhaust pipe.

Another strategy to address the soot emission is to burn the soot prior to the release of the soot to the environment. This strategy employs electromagnetic wave (microwave) radiation to heat conductive elements in a soot trap emitted from a magnetron. In order to achieve this, the conductive elements or the soot trap must reach the soot oxidation temperature of above 600°C and also able to oxidize significant amount of soot.

This experiment is done to in order to justify the soot trap that has been designed previously and the microwave power on the soot oxidation. The soot trapped within the soot trap is expected to be oxidized fully. The constraints in getting to the expected result are whether the soot trap used are able to trap significant amount of soot emitted and whether it can expose all the soot trapped to the microwave in order for it to be oxidized.

1.3 OBJECTIVES

The objectives of this project are as per below:

1. To experimentally investigate the capability of a soot trap to filter and accumulate the soot.
2. To determine the electromagnetic power, exposure period and effectiveness to oxidize soot from a diesel engine.
3. To develop a control system for in-situ oxidation of soot.

1.4 SCOPE OF STUDY

The project is split into two parts; FYP 1 and FYP 2. For the first period of this project which is FYP1, understanding of the problem statements as well as the elements involved in this project such as soot particles, microwave heating and more is emphasized. Related equations as well as formula are derived in order to justify the concept. Experiment methodology, matrix and data acquisition system are also developed in the first stage of this project.

For FYP 2, the latter stage of this project, experiment investigation aspect of this project is done. The data obtained from the experiment will be analyzed, evaluated and also validated. Finally, an improved in-situ oxidation of soot control system will be developed in this stage.

1.5 RELEVANCY OF THE PROJECT

Nowadays, environment pollution is taken seriously. Heavy vehicles using diesel engine usually expels dangerous gases such as NOx & smoke with high opacity that causes global warming. Thus, engineers & researchers have been doing lots of researches in order to reduce the dangerous gases emission and smoke opacity from the exhaust. This project is to address the after treatment of exhaust gases by using soot traps & microwave to oxidize the soot in order to reduce soot & dangerous gases.

1.6 FEASIBILITY OF THE PROJECT

This project is conducted in two phases; FYP 1 & FYP 2. In FYP 1, the process of understanding this project and research as well as review for literatures are being done. Any literature resources for this project are compiled and reviewed as reference for this project. In FYP 2, the major experiment progress is being covered in this phase. The data obtained from the experiment are being recorded and analyzed. This project is feasible, achievable and can be completed within the timeframe.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 SOOT FORMATION

Soot is basically a small particle made up of carbon and small amount of hydrogen and oxygen. It is formed during combustion of hydrocarbon. The deciding factor whether soot would be available during combustion is the competition between soot formation and oxidation (Kennedy, 1997). This means that soot is produced during incomplete combustion as part of its product as well as carbon monoxide and hydrogen. Soot is also an unwelcomed byproduct in combustion systems as it can foul exhaust systems and generate dark exhaust smokes (Stanmore, Brilhac and Gilot, 2001).

$$C_mH_n + a\,O_2 \rightarrow 2a\,CO + 0.5n\,H_2 + (m\text{-}2a)\,C_s$$

Figure 4: Chemical Equation for Soot

There are six identified processes during evolution of liquid or vapor-phase hydrocarbons to solid soot particles and to gas-phase products (Tree & Svensson, 2007). They are pyrolysis, nucleation, coalescence, surface growth, agglomeration and oxidation and the processes are clearly shown in Figure 5 below.

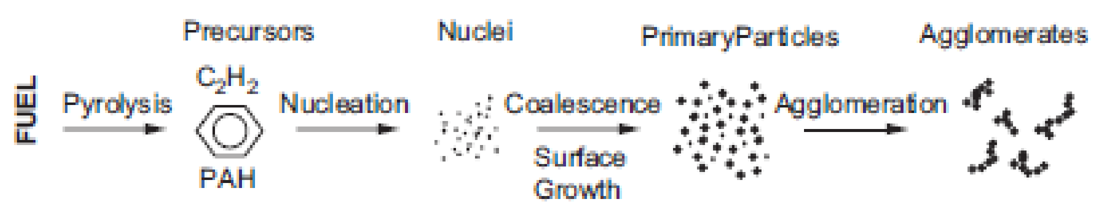

Figure 5: Schematic diagram of steps in soot formation process (Tree et al., 2007)

Soot particles will only be burned off at temperatures of 500°C - 600°C and above (Fraunhofer-Gesellschaft, 2011). However, the usual temperature of exhaust is way below of the temperature where soot will burn off which is around 200°C - 400°C and thus, it is vital for the microwave to be able to heat the soot particles up to the minimum burned off temperature of soot.

2.2 MICROWAVE HEATING PRINCIPLES

In a microwave, an enclosed space, microwave is generated by magnetron. Besides magnetron, Klystrons, Gyrotrons and Travelling wave tubes (TWT) can also be used to generate microwave (Chandra, 2011). However, magnetron is preferred due to low cost and it is easily available. A continuous or pulsed power can be generated from a magnetron with frequencies from 1-40 GHz. The efficiency of magnetron is around 85%. Magnetrons are usually cylindrical in shape and consist of identical cavity resonators arranged in cylindrical patters around cylindrical cathode as per Figure 6.

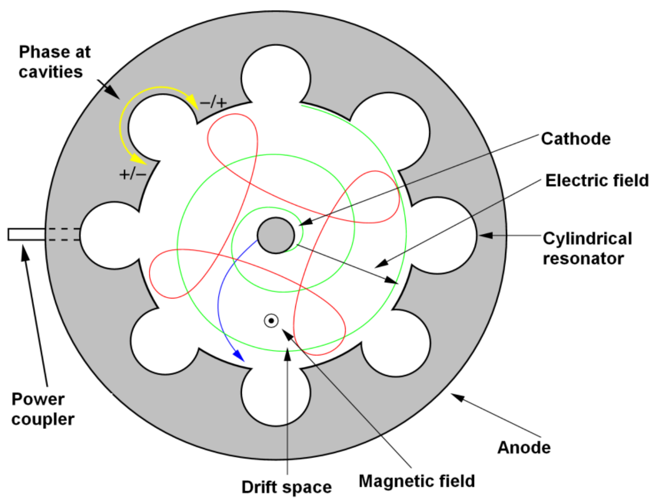

Figure 6: Construction and working of Magnetron (Chandra, 2011)

Electromagnetic radiation emitted by magnetron move back and forth within the enclosed space of the microwave oven. This will then cause the particles within the metals that are put inside the microwave to move back and forth within its border and causing it to heat up. This concept is basically the same as heating up foods in the microwave. The rapid movement of particles caused by the electromagnetic radiation will make heat buildup in the metals or foods. This concept can be seen in Figure 7 below illustrated by Yoshikawa et al. (2006):

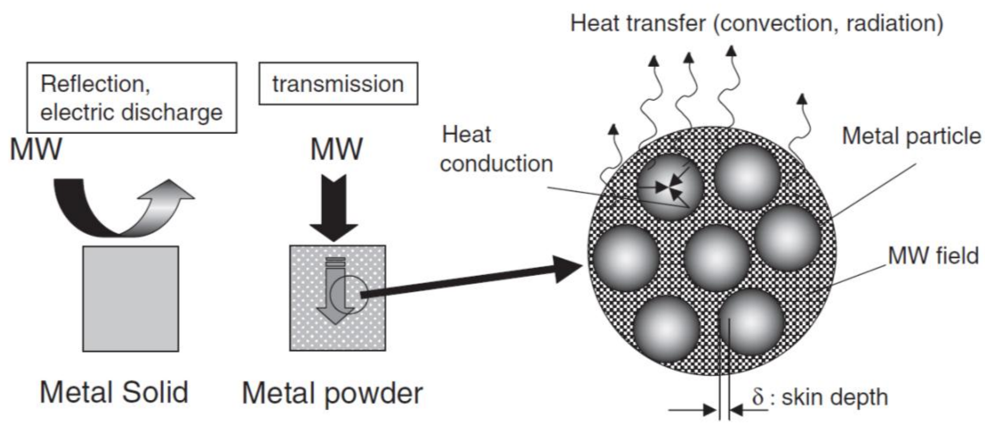

Figure 7: Illustration of Microwave Heating on Metal Particles (Yoshikawa et al, 2006)

Microwave heating is different comparing it to conventional heating due to the mechanism involved in interaction between energy and material (Ma, Fang, Li, Zhu, Lu and Lau, 1997). In conventional heating, heat transferred via conduction, convection and radiation, as compared in microwave heating, generation of heat is due to polarization and losses including electric conductivity, Maxwell-Wagner and magnetic loss. This will then cause a different reaction. Besides that, the core of sample by using conventional heating takes longer time to heat up to its target temperature (Chandra, 2011).

2.3 OXIDATION OF SOOT BY MEANS OF MICROWAVE

Microwave is preferred as the means to oxidize the soot as it can reach high temperatures as the temperature where soot will burn off is said to be at least 500°C - 600°C and also it can reach that temperature faster than conventional methods. By using microwave irradiation, a microwave assisted combustion (MAC) will occur to trapped soot (Barba, Acierno & d'Amore, 2011). By using microwave power to burn off soot, a DPF installed in a diesel engine vehicle will not be removed frequently to burn off trapped soot within its traps as microwave penetration towards the DPF filter and selective absorption of the filter filled with soot will ensure that the DPF filter will not break down due to heat and microwave generator can be installed within the DPF module, enabling it to clean off the soot periodically by itself without even removing the DPF. In Figure 8, a comparison of ceramic filters before and after soot oxidation is shown.

