MICROWAVE TAR THERMAL CRACKING SYSTEM FOR A 10kW DOWNDRAFT GASIFIER

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DECLARATION

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

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LIST OF ABBREVIATIONS

CO	Carbon monoxide
CO_2	Carbon dioxide
CH_4	Methane
ER	Equivalence ratio
GC	Gas chromatography
GI	Galvanized iron
H_2	Hydrogen
HHV_b	Higher heating value of biomass fuel
HHV	Higher heating value
LHV	Lower heating value
LHV_b	Lower heating value of biomass fuel
LHV_{PG}	Lower heating value of producer gas
LHV_{H2}	Lower heating value of hydrogen
LHV_{CO}	Lower heating value of carbon monoxide
LHV_{CH4}	Lower heating value of methane
LPG	Liquid petroleum gas
MW	Microwave
N_2	Nitrogen
NH_3	Ammonia
O_2	Oxygen
PG	Producer gas

PAH	Polycyclic aromatic compound
RF	Radio frequency
SiC	Silicon carbide
SO_2	Sulphur dioxide

ABSTRAK

Gasifikasi biojisim adalah cara yang menjanjikan bagi pengunaan gas pengeluar (PG) untuk menjana kuasa dalam enjin pembakaran dalaman dan turbin. Walaubagaimanapun, kandungan tar di dalam PG adalah satu kelemahan oleh kerana ia menyebabkan penyekatan kepada peralatan apabila PG disejukkan. Untuk menyelesaikan masalah ini, langkah peretakan tar haba adalah pilihan untuk mengeluarkan tar dan pada masa yang sama meningkatkan nilai pembakaran PG. Dalam semua cara peretakan tar haba, peretakan tar haba gelombang mikro (MW) adalah yang terbaik disebabkan oleh ciri-cirinya yang cekap dan jimat kos. Walaubagaimanapun, reaktor MW yang sedia ada yang telah dihasilkan sebelum ini adalah pada saiz makmal. Oleh itu, projek ini bertujuan untuk meningkatkan skala saiz reaktor MW yang sedia ada untuk menbenarkan PG untuk mengalir melaluinya pada kadar aliran yang lebih tinggi semasa proses peretakan tar.

Sistem gasifikasi biojisim menggunakan gasifier draf bawah yang boleh menghasilkan tenaga 10kW telah dicirikan dengan mencari nisbah kesetaraan (ER), komposisi PG dan nilai pembakaran serta kecekapan gas sejuk gasifier. Reaktor MW yang sedia ada telah ditingkatkan skalanya dan dimodifikasi dengan memasang reaktor alumina yang lebih besar diameternya untuk membenarkan PG melaluinya pada kadar aliran PG yang lebih tinggi. Selepas itu, reaktor MW tersebut telah disepadukan dengan system gasifikasi sebelum ini. Peretakan tar haba MW telah dilaksanakan pada suhu reaksi sebanyak 1250 darjah selsius dengan masa residense yang tidak berubah iaitu selama 0.7 saat.

Keputusan menunjukkan process gasifikasi telah dijalankan pada nisbah kesetaraan yang optimum iaitu 0.34 yang telah menghasilkan PG dengan nilai pembakaran iaitu sebanyak 4.79 MJ Nm^{-3}. Kecekapan gas sejuk yang telah diperoleh adalah tinggi iaitu sebanyak 84.92%. Analisis PG mendapati bahawa kandungan tar dalam PG telah berkurang daripada 1600 mg Nm^{-3} kepada 140 mg Nm^{-3} yang merujuk kepada kecekapan penukaran sebanyak 91.25% dan manakala kandungan zarah dalam PG telah dikurangkan daripada 240 mg Nm^{-3} kepada 12mg Nm^{-3} yang merujuk kepada kecekapan penukaran

sebanyak 95% melalui proses peretakan tar haba MW. Komposis PG juga telah berubah oleh kerana kebanyakan tar dan zarah telah ditukarkan kepada gas-gas mudah terbakar melalui proses peretakan tar haba MW. Analisis komposisi PG menunjukkan bahawa H_2 dan CO telah meningkat manakala CH_4 telah berkurang. Nilai pembakaran PG juga telah meningkat daripada 4.79 MJ Nm^{-3} kepada 5.5 MJ Nm^{-3}. Pengurangan kandungan tar dan zarah dalam PG bersama dengan peningkatan nilai pembakaran PG menunjukkan bahawa proses peretakan tar haba MW yang di tingkatkan skalanya telah berjaya.

ABSTRACT

Biomass gasification is a promising way to utilize the producer gas (PG) for power generation in internal combustion engine and turbines. However, tar in the PG is a major drawback since it blocks the equipment when PG is cooled. In order to solve this problem, tar thermal cracking method is the preferred method to remove tar as it increases the heating value of the PG. Among all the tar thermal cracking methods, microwave (MW) tar thermal cracking is the best as it is more efficient and cost-effective. However, the current MW reactor which was developed earlier is only at lab-scale. Therefore, this project aims at upscaling the current MW reactor to allow a higher flow rate of PG through it during the tar cracking process.

The biomass gasification system using a 10kW downdraft gasifier was characterized by finding the equivalence ratio (ER), PG composition and heating value as well as the gasifier cold gas efficiency. The existing MW reactor was upscaled and modified by installing an alumina reactor with bigger diameter in it to allow a higher flow rate of PG. The MW reactor was then integrated with the gasification system. MW tar thermal cracking was done at the reaction temperature of 1250°C with a constant residence time of 0.7s.

The results showed that the gasification was performed in the optimum ER range which was 0.34 and resulted in producing PG with heating value of 4.79 MJ Nm^{-3}. The cold gas efficiency obtained was high which was 84.92%. PG analysis revealed that the tar content in the PG was reduced from 1600 mg Nm^{-3} to 140 mg Nm^{-3} which corresponds to a conversion efficiency of 91.25% while the particulate content in the PG was reduced from 240mg Nm^{-3} to 12mg Nm^{-3} which corresponds to a conversion efficiency of 95% through the MW tar thermal cracking process. The PG composition was also changed since most of the tar and particulate had converted into useful combustible gases through the MW tar thermal cracking process. The PG composition analysis showed that the H_2 and CO was increased while CH_4 was reduced. The heating value of the PG was also increased from 4.79 MJ Nm^{-3} to 5.5 MJ Nm^{-3}. The reduction of tar and particulate content in the PG

together with the increase in the heating value of PG showed that the upscaled MW tar thermal cracking process was successful.

