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Optimization methodology study for plasma gasification process

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Abstract

Plasma gasification has been studied as a new technology which may combine bio-waste treatment and energy generation. Currently, a setup for carrying out gasification experiments has been built up in order to obtain more experimental data for further research. According to previous experimental results, we can see that the gas feeding and feeding material can influence the results of gasification quite obviously. Base on this fact, the gas feeding needs to be adjusted according to verified researching purposes. This project looks into how the gas feeding would influence the gasification results with different feeding materials. Pure lignin and cellulose were used as feeding material, and three groups of experiments were done. The influence of gas feeding condition on gasification result was found in terms of gas composition, carbon conversion and cold gas efficiency. A methodology for optimizing the process is developed based on the experimental results and observations. For experiments which would be carried out later with certain purpose, the result of this research can be helpful to find out the proper gas feeding settings and solve problems when the experimental results are out of expectation.

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Chapter 1 Introduction

This chapter will give some background information of this project including a process description. Also, the research objectives would be defined. A reading guideline and a schematical drawing of the report outline are also included in this chapter.

1.1 Background

The emission of bio-waste and scarcity of energy resource has been two huge challenges for human beings worldwide with the growing population in recent decades. Gasification can be an effective method to reduce the pressure in waste treatment and energy generation at same time, for it can convert bio-waste into fuel gas. As a part of the project named as "Reinventing the toilet",[1] plasma gasification process was studied for its high efficiency in human waste treatment. At present, the process is researched in terms of waste treatment, energy recovery and energy storage.

1.1.1 Plasma

Plasmas are recognized as the fourth state of matter. They are composed of ions, electrons, free radicals, and other neutral species which can be seen as partially ionized gases. Based on this fact, plasmas are electrically conductive and magnetically controllable; also they are very chemically reactive because of its high-energy state.

Apart from natural plasma, which is one of the most abundant states of matters in the universe, artificial plasma can also be generated by different method. Basically, it can be made by partially ionizing the gas with help of heat or electricity or microwave.

Differences in plasma generating methods would give plasmas different thermal properties. Based on the relative temperatures of the electrons, ions and neutrals, plasmas are classified in two categories. Plasmas have electrons and the heavy particles at the same temperature are defined as thermal plasmas, while those without thermal equilibrium are non-thermal plasmas. The non-thermal plasma has been applied for flue gas treatment and has been considered very promising for organic synthesis because of its non-equilibrium properties, low power requirement and its large capacity to induce physical and chemical reactions within gases at relatively low temperatures. The electrons in non-thermal plasma can reach temperatures of 10,000–100,000 K, while the gas temperature can remain as low as room temperature. Typical thermal plasmas are direct current discharge and radio frequency discharge plasmas, while corona discharge and microwave plasmas as non-thermal ones. [2]

1.1.2 Microwave induced plasma gasification

Microwave induced plasma is a type of non-thermal plasma. The microwave provides an electromagnetic radiation, ranging from 300 MHz to 300 GHz, which transmits energy to the electrons of the feeding gases. This energy would accelerate the electrons and cause collisions between them, so that the gases would be heated up and partially ionized, which leads to a high temperature plasma flame consists of high-density activated species.

The intensity of plasma brings the possibility of rapid process for gasification of bio-wastes. When contact with plasma, solid feeding stocks (.i.e. biomass) would be pyrolyzed and partially ionized due to the high temperature above 3000°C. In the highly-reactive environment with plenty of ions and free radicals composed of C, H and O, syngas can be formed in the very short residence time. [3]

Based on these facts, we can see the feasibility to create a relatively small and portable gasification installation for certain applications, such as local destruction of chemical waste or shipborne waste destruction. Apart from using the generated syngas as a renewable energy resource, it can be used for other purposes as well, such as chemical synthesis or electricity generation by fuel cell technology.

1.2 Process Description

At present, a small scale plasma gasification setup has been built for experimental purpose. The aim of this project is to develop a methodology to optimize the plasma gasification process when operating with this certain setup.

A picture of the major process flow sequence is given below.