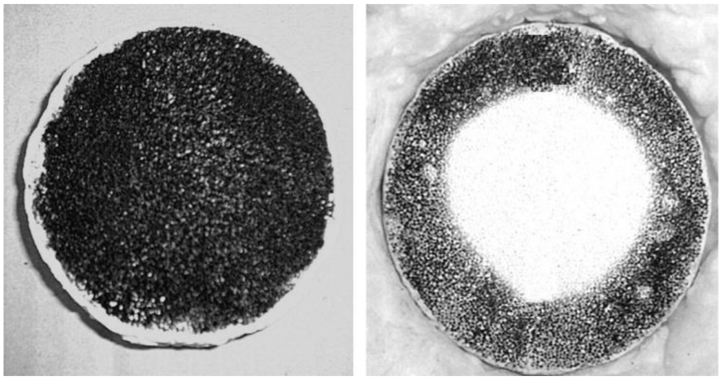

Figure 8: Photos of Ceramic Filters within DPF before and after soot oxidization (Barba et al., 2011)

According to Ma, Fang, Li, Zhu, Lu & Lau (1997), microwave is preferred to be used to get the soot particles to reach its oxidation temperature due to these reasons:

1. Penetrating radiation
2. Controllable electric-field distribution
3. Rapid heating
4. Selective heating of material through differential absorption
5. Self-limiting reactions.
6. Lower energy usage

CHAPTER 3

METHODOLOGY/PROJECT WORK

3.1 RESEARCH METHODOLOGY

Before moving on towards the experimental works of this project, extensive research will be done in order to fully understand the literature review and also in creating a feasible as well as executable plan. Articles, research papers as well as academia books are being read in order to get full understanding of what this project is all about. A project plan has been developed in order to achieve the objective of this project:

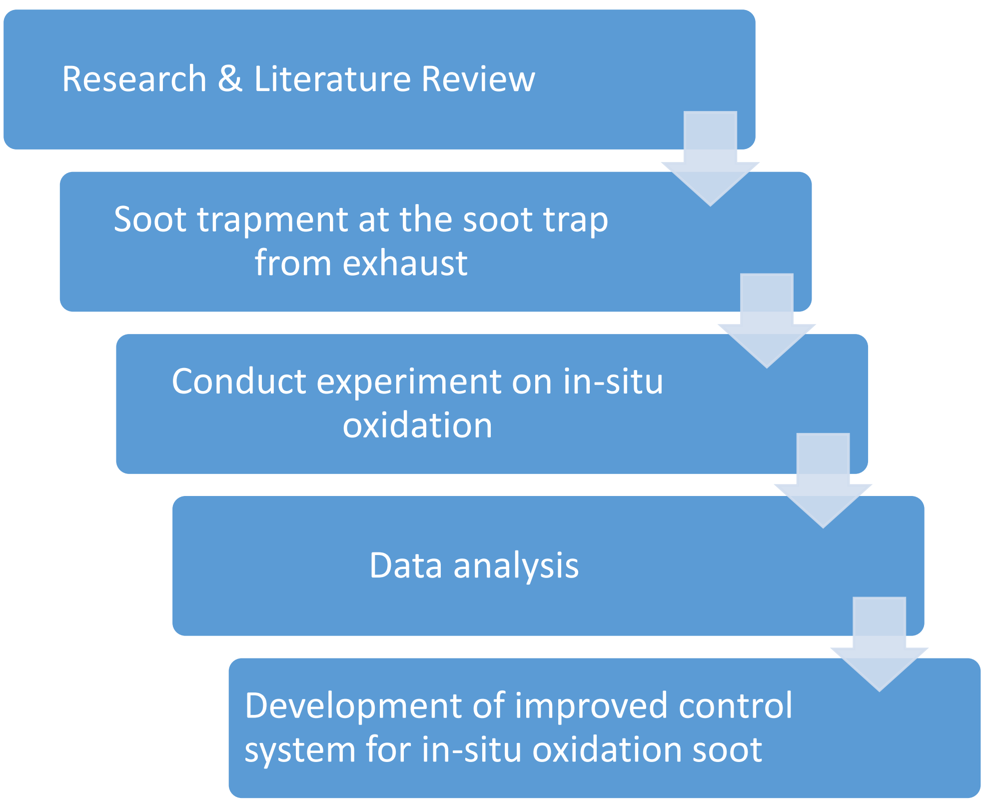

Figure 9: Project Flow Diagram

3.2 EXPERIMENTAL METHODOLOGY

3.2.1 Equipment/Apparatus

The experimental part of this project has been planned during this duration. The assembly drawings for the equipment for this project, Microwave Generator System for Exhaust Gas Experiment can be found in the appendix. The major components of this prototype and its functions can be separated into three different categories:

1. Microwave Module
    a. To generate microwave in order to burn soot.
2. Chamber Assembly / Soot Trap
    a. To trap the soot received from the exhaust emission
3. Exhaust Piping Connection (Inlet & Outlet)
    a. To connect the microwave module as well as chamber assembly with the exhaust inlet and provide the direction of outlet for cleaned gas.

The instruments for measurement are also required in this experiment in order to collect the data that we require. Such measuring instruments are:

1. Microwave Leak Detector
2. Smoke Meter
    a. To detect opacity of smoke
3. Exhaust Emission Analyzer
    a. To detect the amount of NOx, CO, CO_2 & O_2 in pipe outlet

The basic setup of this experiment is as per the schematic diagram below:

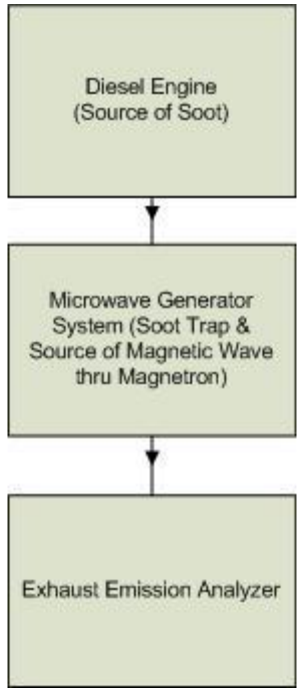

Figure 10: Basic Schematic Diagram

The diesel engine is connected to the microwave generator system using a flexible pipe for soot to accumulate into the soot trap located within the microwave generator system. The soot trap located within the microwave generator system is then exposed to the magnetic waves, generated by the magnetron within the microwave generator system. The maximum amount of power the microwave that can be generated by the magnetron is 3kW, but to be safe, the maximum power of microwave exposed to the soot is 1.5 kW. At the soot trap, soot is collected in the soot trap before the experiment in order to ensure that the soot trap is filled with soot. Once the engine starts running, the trapped soot are to be oxidized according to the time that have been set in the experiment matrix, and simultaneously the exhaust emission analyzer is used to analyze the amount of gases within the smoke emitted from the microwave generator system as well as the smoke opacity. The set-up of this experiment can be seen in Appendix I.

3.2.2 Experimental Matrix

The experiment matrix for the experiment stage which will was done in FYP2 has been developed and can be found below:

Table 1: Experiment Matrix

	Power of Microwave Exposed	**Exposure Time to Microwave**
Case 1	0.5 kW	• T1 = 180 seconds • T2 = 300 seconds • T3 = 420 seconds • T4 = 600 seconds
Case 2	1.0 kW	• T1 = 180 seconds • T2 = 300 seconds • T3 = 420 seconds • T4 = 600 seconds
Case 3	1.5 kW	• T1 = 180 seconds • T2 = 300 seconds • T3 = 420 seconds • T4 = 600 seconds

3.2.3 Data Collection Table

The data collection table that will be used in FYP 2 for data collection has been developed and can be found below:

Table 2: Data Collection Table

No	Data Taken when Microwave Generator is off							Data Taken when Microwave Generator is on						
	Weight of Soot Trap	Amount of NOx	Amount of CO	Amount of CO2	Amount of O2	Smoke Opacity	Pressure Difference	Weight of Soot Trap	Amount of NOx	Amount of CO	Amount of CO2	Amount of O2	Smoke Opacity	Pressure Difference
1														
2														
3														