CHAPTER ONE

INTRODUCTION

1.1 Research background

Global energy demand has led researchers to discover various alternative energy sources which are much more sustainable and efficient compared to the existing ones which may somehow deplete one day. The existing so called reliable and clean energy sources like wind energy, solar energy, geothermal energy, hydroelectric energy and wave energy have not yet been proven economical and does not provide viable solution for certain useful applications. In addition to that, pollution due to emission of carbon dioxide has become a serious issue lately which consequently affect the human population in the form of global warming. However, biomass energy which has been extensively studied proves that it is the best and readily available energy source which has a great share of the global energy demand since World War II [1]. It is estimated that biomass are covering the global energy demand today and will continue to produce approximately 80% of the world's primary energy by 2040 [2]. Besides fulfilling the global energy demand, biomass energy had received great attention in causing less pollution.

Biomass is considered a renewable energy source if it is utilized in a sustainable manner. One of the common utilizations of biomass is the biomass gasification. Biomass gasification is a prime and mature technology that uses a controlled heating process to convert biomass fuels like wastes from plants, animals, sewage and etc. into useful gases which can further be used for many other purposes, without combustion or in other words, incomplete combustion. It is one of the alternative renewable sources of energy which has been widely developed and used due to its sustainability. Gasification had been chosen over combustion since it is more efficient at smaller scale. This is because of the higher potential for the application of a co-generative unused heat recovery, the difficulty in providing large amount of raw material to feed plants as well as the very little effect of the installations on the environment [3]. The product of the gasification process is known as the producer gas (PG) which composed of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4) and other form of impurities as well as solid residues, called char [4]. These gases can be used in internal combustion engines and turbines to generate power and it can also be used to produce gasoline and diesel via a process named Fischer-Tropsch (FT). Biomass gasification is also used for the production of hydrogen via steam reforming of hydrocarbons over a Ni catalyst at 1472° F. Besides, various chemical substances like ethanol and methanol can be produced from biomass gasification products.

There are also some problems associated with biomass gasification which includes the high amount of ash and dust remain in the gases formed as well as the high amount of tar is produced. These impurities are harmful and required to be removed and cleaned after the gasification process as it may affect the efficiency and cause serious problems to the whole gasification system. The ash and dust can be removed by the cyclone separators and a few gas cleaning methods. However, the tar produced is of the major concern as it may cause serious problem to the whole system when it is not well managed. Tar is basically a form of char produced from the biomass gasification process. The tar is usually in vapour form when it leaves the gasifier. After leaving the gasifier, the PG along with the tar will be cooled down. Upon cooling, the tar will start to condense as its dew-point is reached and this will cause it to block downstream pipelines in the gas cleaning process as well fouling engines or turbines during further application of the producer gas [5]. Therefore, methods of removal of tar is crucial in biomass gasification process.

There are a few tar cleaning methods which can be generally classified as physical, chemical and thermal methods. Physical method can be used to capture and remove both particulates and tar from the producer gas and can be divided into two which are dry gas cleaning method and wet gas cleaning method. Dry gas cleaning is done before cooling the gas whereas wet gas cleaning is done after cooling the gas. Some of the devices used for dry gas cleaning includes cyclone, rotating particle separator (RPS), dry electrostatic precipitators (DESP) fabric filters, ceramic filters, activated carbon based adsorbers and sand bed filters. For wet gas cleaning, electrostatic precipitators (ESP), wet scrubbers and wet cyclones are used. Chemical method is basically the use of catalyst to perform tar cracking. Different types of catalyst perform different rate cracking which mainly depends on their composition. There are a few types of catalyst which can perform tar cracking which includes, nickel-based catalysts, non-nickel metal catalysts, alkali metal catalysts, basic catalysts, acid catalysts and activated carbon catalysts. In thermal method, tar thermal cracking is done whereby the tar is broken down into lighter gases by heating it at a certain temperature for a certain residence time.

Tar thermal cracking is one of the most suitable method of tar cleaning or reduction in recent times. Tar thermal cracking is an efficient method as it does not require any form of catalyst substances as in chemical method which will deteriorate and diminish by time and causes the process to be inconsistent. On the other hand, tar thermal cracking method does not require any costly devices which are being used in physical method which requires frequent cleaning and proper maintenance. Previously, electric furnace was used to perform tar thermal cracking. However, this method was inefficient as it consumes high power to generate heat and the heating element as well as the walls of the electric furnace may damage and need to be replaced after some time. Besides, the cracking of the tar was not good enough as expected. Therefore, microwave (MW) tar thermal cracking was implemented using MW reactor as it is much more energy efficient and able to reach a very high temperature to ensure proper tar cracking. It is also developed with the concept of focused heating. Via MW heating, energy is supplied by an electromagnetic field instantaneously to the material and heat can be generated throughout the volume of the material because microwaves can penetrate through and deposit energy [6]. Two important parameters that need to be concerned when it comes to tar thermal cracking are the reaction temperature and residence time. Residence time is the time at which the PG remains during thermal cracking at certain temperature.

1.2 Problem statement

At present, biomass gasification is one of the process of producing useful combustible gases for power generation which is widely being developed by researchers all around the world due to its economic benefits because the main fuel for this process are only waste products from plants, animals and other form of derived waste. These wastes are readily available and easy to be obtained. Most of research done on biomass gasification is directed towards improving the efficiency of the process by producing cleaner gas through tar thermal cracking method. The MW tar thermal cracking is the most preferable method as it can operate at high temperature efficiently. However, effort made earlier was only to carry out the process at lab scale which allows tar removal from the PG at a low flow rate. Such effort was not been able to be implemented for commercial use which requires tar removal at higher flow rate of PG from the gasifiers.

Therefore, upscaling of the MW reactor is put into consideration which would allow tar cleaning of PG from a 10kW downdraft gasifier at a higher flow rate. Such effort is believed to be applied on gasification system for commercial use. Besides, the upscaling of the MW reactor for tar thermal cracking would also allow the gasification system in which it is being implemented to be used for commercial power generation.

1.3 Objectives

The specific objectives of the research are:

1. To modify an industrial MW reactor to an upscaled MW tar thermal cracking system.
2. To characterize an upscaled MW tar thermal cracking system and its integration with a 10kW downdraft gasifier for PG tar removal.
3. To evaluate the tar cleaning performance of the developed system.

1.4 Scope of project

A 10kW downdraft gasifier and a MW reactor has been developed for this project. This project aims to upscale the existing MW reactor to perform tar thermal cracking at a higher flow rate. The tar thermal cracking process mainly depends on the MW reactor temperature and the residence time. Tar removal efficiency of this MW tar cracking system will be determined along with the heating value of PG.