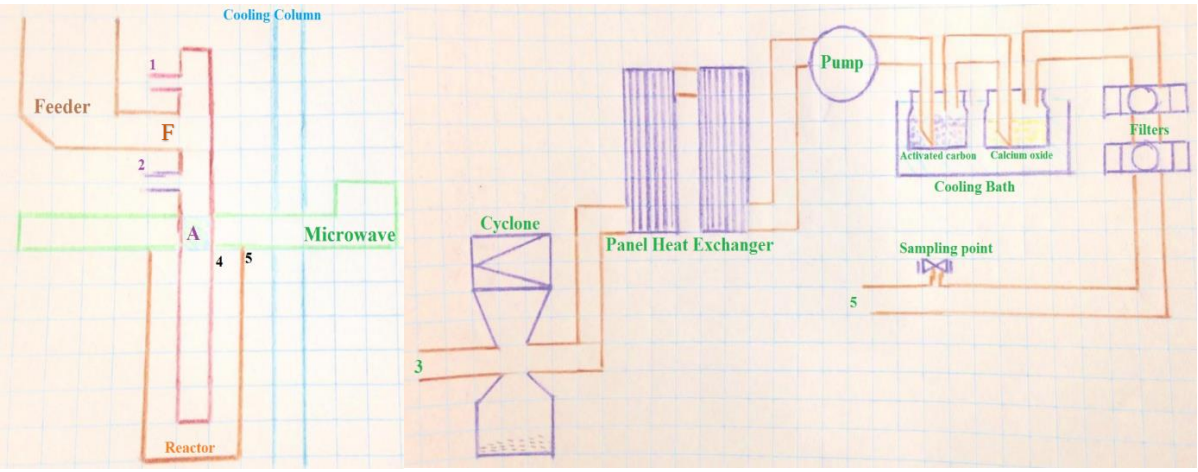

Figure 1 Plasma gasification process flow diagram

The bio-mass feed stock enters the reactor from the top (F). A top process flow gas feeding above (No.1) F would carry the feed stock all the way down to the microwave field. A swirl process flow feeding (No.2) is introduced through an opening below the bio-mass feeding point. This gas is fed at an angle against the reactor wall, so that a swirled gas flow is created around the plasma. The flow patent is shown in the picture below, where the blue stream indicates the swirl flow while the read stream refers to the top flow.

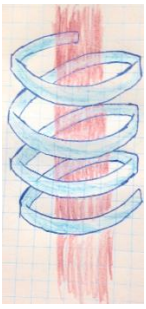

Figure 2 Flow patent inside the reactor

In A field, under the microwave power, the process gases are transformed into plasma and react with the solid feedings. A thermometer is placed here to detect the reactor wall temperature, which is part of the control loop for automatic power adjustment.

After being cooled preliminarily the product gas splits into two parts. The majority of the gas would go through the opening No.4 to the cooling column and be led to the top of the reactor where is connected to the flare outside the building. Part of the gas exits from opening No.3 would be sent to the gas conditioning system for sampling.

The gas comes out of opening NO.3 is cooled by the two heat exchangers and then pushed through activated carbon and calcium oxide bottles sitting in the cooling bath, followed by two filters, so that the moisture, tar and particles are removed in the product gas, which is necessary for the GC analysis. If samples are not taken, the gas will continue flowing to opening No.5 which is also connected to the flare.

1.3 Objective

This project looks into the plasma gasification process based on experiments carried out with the setup built by Process & Energy faculty in Delft University of Technology. Study objectives of this project are:

- Review the literature about plasma gasification working theory
- Carry out experiments with the setup and develop a clear experiment procedure with guideline for optimization methodology
- Record problems and observations during experiments and find solutions to the problems
- Find how the feed stock and gas feeding condition varieties influence the results

1.4 Reading guideline

This report includes 5 chapters. The introduction gives information about relative theories and a process description. Second chapter includes a detailed introduction on the experimental equipment as well as the operation procedure for preparing the feed stock and conducting gasification tests. Calculation method for data analysis is also given in this chapter. The results of this project contain three parts: research pathway, problem locating and results of the experiments. An overall discussion and conclusion would be included in chapter four and five.