3.3 PROJECT ACTIVITIES

3.3.1 Gantt Chart

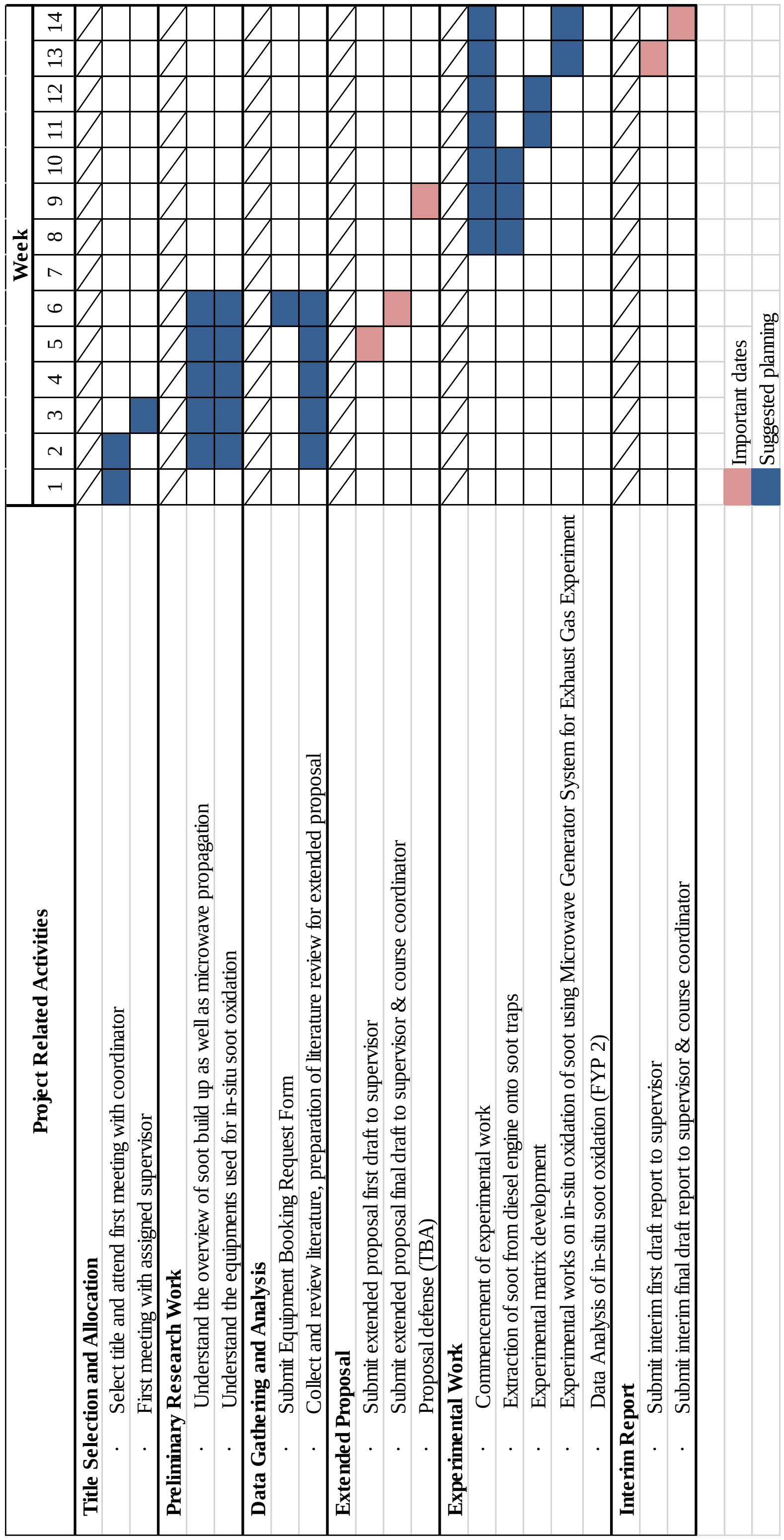

Figure 11: Project Gantt chart for FYP 1

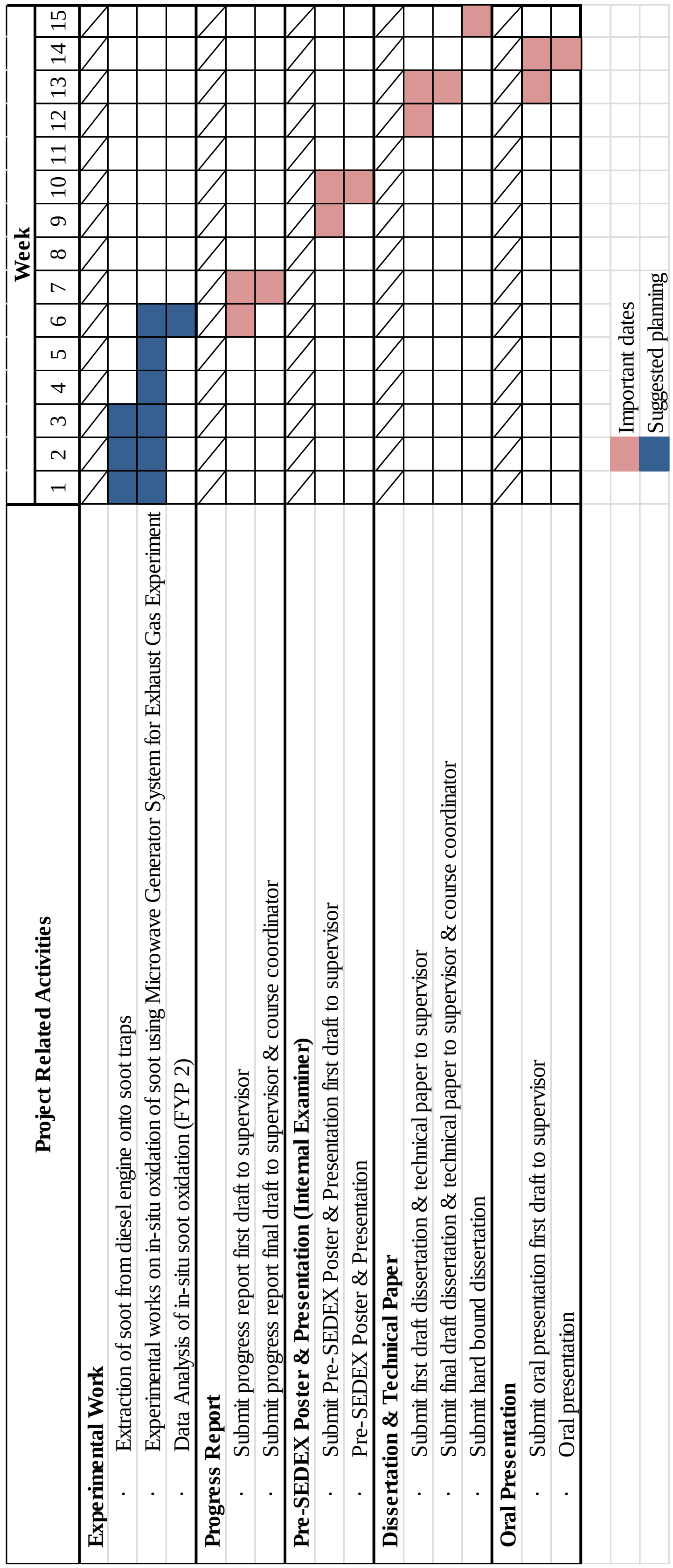

Figure 12: Project Gantt chart for FYP 2

3.3.2 Project Key Milestones

The project important milestones for FYP 1 & 2 are as per listed in the table below:

Table 3: Project Key Milestones

No.	Project Key Milestones	Estimated Date Completion
1	Soot from diesel exhaust is trapped within the soot trap	Mid-March 2014
2	Dry run of experiment	End of March 2014
3	Experimental matrix & data acquisition system developed	Mid April 2014
4	Obtain the data of smoke & gas reading for experiment as per data acquisition table	End of June 2014
5	Data analysis of smoke & gas reading of the experiment	Mid July 2014

CHAPTER 4

RESULTS AND DISCUSSION

4.1 RESULTS & DISCUSSION

4.1.1 Smoke & Gas Reading of Soot Exposed to Electromagnetic Waves

Table 4 shows the amount of opacity limit of smoke (%) and the gas reading for 5 different elements which are CO_2 (%), CO (%), HC (ppm), O_2 (%) and NOx (ppm).

Table 4: Gas & Smoke Analyzer Data Collection for Soot Exposed to Electromagnetic Waves

Power Rating (kW)		Smoke Reading				Gas Reading				
		Time (mins)					Time (mins)			
		3	5	7	10		3	5	7	10
0.5	Opacity limit (%)	17.7	17.3	16.9	16.2	CO_2 (%)	2.23	2.71	3.24	3.52
						CO (%)	0.08	0.08	0.08	0.08
						HC (ppm)	8	7	8	6
						O_2 (%)	17.62	17.58	17.55	17.67
						NOx (ppm)	190	183	180	172
1	Opacity limit (%)	15.1	14.3	13.1	12	CO_2 (%)	2.37	2.87	3.35	3.72
						CO (%)	0.08	0.08	0.08	0.08
						HC (ppm)	7	8	8	6
						O_2 (%)	17.47	17.62	17.59	17.78
						NOx (ppm)	183	181	177	168
1.5	Opacity limit (%)	11.9	9.7	7.8	5.6	CO_2 (%)	2.81	3.25	3.74	4.12
						CO (%)	0.08	0.08	0.08	0.08
						HC (ppm)	6	7	6	6
						O_2 (%)	17.52	17.66	17.81	17.84
						NOx (ppm)	171	167	153	141

In order to get the comparison of this project, the smoke & gas reading without exposure to the electromagnetic waves are also taken. The table below shows the data:

Table 5: Gas & Smoke Analyzer Data Collection for Soot Not Exposed to Electromagnetic Waves

Smoke Reading		Gas Reading	
Opacity limit (%)	25.4	CO_2 (%)	1.44
		CO (%)	0.08
		HC (ppm)	17
		O_2 (%)	16.71
		NOX (ppm)	205