CHAPTER TWO

LITERATURE REVIEW

Biomass gasification system has been developed earlier by researchers and is being continuously studied to improve the process as a sustainable energy production method. Various types of gasifiers have been developed which includes the fixed bed gasifiers such as downdraft, updraft and cross-draft gasifiers and another type which is the fluidized bed gasifier. From the review of limitations and advantages, downdraft gasifier is selected as the suitable gasifier to be used in this work. Besides the type of gasifier, the problems associated with the product of the gasification which is tar and ways to overcome them is also another subject of interest in this work. In this review, the problem solving method related to the gasification product which is tar by using MW tar thermal cracking are studied. This chapter also reviews on the parameter that can be optimized to achieve a MW tar thermal cracking system which can be used commercially.

2.1 Tars and its classes

Tars are condensable organic compound produced under thermal or partial oxidation of organic fuel during gasification which are generally assumed to be largely aromatic [5]. Tars usually exist in vapour form during gasification process. Tars are not considered as the waste products of biomass gasification as it can be further breakdown into useful lighter combustible gases. An efficient biomass gasification should produce less amount of tars. The thermochemical conversion of biomass creates thousands of tar species depending upon the operating parameters of the process such as the feedstock composition, operating temperature and pressure, gasifying agent and feedstock residence time. The type of gasifier also influences the amount of tar produced at the end. Based on previous study, it has been proven that downdraft gasifier is more likely to produce the least amount of tar compared to other gasifiers. Tar compound can be classified into five classes based on their chemical property, solubility and condensability. Those five classes are GC-undetectable, heterocyclic, light aromatic (1 ring), light PAH compounds (2–3 rings) and heavy PAH compounds (4–7 rings) [5].

The following table shows the classes of tars with their respective properties and representative compounds;

Table 2.1: List of tar compounds that are considered for different tar classes with their respective properties and representative compounds [5].

Tar class	Class name	Property	Representative compounds
1	GC-undetectable	Very heavy tars cannot be detected by GC	Determined by subtracting the GC-detectable tar fraction from the total gravimetric tar
2	Heterocyclic	Tars containing hetero atoms; highly water soluble compounds	Pyridine, phenol, cresols, quinoline, isoquinoline, dibenzophenol
3	Light aromatic (1 ring)	Usually light hydrocarbons with single ring; do not pose a problem regarding condensability and solubility	Toluene, ethylbenzene, xylenes, styrene
4	Light PAH compounds (2–3 rings)	2 and 3 rings compounds; condense at low temperature even at very low concentration	Indene, naphthalene, methylnaphthalene, biphenyl, acenaphthalene, fluorene, phenanthrene, anthracene
5	Heavy PAH compounds (4–7 rings)	Larger than 3-ring, these components condense at high-temperatures at low concentrations	Fluoranthene, pyrene, chrysene, perylene, coronene

Tar formation are usually undesirable as it may cause some problems during its further application. The problems created by tar is not about its quantity but rather its properties and composition. In this situation, the property which plays an important cause of the problems is the dew point of the tar. The problems usually happen when the tar starts to condense at its dew point. While class 1 tars which are heavy tars remains undetected by gas chromatography (GC), class 2 and 4 tars reaches its dew point at about 25°C at a very low concentration [5]. Class 5 tars dominate the dew point at about 100°C at similar low concentration [5]. From Table 2.1, it can be seen that from its property, class 3 tar would not give rise to such problems. The dew point of tars is closely related to its concentration whereby the higher its concentration, the greater the dew point will be. The problems associated with tar is it can cause fouling in engines and turbines used for heat and power generation. Besides, it can also cause blockage in downstream pipelines which will be a big mess during its cleaning process. The removal of tar from the gasifier itself is known as the primary method while in most cases, secondary method which is done outside the gasifier is often crucial.

2.2 Types of gasifier used in biomass gasification

Biomass gasification is a process which is carried out using a gasifier to produce combustible gases known as PG. There are a few types of gasifiers which have been designed and developed which can be classified into two categories, namely, fixed bed gasifier and fluidized bed gasifier. Fixed bed gasifier is those in which the fuel and the gasification medium moves either concurrent or counter current to each other as the fuel are converted into combustible gases whereas fluidized bed gasifier has a bed made of an inert material such as sand, ash or char that acts as a heat transfer medium [7].

Fixed bed gasifier is the type of gasifier which is widely used nowadays compared to the fluidized bed gasifier due its ease of operation. Fluidized bed gasifier is not preferable since the amount of tar produced from the gasifier will be much higher compared to fixed bed gasifier. Fixed bed gasifier can be further divided into three types which are updraft, downdraft and cross-draft gasifiers. One of the main differences which can be spotted between these gasifiers is the arrangement of zones inside the gasifier besides the direction of flow of the producer gas produced. There are four distinct zones in each of these gasifiers which includes drying, pyrolysis, combustion and reduction [7]. In the drying zone, the moisture from the fuel is removed which later serves as the gasifying agent. In the pyrolysis zone, most of the tar and other volatile compounds are driven off. In the combustion zone, the fuel reacts exothermically with the oxygen to produce carbon dioxide and water vapour for a complete combustion while in reduction zone, the carbon dioxide and water vapour are reduced endothermically into carbon monoxide and hydrogen gas having the capability of reducing the gas temperature.

In an updraft gasifier [Figure 1], the fuel is introduced into the gasifier at the top while the gasifying agent is injected at the bottom. As the fuel moves downwards through successive zones of progressively increasing temperature from the top which are drying, pyrolysis, reduction and combustion, the gasifying agent moves upwards from the bottom while the gasification process occurs. Therefore, the gasification process will begin from the bottom zone which is combustion zone followed by reduction zone, pyrolysis zone and drying zone. The PG formed together with tar from the gasification process will be released from the top of the gasifier while the ash formed will settle down at the bottom of the gasifier which can be later removed. As the tar produced could only pass through the reduction zone after the pyrolysis zone along with the PG, effective tar thermal cracking could not be achieved resulting in high tar loads [4].

In a downdraft gasifier [Figure 2], the fuel is introduced into the gasifier at the top while the gasifying agent is introduced through a set of nozzles from the side of the gasifier. As the fuel moves downwards, the gasification process begins from the top in the drying zone followed by pyrolysis zone, combustion zone and reduction zone. The moisture evaporated from the biomass fuel will serve as the gasifying agent. The PG formed together with the tar from the gasification process will be released from the bottom of the gasifier. The amount of tar produced from this gasifier is substantially less compared to the updraft gasifier because the tar produced are thermally cracked through the combustion zone at about 1300°C before being released.

Cross-draft is much more similar to downdraft gasifier except that the orientation of the zones is different. The fuel is introduced into the gasifier at the top while the gasifying agent is introduced at only one side of the gasifier near the bottom. The combustion and reduction zones are concentrated around the sides of the gasifier. The PG formed is released at the opposite side of the entrance of the gasifying agent. However, the gasifier is sensitive to changes in the fuel composition and moisture content [7].