1.5 Outline

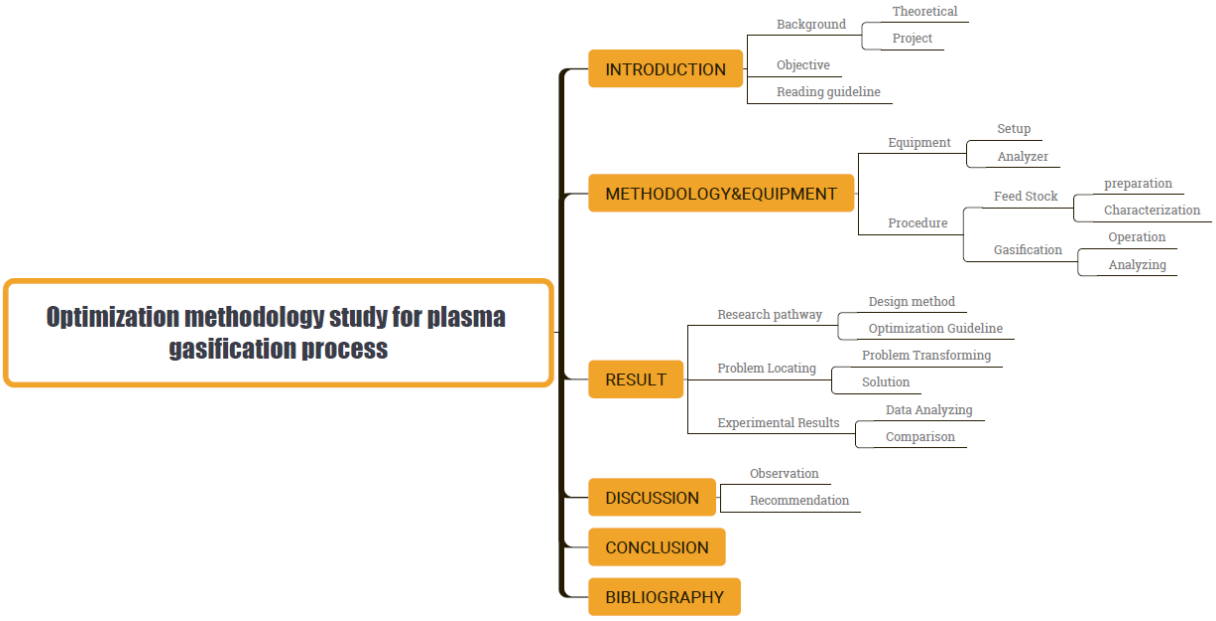

Figure 3 Outline schematical drawing

Chapter 2 Research Methodology & Equipment

During this research, two feeding materials were studied about: cellulose and pure lignin. And a mixture of air and pure nitrogen was used as the feeding gas. And a small scale plasma gasifier was built for gasification experiments. This chapter would introduce the equipment and procedure of the experiment and also explain how the experiments should be planned.

2.1 Plasma gasification set up

The setup is mainly made up of four parts: Feeder, microwave generator, plasma reactor generator and gas cleaning system.

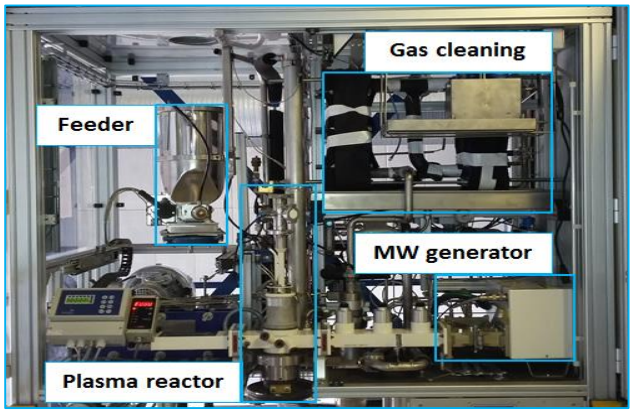

Figure 4 Experimental setup

Feeder: A vessel, a feeding pipe and a control panel forms the feeder that is applied currently.