4.1.2 Smoke Reading Analysis

One of the major trends that can be analyzed from the data is that the opacity limit of the smoke decreases as the exposure time of the soot to the electromagnetic waves is increased. The opacity limit of the smoke also decreases as we increase the power rating of the electromagnetic waves. The graph showing the trends of the smoke reading in terms of opacity are shown in Figure 13 below:

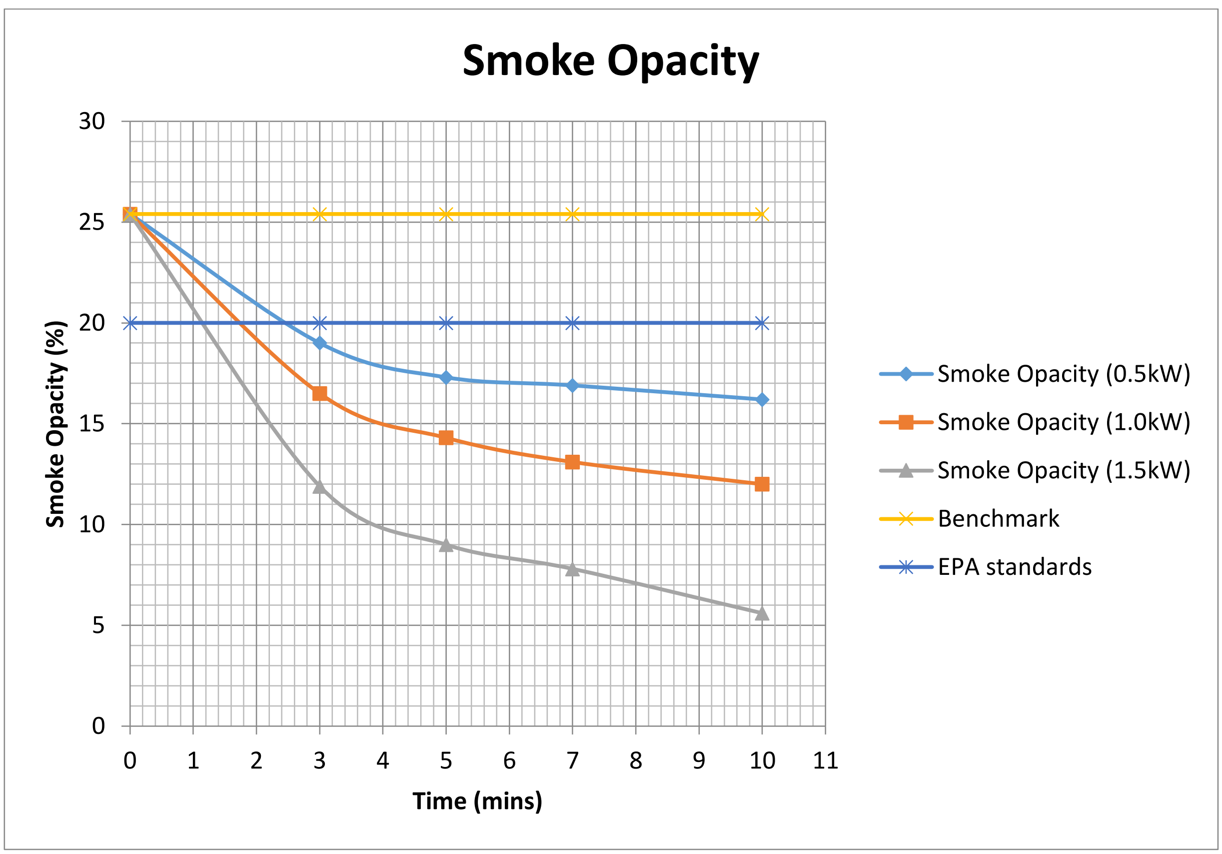

Figure 13: Graph of Smoke Opacity

From the graph in Figure 13, at 3 minutes of electromagnetic wave exposure, the smoke opacity decreases as the power of the electromagnetic wave increases. This is due to more soot are being oxidized as more electromagnetic waves are being emitted, thus reducing the opacity of the smoke. At 3 minutes, the average smoke opacity for all level of electromagnetic wave is 14.9%, and the smoke opacity is reduced by 41.3% compared to the level of smoke reading for soot that is not exposed to the electromagnetic waves. The average reduction for all levels of electromagnetic wave intensity is 46.8% for 5 minutes, 50.4% for 7 minutes and 55.64% for 10 minutes. According to EPA Standards, the amount of smoke permitted is at 20%, thus, for soot that is exposed to 0.5 kW of electromagnetic waves, it requires 2.4 minutes of exposure to reach the 20% smoke opacity, 1.7 minutes of exposure for 1.0 kW of electromagnetic waves and 1.1 minutes of exposure for 1.5 kW of electromagnetic waves. Thus, as the level of electromagnetic waves increases, the time required to reach the value of smoke opacity permitted decreases.

4.1.3 Gas Reading Analysis

There are 5 elements that are being recorded during the experiment, which are CO_2 (%), CO (%), HC (ppm), O_2 (%) and NOx (ppm). However, the analysis is done for the CO_2 (%) and NOx (ppm) only as the amount of CO2 indicates the soot oxidation that occurs and reduction of NOx is required to reach the allowable amount of NOx to be emitted.

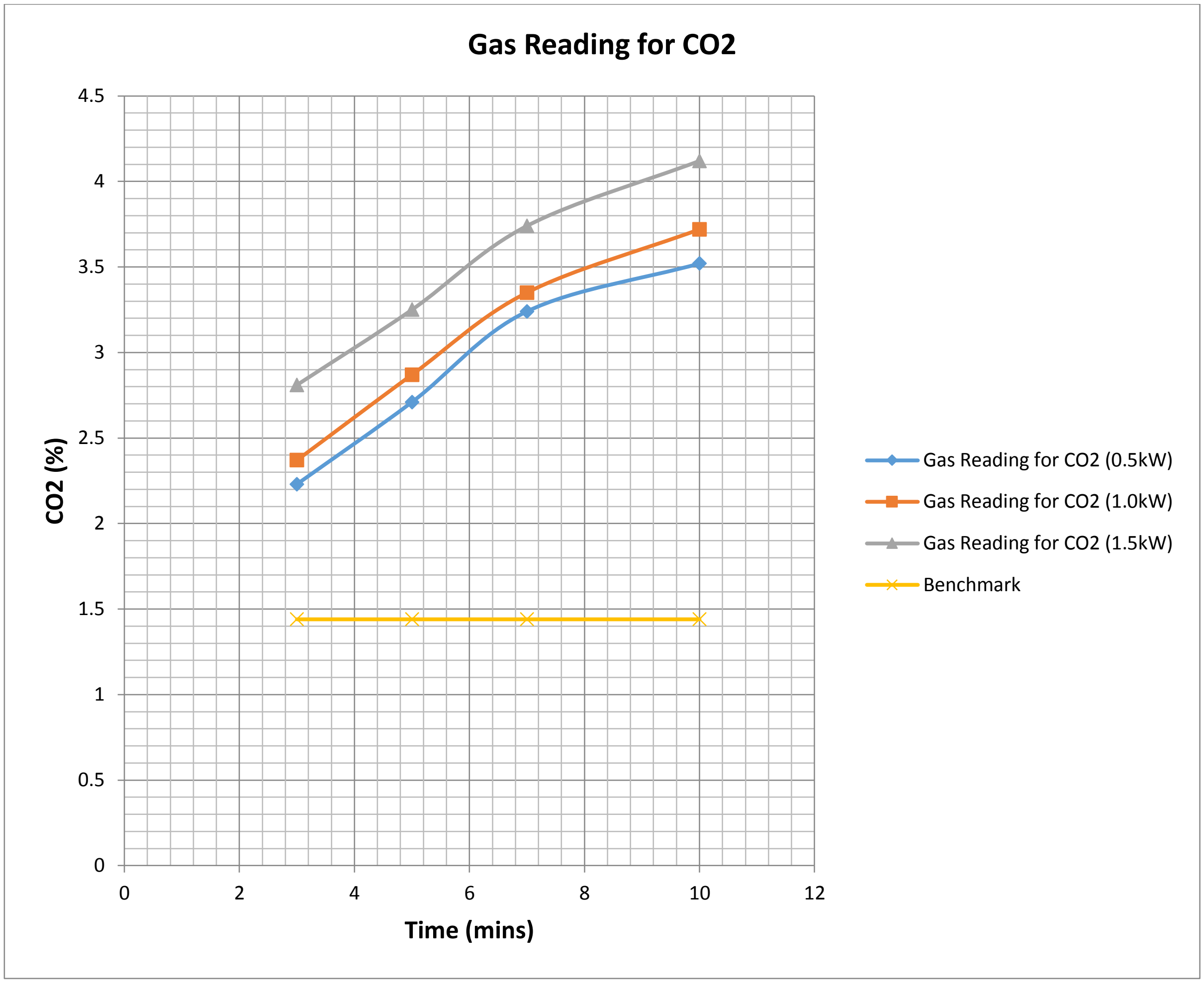

Figure 14: Graph of Gas Reading for CO_2

From the graph, it can be seen that CO_2 increases as the intensity of the electromagnetic waves are increased. This is due to more soot being oxidized with more electromagnetic waves are being emitted. As the time goes on, the level of CO_2 increases as well as the exposure time for the soot to electromagnetic waves are longer, thus more soot oxidation.