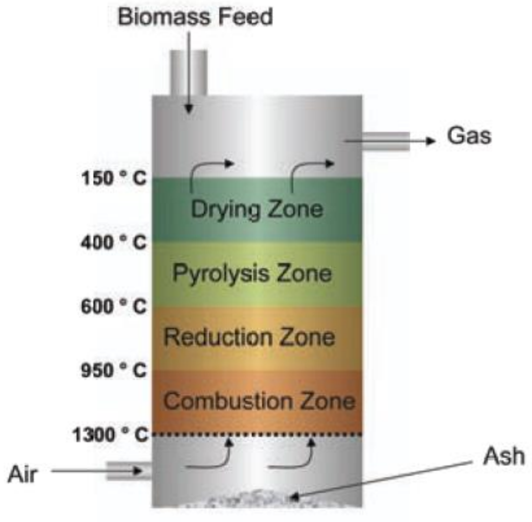

Figure 2.1: Updraft fixed bed gasifier [7].

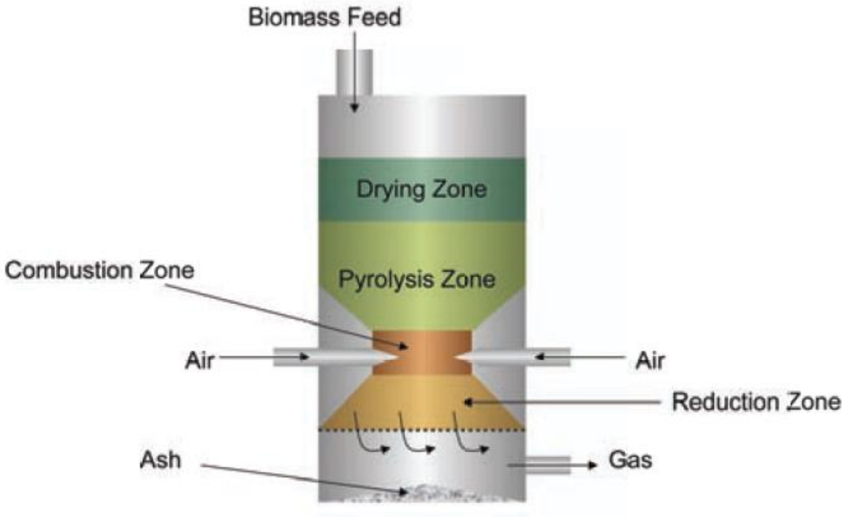

Figure 2.2: Downdraft fixed bed gasifier [7].

The following Table 2.2 shows the comparison of current main designs of fixed bed biomass gasifiers and the Figure 2.1 & 2.2 shows the updraft and downdraft fixed bed gasifiers respectively;

Table 2.2: Comparison of current main designs of fixed bed biomass gasifiers [4].

	Downdraft	Updraft	Crossdraft
Gasification agent	Air	Air	Air
Fuel size (mm)	20-100	5-100	5-20
Allowable fuel moisture (%)	12(< 25)	43(< 60)	10-20
Syngas temperature (°C)	700	200-400	1250
Reaction temperature (°C)	~1090	-	-
Syngas LHV (MJ/Nm^3)	4.5-5.5	5.5-6	~5
Tar in producer gas (g/Nm^3)	0.01-5	30-150	0.01-1
Particles in producer gas (g/Nm^3)	0.02-8	0.1-3	-
Ash in syngas	Low	High	High
Reactor size MW_{th}	< 1	0.1-20	~0.01
Residence time (of biomass particles)	Remain in bed and gasified	Remain in bed and gasified	Remain in bed and gasified
Hot gas efficiency (%)	85-90	90-95	-
Technology	Simple, low investment cost	Simple, low investment cost	Simple, low investment cost
Gasifiers manufactured (%)	75	2.5	Remaining

From the table, it can be seen that the cross-draft gasifier produces the least amount of tar as compared to other gasifiers. However, by comparing it with the downdraft gasifier, the impurities produced by the cross-draft gasifier such as the ash is higher. The fuel size which can be used for downdraft gasifier is also larger compared to the cross-draft gasifier. This proves that the downdraft gasifier is in favour to be used if the aim is to produce the PG with less amount of tar.

2.3 Gasifier performance

The quality of the PG formed from the gasification process greatly reflects the gasifier performance. One of the main important measure of the gasifier performance is the cold gas efficiency (η_{cg}). The cold gas efficiency is defined as the ratio between the flow of energy in the gas and the energy contained within the fuel. It is called cold gas efficiency as it does not take into account that the PG exiting the gasifier is hot. The cold gas efficiency can be obtained by obtaining the Lower Heating Value of PG (LHV_{PG}) formed as well as the Lower Heating Value of biomass fuel (LHV_b) first. The cold gas efficiency can be mathematically expressed as;

$$\eta_{cg} = \frac{LHV_{PG} Q_{PG}}{LHV_b \dot{m}_b} \times 100$$

Where:
LHV_{PG} = Lower heating value of PG.
Q_{PG} = Volumetric flow rate PG.
LHV_b = Lower heating value of biomass fuel.
$\dot{m}_b$ = Mass flow rate of biomass fuel.

The LHV_{PG} can be calculated based on the percentage volume fraction of the PG which can be obtained through gas chromatography (GC) method. The LHV_{PG} depends on the percentage volume fraction of H_2, CO and CH_4. It can be mathematically expressed as;

$$LHV_{PG} = x_{H_2} LHV_{H_2} + x_{CO} LHV_{CO} + x_{CH_4} LHV_{CH_4}$$

where x is the volume fraction of each gas. The LHV of each gas is 10.757, 12.641 and 35.787 MJ Nm^{-3} for H_2, CO and CH_4 respectively [12]. The LHV_b can be obtained by performing bomb calorimeter test on the biomass fuel.