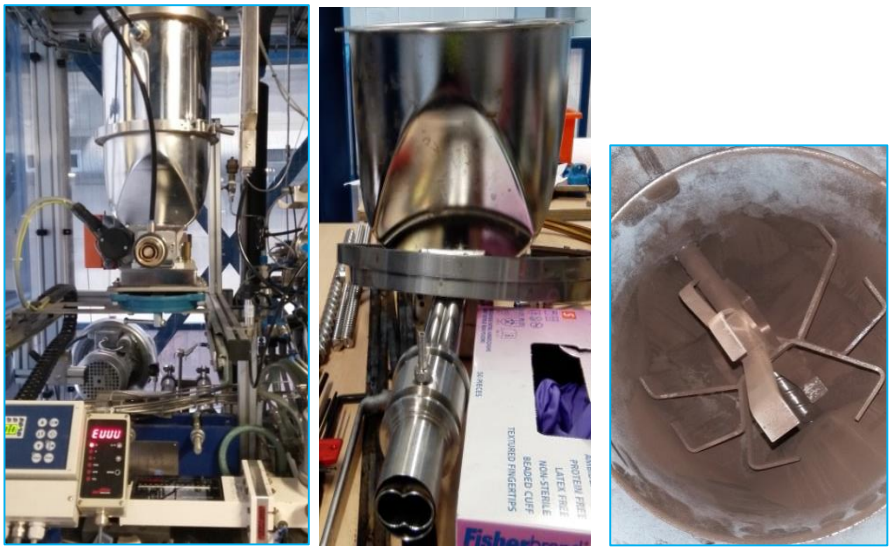

Figure 5 Feeders and inside structure

Inside the vessel a blending blade is placed to help moving the feeding materials. An endless screw is fixed in the feeding pipe; the particles would be carried by it and sent to the reactor. The control panel is connected to the computer, from where the rotating speed can be adjusted according to the requirement of the experiment. The start and stop button can be used for starting or stopping the feeder directly when necessary as well.

Two types of feeders are used at present for different feeding materials: The feeder with one endless screw is suitable for feeding material with relatively large particle size. Another feeder with two endless screws can be used for much finer power and with same rotation speed the feeding rate is higher than that of the single-screw one.

The feeders can be switched easily by removing and placing on the base.

Figure 6 Feeder base

Microwave generator: Located at the left bottom corner of the setup, the microwave generator is providing the microwave power to sustain the plasma flame. [4]

Figure 7 Microwave generator

The four parts forming this microwave generator are:

- A 2.45 GHz microwave generator with a maximum output power of 6 kW. The running state of it can be read through the control screen below.
- An isolator, which is a microwave circuit element that protects the microwave generator from exposure to a reflected microwave field.
- An impedance transformer, for tuning the field to improving the efficiency of the microwave power.
- A variable reflector that can be used to position the field at the plasma flame, maximizing energy transfer.

Plasma reactor: The reactor is made up of two parts: the outer cooling shell and the inner pipe that holds the plasma flame. It is placed in the middle of the setup as shown in figure 4.

Figure 8 Inner reactor pipe

Figure 9 Outer cooling shell

- The inner pipe is made up of two parts. The upper pipe with inner diameter of 31mm and made of quartz is placed where the plasma would be started. The down part is a 50cm long pipe shelled in a steel pipe with copper cooling coil surround and nickel plating on the top. The pipes made of borosilicate and quartz was used up to now. In the space between the borosilicate/ quartz pipe the steel pipe, layers of brass were used to help cooling.
- The outer cooling shell is used for cooling down the gases and holding the remained particles. The outer shell is perfectly air-tight to prevent dangerous gases (.i.e. CO) escaping to the environment.

Gas cleaning system: After exiting the reactor, main part of the product gas would be combusted by a flare out of the building. Small part of the produce gas would go through the gas cleaning system and pass by the sampling exit.

Figure 10 Sampling point

This gas cleaning system is designed for the composition analysis using microgas chromatograph (CP-Molesieve 5Å & PoraPlot U). Based on the requirement of the GC column, particles, tar and moisture in the gas sample need to be removed.

The gas comes out of the reactor would go pass by a tubular cooler, a cyclone then enter two plate heat exchangers. A pump helps the pre-cleaned product gas to go through test tubes filled with activated carbon and calcium oxide and cooled to a lower temperature in the cooling bath at -10°C. After this, a series of filters (FP 050/1 & GF/C™) would finalize the gas cleaning, so that the product gas would be ready for GC analysis.

2.2 Feed stock preparation & characterization method

Base on the truth that the result of plasma gasification is influenced significantly by the physical and chemical properties of the feeding material, necessary characterizations need to be carried out.

2.2.1 Pre-treatment of feeding material

Pre-treatment of the feeding material is important at this moment, in order to make sure it fits the requirement of our setup and all characterization experiments.

1. Drying
   The feeding material need to be dried if it has relatively high moisture content, for the current setup is only used for gasifying solid materials.
2. Grinding
   The feeder being used now is only able to feed material with a particle size smaller than 2mm, so the feeding material need to be grinded to the proper size before further process.
3. Sieving
   The grinded feeding materials need to be sieved by hand or an electronic shaker. In this step, the feeding materials would be separated into mainly four types with particle size larger than 2mm, between 1mm and 2mm, between 1mm and 0.2mm and smaller than 0.2mm. The largest and smallest types of particles are not suitable to be used at this moment due to the feeder requirement.

Figure 11 Sieves

2.2.2 Physical properties characterization

Mainly three experiments need to be done to define the physical properties of the feeding materials : density (bulk density),particle size distribution and calculate the calibration curve for feeding speed.