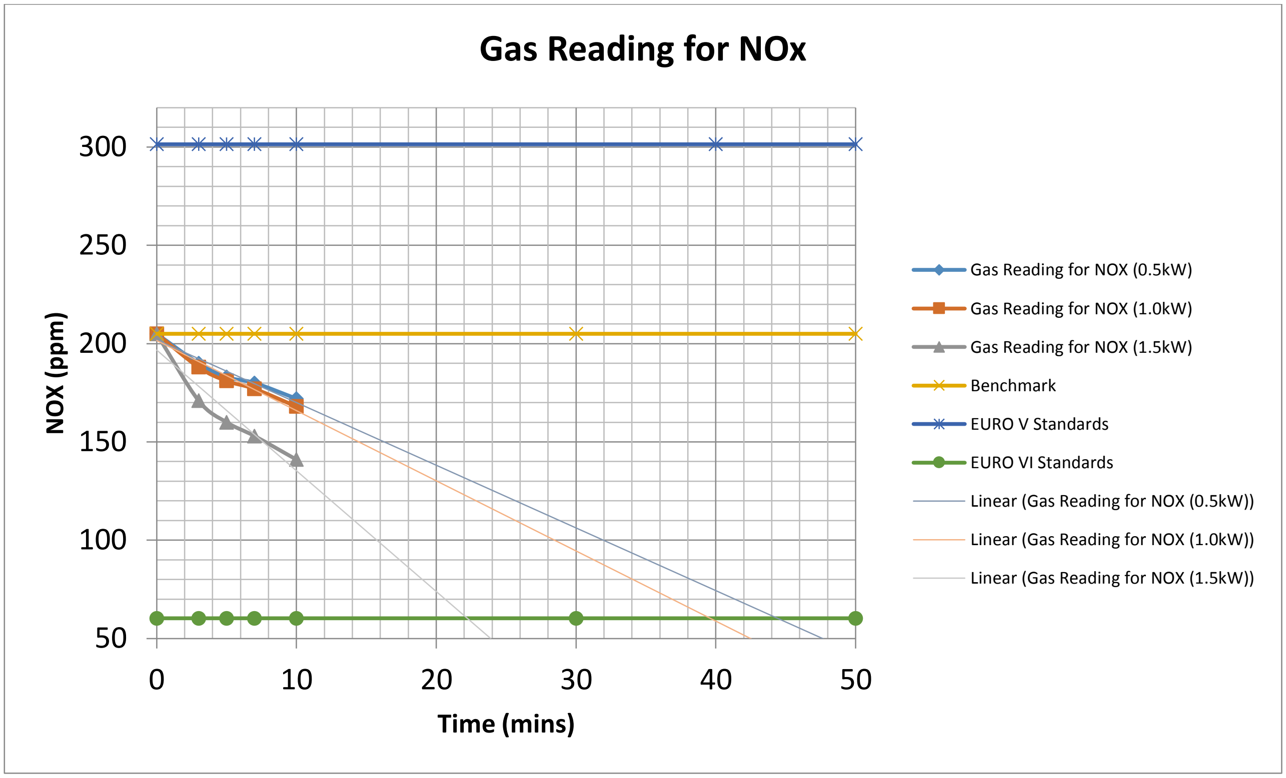

Figure 15: Graph of Gas Reading for NOx (ppm)

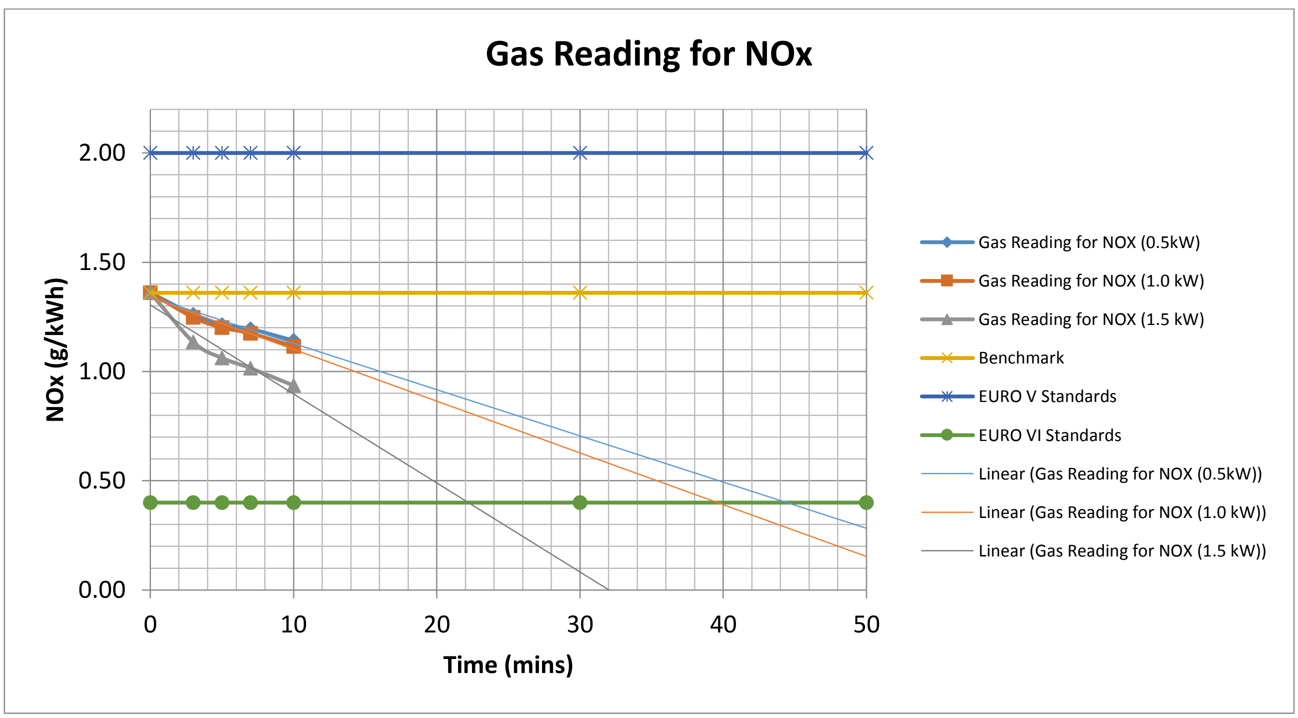

Figure 16: Graph of Gas Reading for NOx (g/kWh)

The two graphs for NOx is the same, the difference is just the unit of the NOx, where in graph of Figure 15, the unit of NOx is in ppm while the unit of NOx for the graph in Figure 16 is in g/kWh. The graphs indicate a decrease trend in NOx as the minutes passed by for each different level of electromagnetic wave exposure. The amount of NOx decreases more as the intensity of the electromagnetic wave increases, due to more soot are exposed to the electromagnetic waves. For soot that are exposed to 0.5 kW level of electromagnetic waves, the time required for it to reach the permitted amount of NOx according to EURO VI is 44.4 minutes, 39.5 minutes for soot that are exposed to 1.0 kW level of electromagnetic waves and 22.2 minutes for soot that are exposed to 1.5 kW level of electromagnetic waves. Thus, as the level of electromagnetic waves increases, the time required for NOx levels to reach the permitted level according to EURO VI is less.

4.1.4 Adherence to International Standards

The standards that are most commonly referred to in exhaust emissions are EURO standards which are being applied in most countries, EPA standards used in the United States and the Japanese Air Pollution Control Act that is being used in Japan. However, for this experiment, the EURO standards will be used for comparison. In the latest revision of EURO standards which is EURO VI, the limit in NOx emission is 400 milligrams per kilowatt hour (mg/kWh). As for EURO V, the limit in NOx emission is 2 grams per kilowatt hour (g/kWh). In Malaysia, the emission standard compliance is up to EURO III only. Therefore, having an EURO VI fuel compliance would be one of the key factors to reduce the amount of oxidation time.