2.4 Effects of equivalence ratio on gasification process

Equivalence ratio (ER) is the ratio between the actual air-fuel ratio to the stochiometric air-fuel ratio. ER is another important parameter in gasification process which affects the performance of the gasification process and hence the composition of the PG formed as well as the calorific value of the PG significantly. It is commonly used to indicate quantitatively whether a fuel oxidizer mixture is rich, lean or stoichiometric. When the tar formation is of the main concern, ER value is one of the important parameters as it affects the conversion of the biomass into PG. The theoretical gasification occurs between ER values of 0.19-0.43 [11]. Lower ER yields high amount of tars. Therefore, to obtain a better performance of the gasification process, the suitable ER value should be maintained. Besides affecting the conversion rate of biomass, ER also affects the heating value of the PG which is also its calorific value. To obtain a higher heating value of the PG, the ER should not be too large as optimum oxidation is required for the conversion process. ER is expressed mathematically as follows;

$$ER = \frac{Air\ flow\ rate}{Biomass\ consumption\ rate} / \frac{Air\ flow\ rate}{Biomass\ consumption\ rate}\Big|_{\text{Stoichiometric}}$$

The air flow rate is the amount of air flow per unit time. The biomass consumption rate is obtained by taking the amount of biomass supplied per duration of the run of the gasifier. The stoichiometric ratio of air flow rate to biomass consumption rate is 5.22 m^3 air/kg of wood [11].

2.5 Conventional tar thermal cracking methods

Tar which is a major problem in biomass gasification since then has led to the development of conventional tar thermal cracking methods which includes the commonly used electric furnace tar cracking and steam cracking. Electric furnace used for the tar cracking produce heat from the electric heating element. Circuit breakers are usually used to control the heating element. The transfer of heat to the fuel is through convection. The air inside the furnace will be the medium for convection to occur. However, there are a few drawbacks from the use of electric furnace to perform the tar thermal cracking. This is often a slow process, requiring high external temperatures and thus more energy against heat transfer resistances and heat losses to surrounding to generate the temperature differences required inside the reactor [9]. This process transfer heat by heating the surface of the reactor and causes non-uniform heating. This phenomenon is known as wall effect. This method is also costly as it consumes much electrical energy to heat up the heating element. Besides, the heating element will easily get damage due to the high temperature and need to be replaced by time. A type of electric furnace known as the drop tube furnace has been developed and tested where the operating temperature was varied over the range of 600-1400°C [10]. The destruction of tar is based on three different conversion processes:

pyrolysis (in a pure nitrogen stream), steam gasification (in a mixture stream of steam and nitrogen), and partial oxidation (in a mixture stream of oxygen and nitrogen). The feeding rate of feedstock was set to keep in the range of 60–70 g/h. The gas residence times in the reactor tube were 2–4 s. The results obtained are based on the yields of major tar compounds. It is found that raising the temperature remarkably decreases tar evolution. Benzene and toluene are the most difficult condensable tar species to destroy. The achievement of their complete destruction in the product gas requires extremely high temperatures above 1200 °C, regardless of the gasifying agents. The following Figure 2.3 & 2.4 shows the effect of temperature on tar formation based on the experiment;

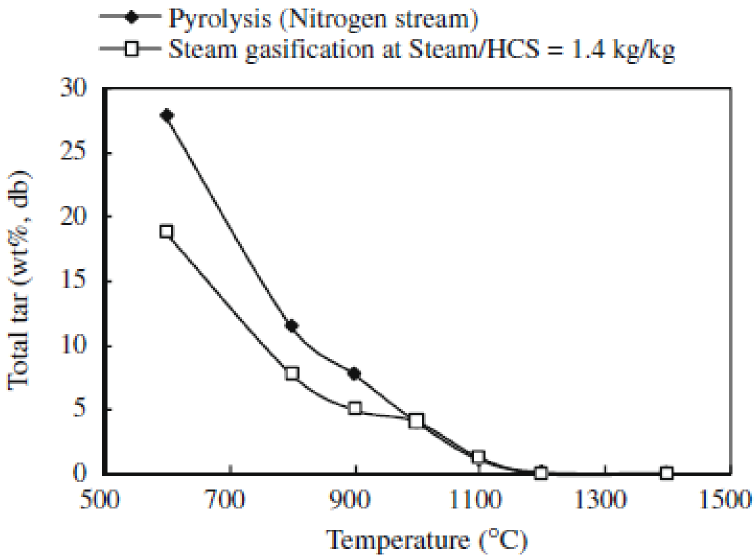

Figure 2.3: Effect of temperature on yields of total tar resulted from pyrolysis and steam gasification of HCS [10].

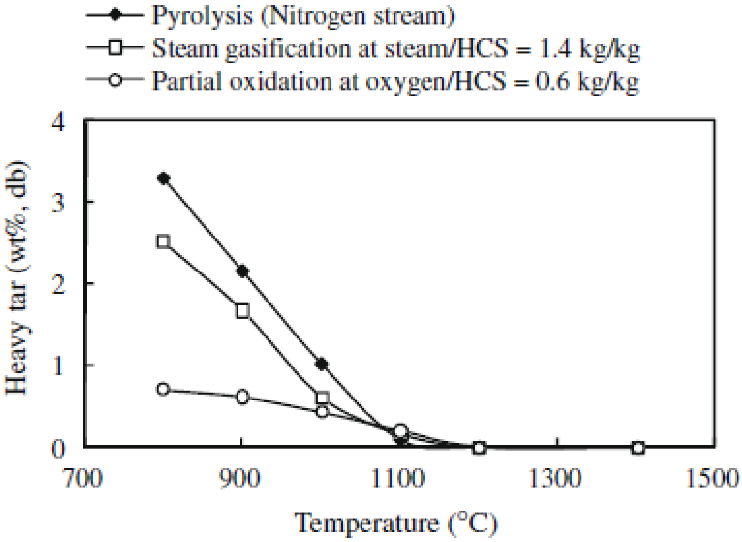

Figure 2.4: Effect of temperature on yields of heavy tar resulted from pyrolysis, steam gasification, and partial oxidation of HCS [10].

In steam cracking, the producer gas is diluted with steam and briefly heated in the furnace without the presence of oxygen. Although the reaction temperature is high but the reaction in only allowed to take place very briefly. The fuel to steam ratio is a very important parameter in this process which determines its efficiency. Almost like the electric furnace, the steam cracking furnace can usually only run for a few months at a time between de-cokings. Decokes require the furnace to be isolated from the process and then a flow of steam or a steam/air mixture is passed through the furnace coils. This converts the hard solid carbon layer to carbon monoxide and carbon dioxide. Once this reaction is complete, the furnace can be returned to service. Such situation which is time consuming and costly due to its maintenance becomes the main drawbacks of this method.

2.6 MW tar thermal treatment

The quality of gas produced from the biomass gasification process is the outmost important when it comes to the application of the gas for heat and power generation through internal combustion engine, gas turbine and fuel cell. However, the PG formed always contains impurities like tar and some other particulates. Tar formation is the main concern in this scenario as it may cause serious problems like fouling engines and block downstream pipelines. Therefore, efforts have been devoted to develope various tar cleaning methods which includes physical, chemical and thermal methods to be general. Until now, it is undeniable that the conventional thermal treatment process improves the composition of the PG, however little attention has been paid in its development since it reflects a poor efficiency and requires high additional energy and cost to achieve the desired operating temperatures [8].