The gas and smoke analyzer measures the smoke and gases by using unit of parts per million (ppm) and volume percent (%), which is different from the EURO standards. Thus, a conversion is required in order to compare the results with the established standards. According to Pilusa, Mollagee & Muzenda (2006), previous research has established the relationship between emission gas relationship (ppm) and specific fuel consumption and the result of this work has proven that 1 ppm of specific pollutant gas is 8.4 times its density in milligrams per kilometer (Alkama et al., 2006). The general conversion from unit of parts per million (ppm) to specific fuel consumption (g/kWh) for heavy duty vehicles is as per below:

$$\boldsymbol{NOx}\left(\frac{g}{kWh}\right) = \mathbf{6.636}\ x\ \mathbf{10^{-3}}\ x\ \boldsymbol{NOx}\ (\boldsymbol{ppm}) \text{ ——— } (1)$$

$$\boldsymbol{CO_2}\left(\frac{g}{kWh}\right) = \mathbf{63.470}\ x\ \boldsymbol{CO_2}\ (\boldsymbol{vol}\ \%) \text{ ——— } (2)$$

Figure 17: General Conversion Formula for Heavy Duty Vehicles

Thus, by using the general conversion formula, we have obtained the values of NOx & CO_2 in g/kWh unit as shown in the table below:

Table 6: Gas Reading for Soot Exposed to Electromagnetic Waves in g/kWh units

Power Rating (kW)	Gas Reading				
		Time (mins)			
		3	5	7	10
0.5	CO_2 (g/kWh)	141.54	172	205.64	223.41
	NOx (g/kWh)	1.26	1.21	1.19	1.14
1	CO_2 (g/kWh)	150.42	182.16	212.62	236.11
	NOx (g/kWh)	1.21	1.2	1.17	1.11
1.5	CO_2 (g/kWh)	178.35	206.28	237.38	261.5
	NOx (g/kWh)	1.13	1.11	1.02	0.94

The value of CO_2 is still within the limits but for NOx, each data indicates that it already exceeds the emission limit of EURO VI which is 0.4 g/kWh initially but after a linear projectile has been done, the level of NO_x will meet the emission limit of EURO VI at different times where for soot exposed to 0.5 kW of electromagnetic waves will reach the emission limit of EURO VI after 44.4 minutes, 39.5 minutes for 1.0 kW and 22.2 minutes for 1.5 kW. The level of NOx for all levels is below the limits of EURO V which is 2 g/kWh.

As for smoke opacity limit, EURO standards does not emphasize more on smoke opacity as it is more detailed on NOx & PM emissions. Therefore, EPA standards are being used for the adherence of smoke opacity in this experiment. According to Delphi (2013), EPA states that the smoke opacity limit for acceleration is 20%, 15% for lugging and 50% for peak. The engine that is used in this experiment is experiencing acceleration experience, thus the limit for the smoke opacity is 20%. The soot that are exposed to 0.5 kW, 1.0 kW and 1.5 kW levels of electromagnetic waves are able to reach the EPA standards of 20% at different times, which are 2.4 minutes, 1.7 minutes and 1.1 minutes.

Thus, by using the apparatus that is used in this project, the proposed level of electromagnetic waves is at 1.0 kW and the time of soot exposure to the electromagnetic waves is 45 minutes in order for the soot emitted to meet the EPA Standards for smoke opacity and EURO VI standards for NOx & CO_2. The total duration time for the cycle is 90 minutes, where the first initial 45 minutes will be the soot exposure and the remaining 45 minutes is for the soot trap to accumulate the soot and rest time for the electromagnetic wave module.

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 CONCLUSION

As a conclusion, the project has shown that as the intensity of the electromagnetic waves increase, the amount of smoke opacity and NOx reduced and CO2 increment will be more. The amount of time required for 0.5 kW of electromagnetic wave power to reduce the smoke opacity from 25.4% to 20% which is the standard is 2.4 minutes, 1.7 minutes for 1 kW and 1.1 minutes for 1.5 kW. As for NOx, the amount of time required for 0.5 kW of electromagnetic waves to reach the standard which is from 1.36 g/kWh to 0.4 g/kWh is 44.4 minutes, 39.5 minutes for 1.0 kW and 22.2 minutes for 1.5 kW. Nevertheless, the objectives of this project are achieved. A further development of a better in-situ oxidation of soot device needs to be done and mass produced into the market. Thus, this would then enable an environment of less soot and a much healthier air for us to breathe in. Furthermore, nowadays, green technology is being emphasized more and more due to the high rate of pollution that Earth is experiencing.

Other than that, Malaysia has lots of diesel engine vehicles moving throughout its webs of highways, thus, by pursuing more on this project, a system that can trap and burn soot from these vehicles can be developed and as mentioned earlier, providing a greener environment for us in Malaysia.

5.2 RECOMMENDATION

As a recommendation, a longer soot exposure period to electromagnetic waves should be taken into consideration as well in order to reduce the NOx & smoke opacity more. Nevertheless, the amount of oxidation time that is required in this project to oxidize the soot is very long which is 45 minutes. This is due to the fuel that is being used that is up to EURO III compliance. Therefore, if the fuel used is up to EURO VI compliance and above, the oxidation time would be reduced by quite some time as less soot are being produced.

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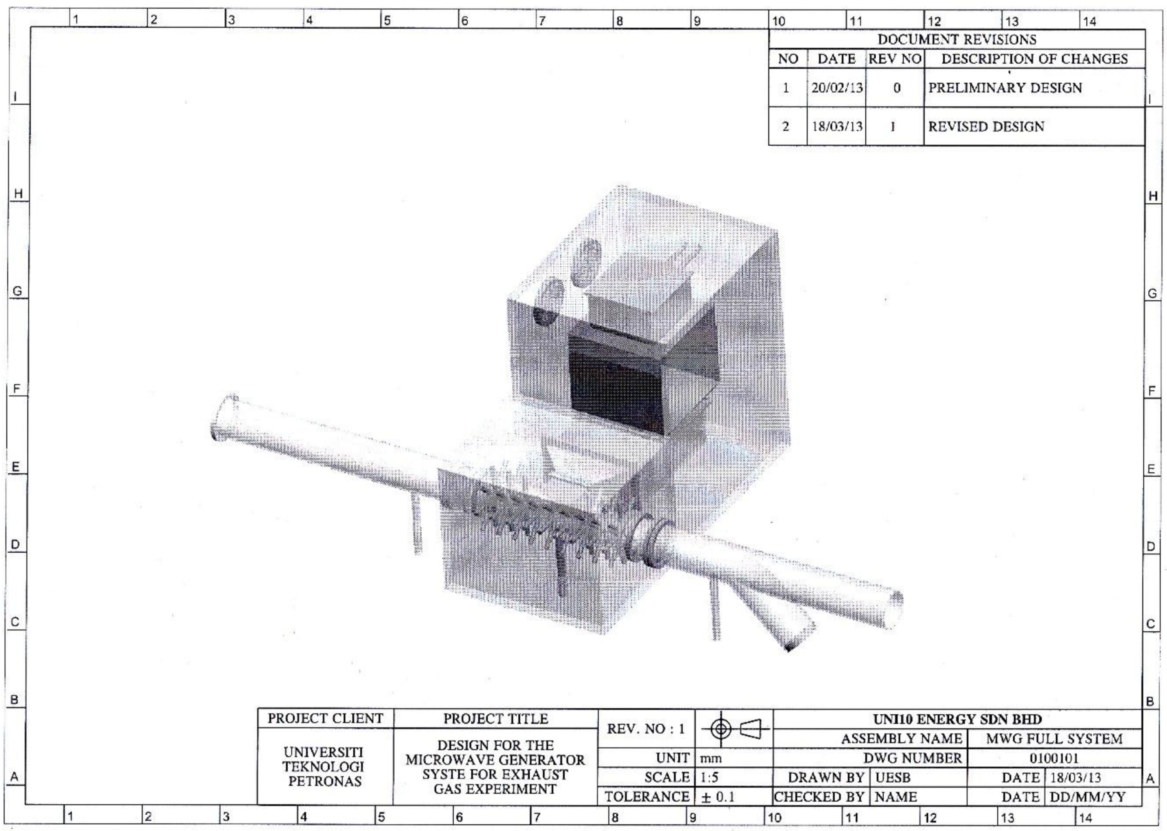
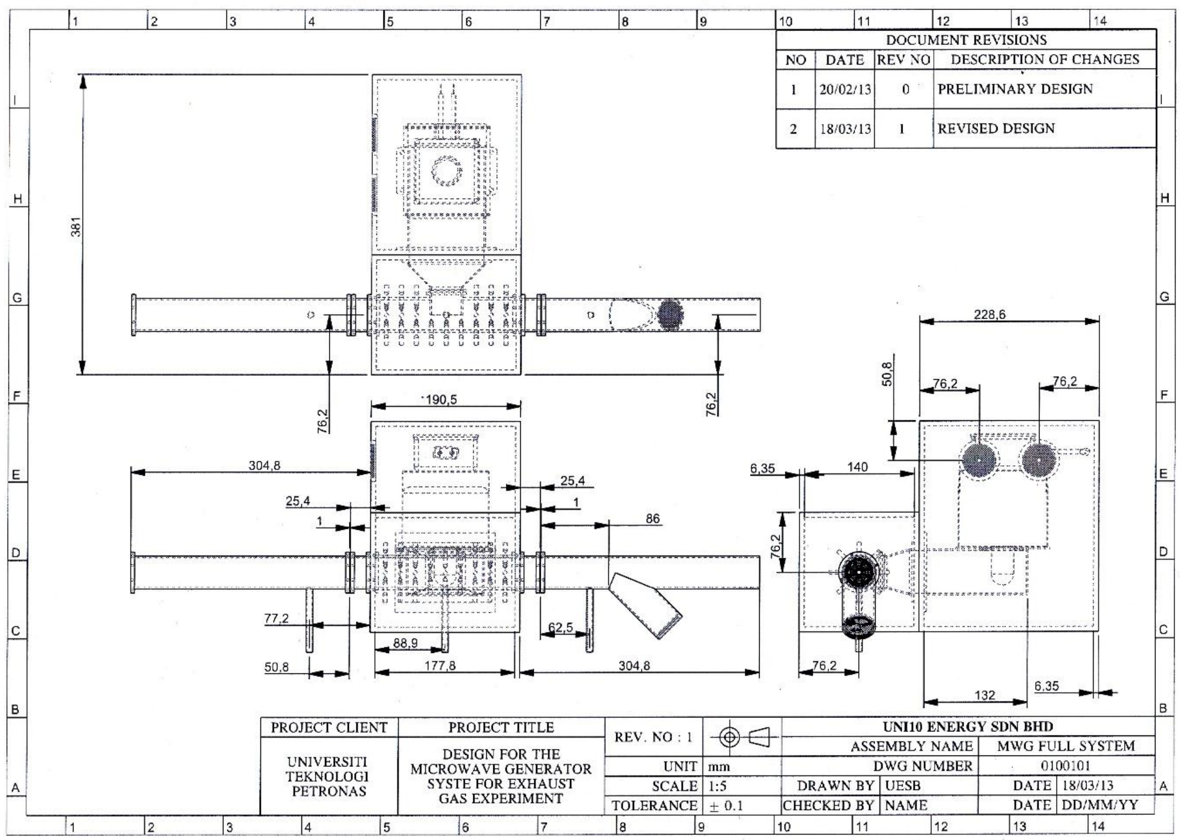
APPENDICES

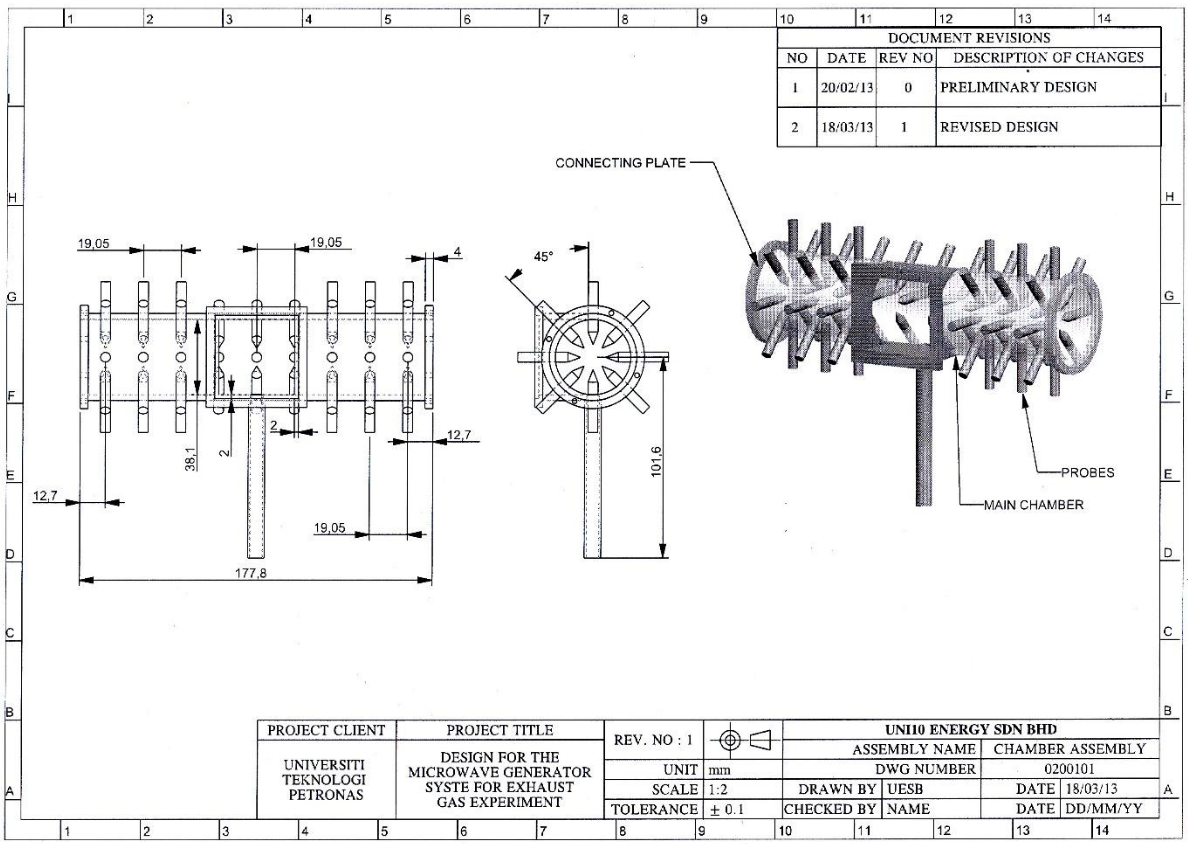
APPENDIX A. 3D DRAWING OF MICROWAVE GENERATOR SYSTEM FOR EXHAUST GAS SYSTEM



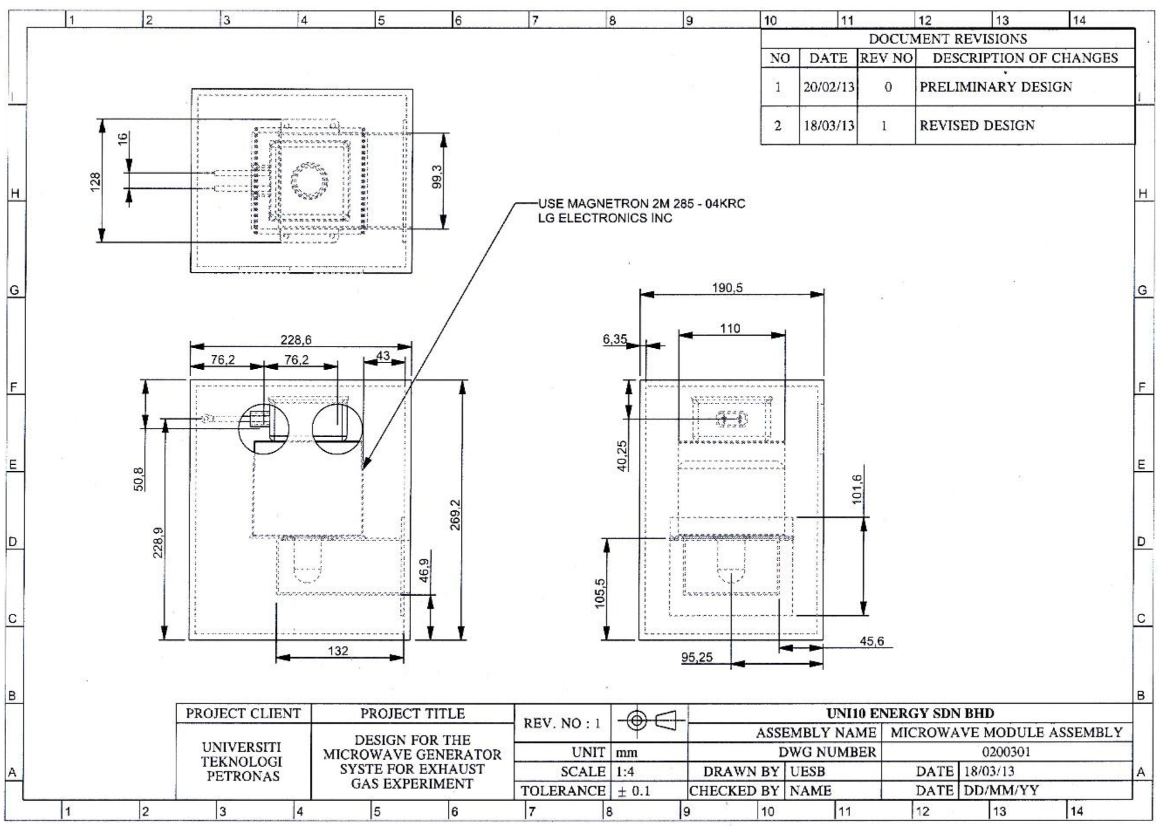
APPENDIX B. FULL ASSEMBLY DRAWING OF MICROWAVE GENERATOR SYSTEM FOR EXHAUST GAS SYSTEM