At an economic point of view and for efficient tar removal, radio frequency (RF) tar thermal treatment would be a much more realistic option. This development requires the use of a MW to perform the heating process. In this process, heat energy is transferred to the PG via the interaction of the gas molecules with the electromagnetic waves [8]. In this way, the heating process can occur rapidly, thus resulting in significant energy saving. The radio frequency or MW oven with an operating frequency of 2.45GHz utilised in this tar thermal treatment contains a reactor tube which is made up of alumina or ceramic material. This reactor tube is installed vertically inside the MW oven and filled with silicon carbide balls which acts as the heat susceptor which absorbs and convert the RF energy into heat energy. With the presence of the susceptor material, the process will be energy saving, faster, improving the yields and compatible with environment. Besides the temperature which affect the rate of tar treatment, the flow rate of the PG in the reactor at certain residence time is of main interest in improving the tar treatment process which produces less amount of tar. Usually a higher volume flow rate at a longer residence time is necessary for a thorough tar treatment process. Therefore, upscaling of the reactor can be done to achieve a complete tar treatment process and subsequently to be used in the commercial power generation system.

According to an experiment conducted at lab scale, the temperature for the MW tar thermal treatment was varied from 900 to 1200 °C whereas the residence time was in the range of 0.12–0.13s [8]. It shows that the amount of tar reduces as the temperature rises. The results obtained for the gas composition, high heating value (HHV), tar and particle concentrations during the thermal treatment of the PG are as shown in Figure 2.5 & 2.6;

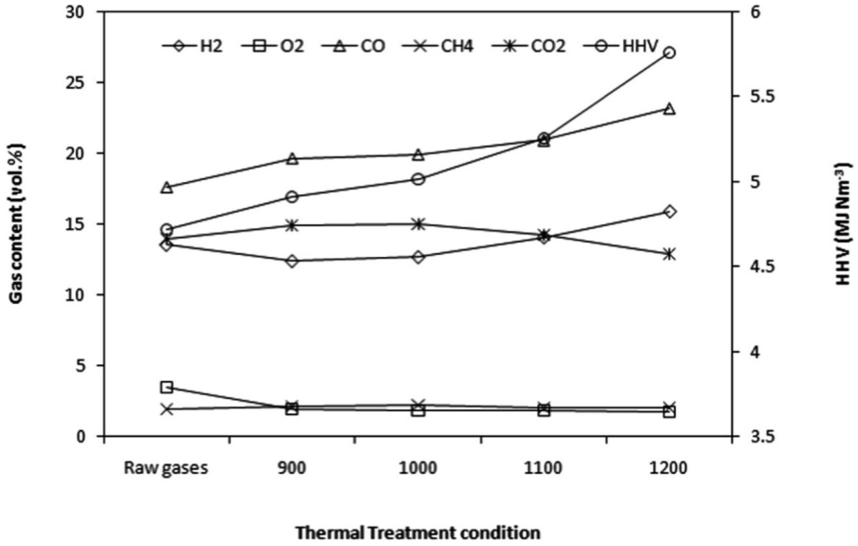

Figure 2.5: Gas composition and HHV during thermal treatment of producer gas [8].

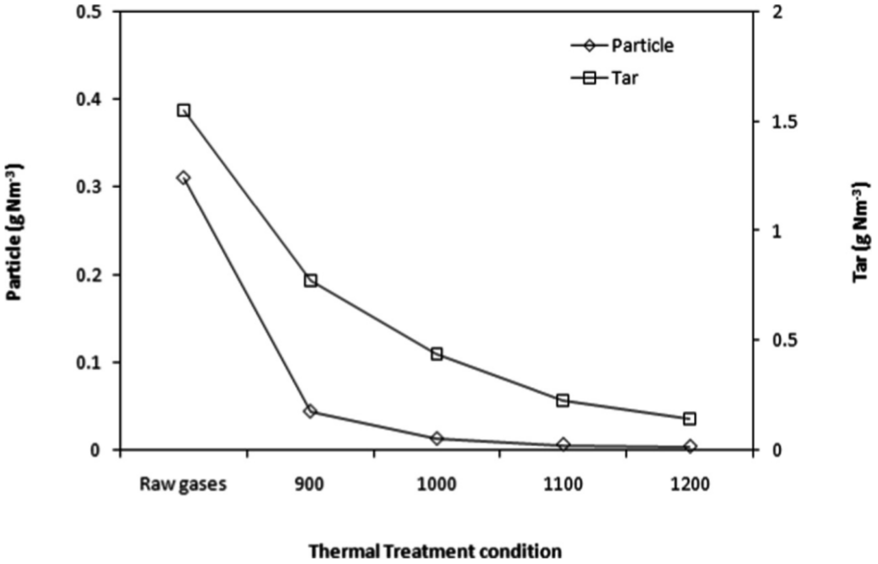

Figure 2.6: Tar and particle concentration during thermal treatment of producer gas [8].

From figure 2.5, it can be observed that the HHV increases with increasing temperature. The composition of the PG of CO, H_2 and NH_3 increases with increasing temperature while CO_2 and O_2 decreases. From figure 2.6, it can be observed that the amount of tar and particles from the PG decreases with increasing temperature.

CHAPTER THREE

METHODOLOGY

This chapter describes the methods as well as procedures implemented to carry out the study together with experiments throughout the project. It also reflects the various material and equipment used to perform the study and experiments. Section 3.1 presents the equipments used to perform the biomass gasification process together with their integration and the procedures for the characterization of the gasifier. The methods of upscaling the MW reactor are described in section 3.2. Section 3.3 presents the integration of the MW reactor with the gasification system and the procedures performed for the MW tar thermal cracking process. The chapter is concluded with characterization and analytical methods which includes obtaining the Higher Heating Value of the biomass fuel (HHV_b), proximate analysis, setting up PG sampling system and finally tar and particulate analysis using appropriate equipments and tools.

3.1 Biomass gasification system

The biomass gasification system was set up which consists of a 10kW downdraft gasifier, a rotary blower, a rotameter, a cyclone separator, a flare port, a cooling coil and a gas sampling nozzle. The main components like the gasifier, cyclone separator, flare port and gas sampling nozzle are connected using 2-inch galvanized iron (GI) pipes. The biomass gasification system set up for the PG generation is shown in Figure 3.1 below.