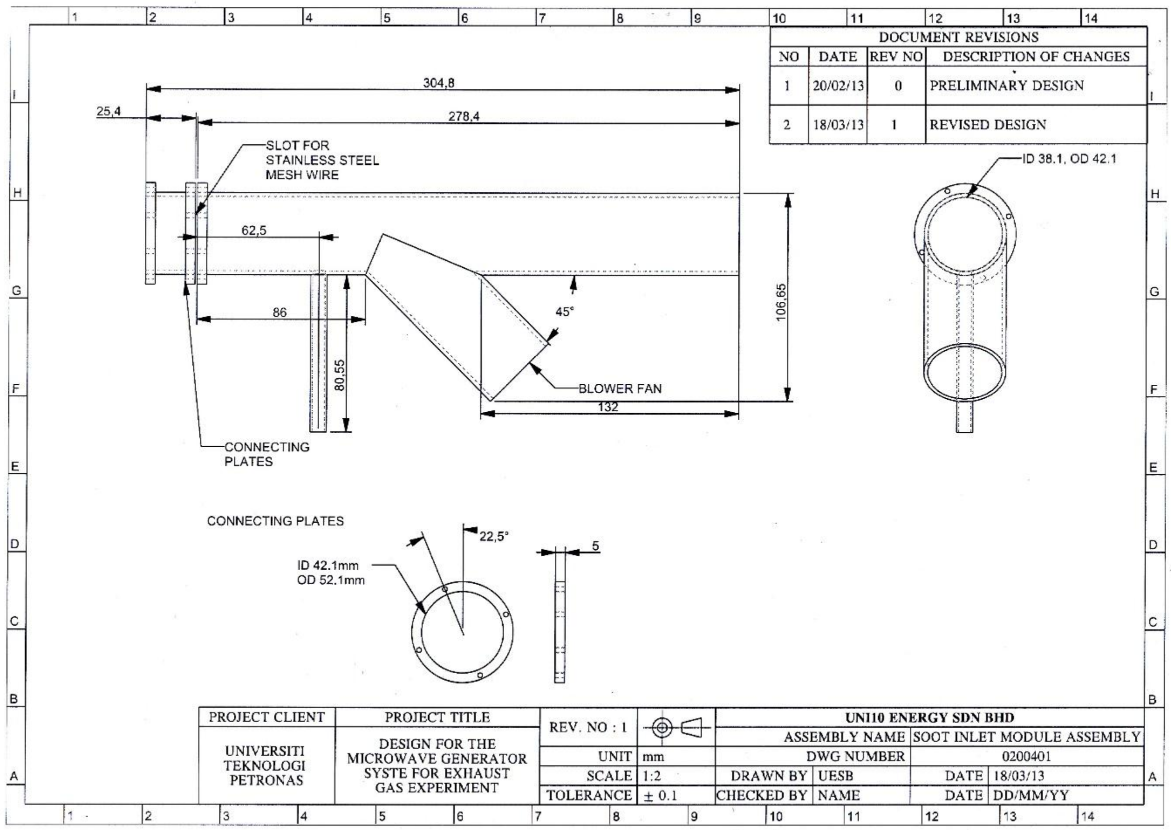
APPENDIX C. CHAMBER ASSEMBLY DRAWING OF MICROWAVE GENERATOR SYSTEM FOR EXHAUST GAS SYSTEM



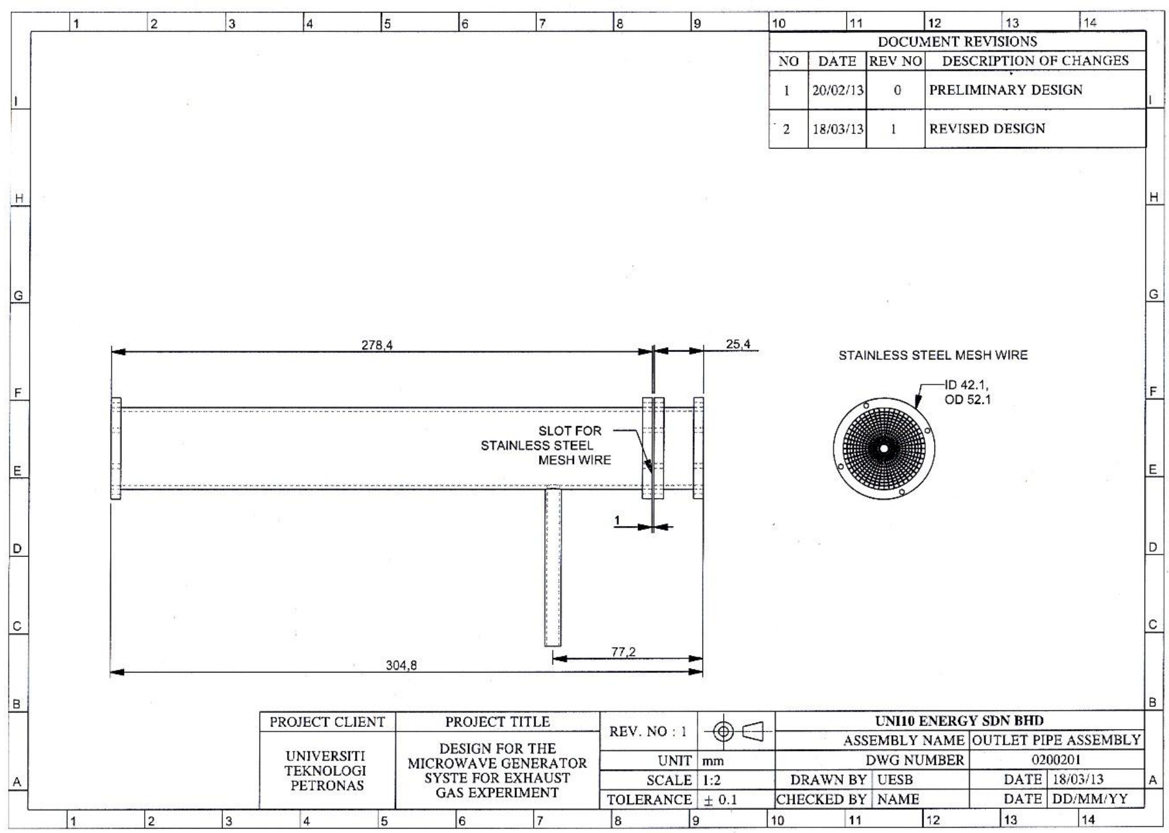
APPENDIX D. MICROWAVE MODULE ASSEMBLY DRAWING OF MICROWAVE GENERATOR SYSTEM FOR EXHAUST GAS SYSTEM



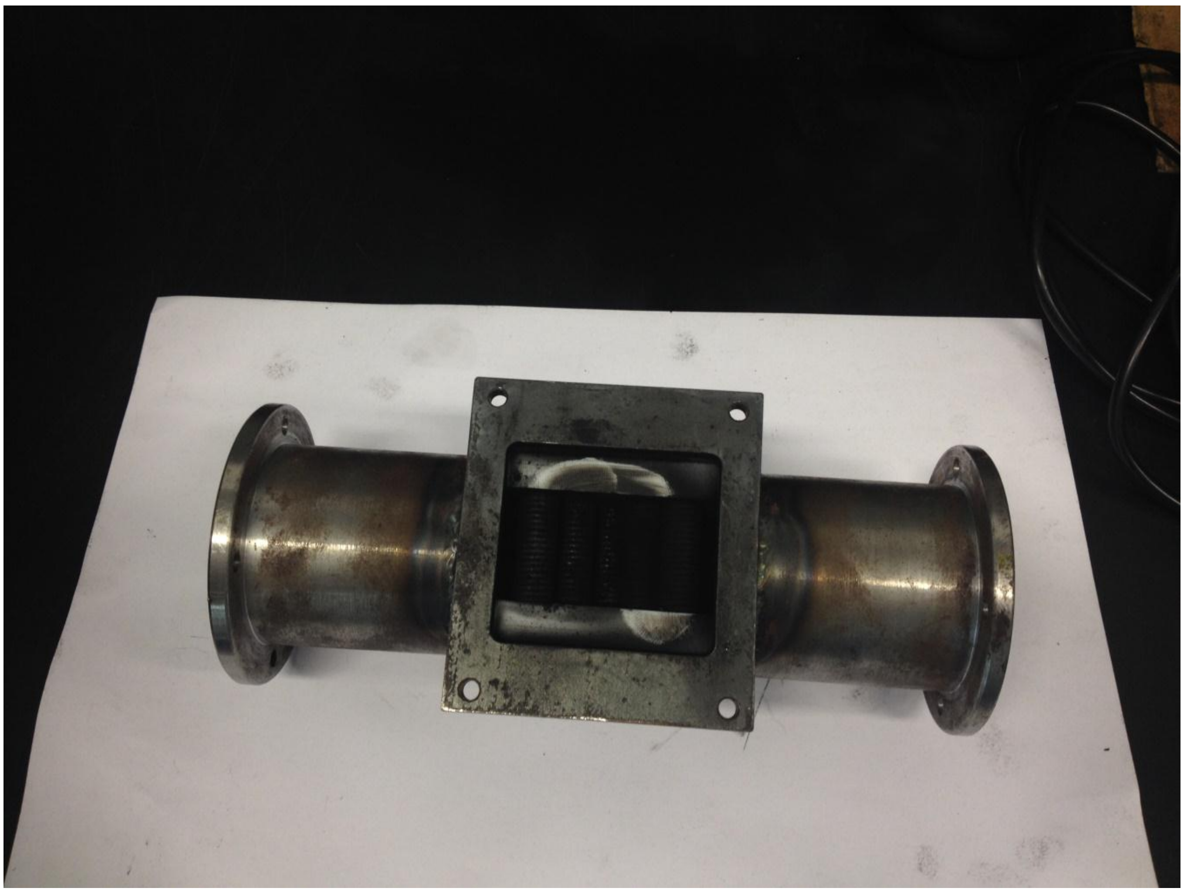
APPENDIX E. SOOT INLET ASSEMBLY DRAWING OF MICROWAVE GENERATOR SYSTEM FOR EXHAUST GAS SYSTEM



APPENDIX F. OUTLET ASSEMBLY DRAWING OF MICROWAVE GENERATOR SYSTEM FOR EXHAUST GAS SYSTEM



APPENDIX G. SOOT TRAP



APPENDIX H. EXHAUST EMISSION ANALYZER

APPENDIX I. EXPERIMENT SET UP