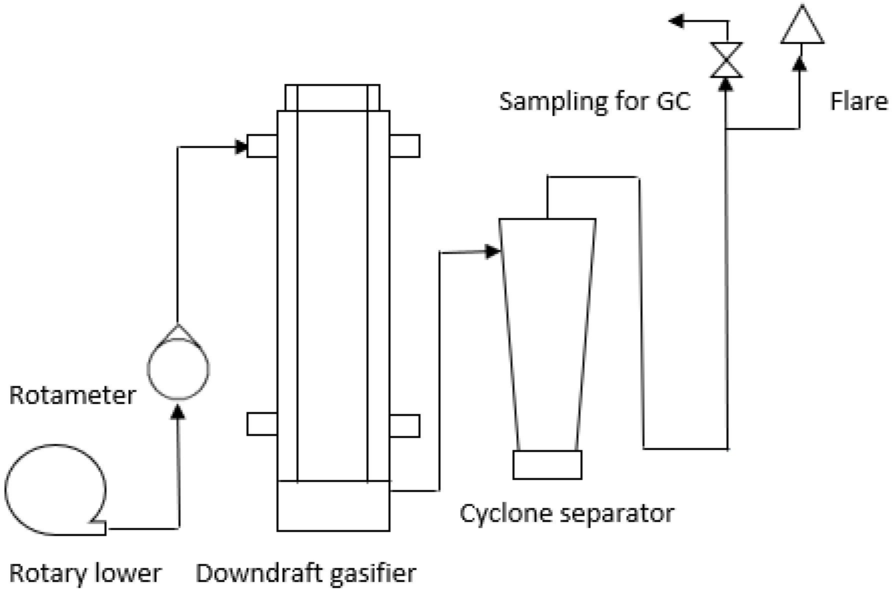

Figure 3.1: Schematic diagram of the biomass gasification system.

3.1.1 Biomass material

The biomass fuel used for the production of PG in this experiment is the wood pellets which were obtained from the Bioenergy laboratory of USM. These wood pellets are made from compacted sawdust. The wood pellets have a bulk density of 680kg/m^{-3}. Each wood pellet has a size of 8mm in diameter and 30 mm in length. Their regular geometry and small size allow them to be fed into the gasifier easily and the level of it inside the gasifier can be adjusted properly. The wood pellets used for the gasification process is shown in Figure 3.2 below.

Figure 3.2: Wood pellets.

3.1.2 Downdraft gasifier

The gasifier used in this project was a 10kW downdraft fixed bed gasifier which was designed and developed in Bioenergy laboratory of PPKM USM. It has an output of about 10kW with a cylindrical geometry of inner diameter of 0.15m and 1.06m height. A grate is used inside the gasifier to support the wood pellets which are the biomass fuel and maintain stationary reaction zone. The grate is removable from top. The gasifier has six opening ports on its sides where two are near the upper part and another four are near the lower part. One of the opening port near the upper part is to allow the flow of air from the rotary blower whereas one of the opening port near the lower part is to insert the flame from burning the Liquefied Petroleum Gas (LPG) using a pipe to initiate the burning of charcoal at the bottom of the gasifier. Another opening port near the lower part is to allow the flow of the PG. A big opening port near the lowest part of the gasifier is for the removal of ashes after the gasification process has completed. The 10kW downdraft fixed bed gasifier used in the project is shown in Figure 3.3 below.

Figure 3.3: 10kW downdraft fixed bed gasifier.

3.1.3 Experimental procedure for gasifier characterization

The biomass gasification system was run using the wood pellets to obtain performance of the gasifier in terms of the cold gas efficiency and certain other condition like the ER for the gasification process. Besides, the properties of the PG in terms of its composition and heating value were also obtained. The air flow rate into the gasifier was maintained at 140 LPM at the beginning when 0.5 kg of charcoal which consists of rubber seeds was fed into the gasifier and ignited using flame from LPG through the ignition port on top of the charcoal level. The flame was placed just above the level of charcoal. As the charcoal start to burn, the flame is removed and the charcoal is let to burn for about 15 minutes until it becomes red hot. After the combustion of the charcoal until it becomes evenly red hot begins, 3.5 kg of biomass fuel which was the wood pellets was fed into the gasifier. The gasifier top was closed tightly and the stopwatch was started to measure the time taken for the gasification process to complete which is when the biomass fuel has been completely consumed in the gasification process. The air flow rate was controlled using a frequency inverter connected to the rotary blower and measured using the rotameter with scale range of 100-1400 LPM. The rate of biomass consumption and the air flow rate was used to calculate the ER value of the gasification process. After 20-30 minutes, the PG released from the flare port was ignited with flame to observe if flare could be produced. When flare could be produced as shown in Figure 3.4, it indicates that the gasification process is occurring steadily. At this point, PG sampling was done by taking the PG sample from the gas sampling nozzle using a gas sampling bag. Since the PG from the gasification process was hot and the gas sampling bag could only withstand temperature of 70°C, a cooling coil was connected to the gas sampling nozzle before collecting the PG into the gas sampling bag. The gas was then sent to test for its composition using gas chromatography method which was done at the Engine Laboratory of School of Mechanical Engineering, USM. From the gas composition, the LHV_{PG} was obtained and used to calculate the cold gas efficiency. The experimental setup of the biomass gasification system is shown in Figure 3.5.

Figure 3.4: Flare produced at flare port.

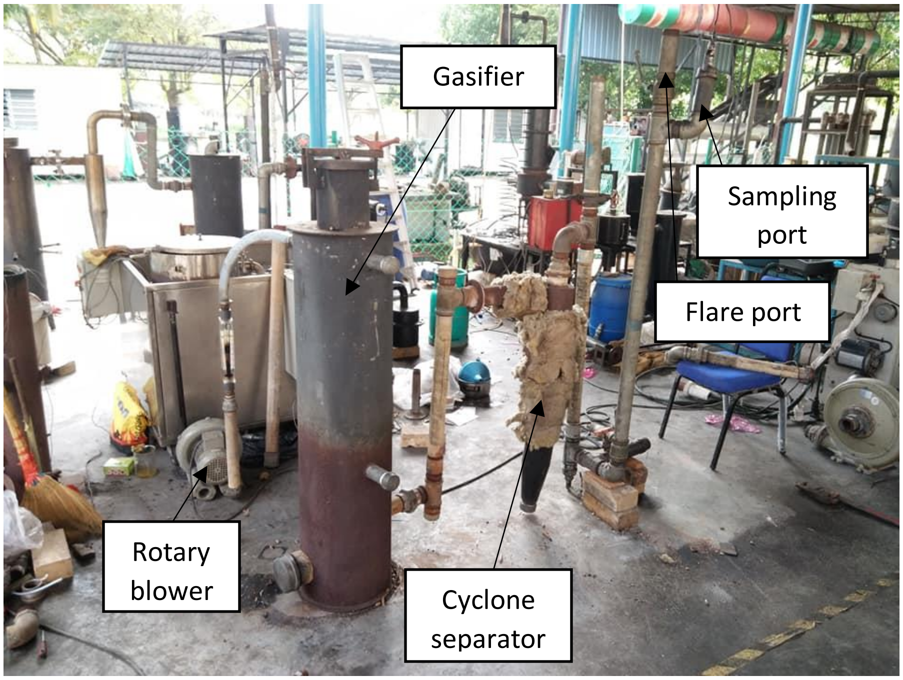

Figure 3.5: Experimental setup of the biomass gasification system.

3.2 MW tar cracking system

The MW tar cracking system basically consist of an industrial MW oven which was modified earlier to hold an alumina pipe inside the MW cavity. The alumina pipe was selected as the reactor to perform the tar cracking in it as it could sustain a very high temperature up to 1600°C and it is transparent to the microwaves. Initially, the alumina pipe which is the reactor has an internal diameter of 74mm and thickness of 6mm. The alumina reactor was installed inside the MW cavity by cutting holes on the top and bottom wall of the MW oven. The alumina reactor was held in position inside the MW cavity by using steel flanges on the top and bottom of the MW oven. In this project, the MW oven was upscaled by upscaling the size of the alumina reactor in it to allow a higher flow rate of PG of 250liter/min and a residence time of 0.7s in the alumina reactor. The size of the alumina reactor required to allow such flow rate was calculated as shown below.

$$T_R = \frac{V_R}{Q}$$

Where,

T_R: Residence time = 0.7s

V_R: Volume of reactor

Q: Flow rate of producer gas = 250L/min ~ 4.167L/s

$$0.7 = \frac{V_R}{4.167}$$

$$V_R = 2.9167\ L \sim 2.9167 \times 10^{-3} m^3$$

$$V_R = \frac{\pi D^2 h}{4}$$

$$2.9167 \times 10^{-3} = \frac{\pi D^2 (0.5)}{4}$$

$$D = 0.0862m \sim 86.2mm$$

Since the alumina reactor with the accurate internal diameter as calculated cannot be obtained, a close internal diameter of 90mm with external diameter of 100mm was purchased. The holes on top and bottom of the MW reactor were cut bigger using grinder machine to install the upscaled alumina reactor. The steel flanges on top and bottom of the MW oven were also upscaled to fit the alumina reactor. For the steel flanges, two 3mm thick mild steel was cut into a square shape using the hydraulic shearing machine available at the school workshop. A hole of diameter 106mm was cut at the centre of the steel plate to allow the 100mm alumina pipe to pass through it. A flange is the welded at the drilled hole for the alumina pipe to sit in it. 8 small holes of diameter 4 mm were drilled around the plate to integrate it with the MW oven using 4mm screws and nuts. 3 pieces of gaskets on each side was prepared with the same size and shape of the steel plate made earlier. The top and bottom flanges together with the gaskets fabricated are shown in Figure 3.6. The upscaled MW oven with installed reactor is shown in Figure 3.7 and 3.8 below.

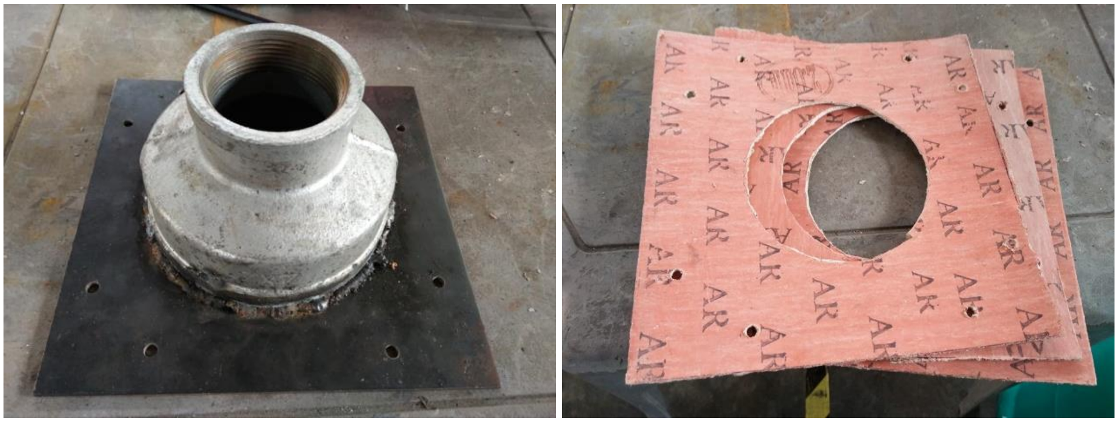

Figure 3.6: Steel flanges and gaskets.

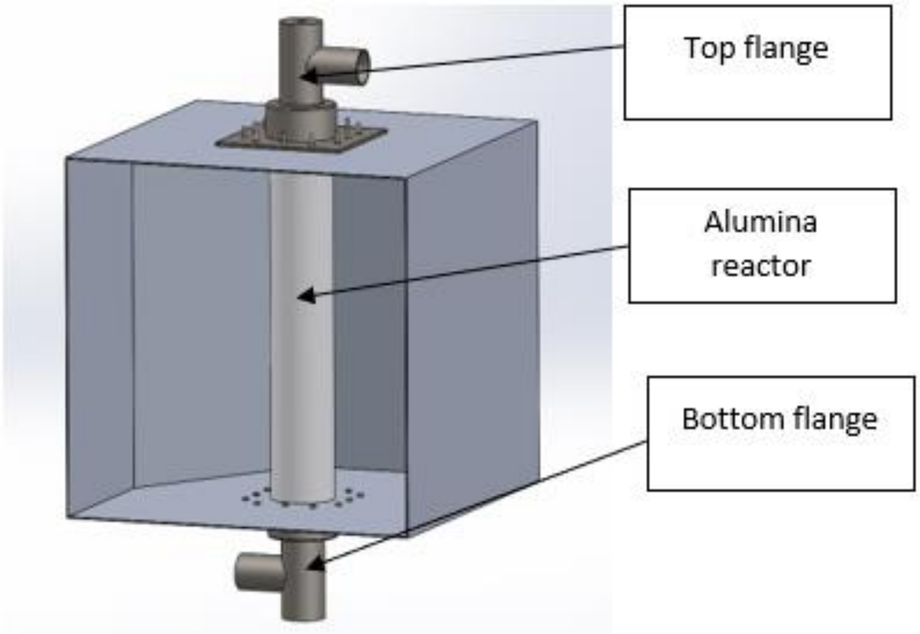

Figure 3.7: Solidworks model of the microwave reactor.