1. Density
   To define the bulk density of the feeding material can be carried out by weighing the feeding material of certain volume and use the formula: $\rho=m/v$ to obtain the results. Same measurement need to be repeated for at least 3 times and the average value of the results would be used as the final results.
2. Particle size distribution
   After sieving, feeding materials with particle size within certain range would have been separated. To get a more accurate value for the particle size distribution, Microtac can be applied to find the particle size distribution. The operation procedure for Microtac can be found in appendix 4.

3. Calibration curve for feeder
   The calibration curve is very important for converting the feeding speed with unit of g/s to that of rpm. Controlling the feeding speed is quite important base on the fact that it influence the carbon conversion and CGE of the process significantly.
   The calibration curve can be obtained by using Microsoft Excel to model the correlation between rpm and mass flow rate.
   The following steps would help to finish the work.
   1. Fill the feeder with your feeding material, make sure it was clean before put anything inside.
   2. Start the feeder with a beaker at the exit of the feeder. Run the feeder until solids start to fall out from the exit.
   3. Set the feeder at 100rpm, 200rpm, 300rpm, 400rpm and 500rpm, collect the solids exit the feeder within 10 seconds and record the weight of each run.
   4. Enter the data into an excel file, and plot the feeding speed of g/s against rpm. Then by adding trend line and solver, a relatively accurate model can be built.

2.2.3 Chemical properties analysis

It is important to know the chemical composition of the feeding material for calculating the carbon conversion and CGE. Also, this can help to define some influential factors of the feeding material, such as moisture and ash content.

ICP-OES analysis: The full name of this analysis technique is: inductively coupled plasma-optical emission spectroscopy, which is used for the detection of ions in the solution of the samples. [5]An example of the ICP-OES analysis is attached below:

ppm	mg/kg																
	Al	Ca	Fe	Mg	Mn	PO4	Si	SO4	Cl	Na	K	Ti	Cr	Zn	Sr	Ba	B
Pure lignin black (TCI)	10.44	743.76	82.57	300.02	0.91	90.13	43.48	123361.96	158426.34	68027.79	216.05	29.83	0.52	1.29	1.48	0.8	62.13
<150 microns																	

Table 1 ICP-OES analysis result example

Contact M.M. van den Brink for the analysis.

TGA analysis: This technique can give information of how physical and chemical properties of the sample change with increased temperature. This is mainly used for defining the moisture content of the feed stock. Mr. G.A. Tsalidis can be contacted for carrying out this analysis.

Ultimate analysis: This can give information of the weight composition of each element in the feed stock sample. The analysis is done externally. Contact Mrs. M. Di Marcello for sending the samples.

2.3 Experimental Procedure

As a process where the biomass solids are destructed into gases, the plasma gasification operates at high temperature, up to 4000°C. The gas come out of the reactor is normally a mixture with hydrogen, carbon monoxide and nitro oxides inside. Due to the presence of high temperature and hazardous gases, the steps to operate the set up need to be followed strictly.

Feed stock loading

1) Disconnect the feeder from the reactor, unplugged the signal line with help of a screw driver. Make sure the orange box in the back is unlocked, for this shut down the power supply of this feeder to avoid any risk of electric shock.
2) Remove the feeder from the bottom by sliding it out carefully, and place it stably on a table.
3) Open the top lid of the feeder, remove the biomass inside. For the biomass accumulates at the bottom, remove the endless screw with help of pliers and pour out the biomass from the feeding pipe.
4) If necessary, clean the feeder with acetone. Then the feeder can be assembled and filled with your feed stock.
5) When put back the feeder, make sure the electric and signal lines are plugged correctly. Check if the o-ring on the feeding pipe, which prevents the biomass powder and gases escaping out, is properly located.

Cooling system

This water circuit is used to cool down the microwave generator as well as the reactor, both around the main tubular reactor and outside the vessel.

Open manually the cooling water valves. There are two red valves at the top left hand corner behind the setup, one for the inflow of water and the other one for the outflow. The third one is used for draining the system when the cooling system needs a cleaning, and it should be closed during operation.

Figure 12 Cooling water valves

Remember that these valves should be parallel to their pipe to be opened and perpendicular to be closed. Afterwards, turning the black round valves of the all the rotameters, make sure all the flows are between 80 and 100 l/h, the design parameter for cooling the reactor.

Figure 13 Rotameters

Gas cleaning system

This step is necessary for the gas chromatographer analyser used for analysing its composition. Check that the pump is on. It is situated in a tray inside the cabinet at the top right part.

Figure 14 Pump

Control panel

Before start the operation, the control panel need to be checked. The green light labelled “leakage test” needs to be on before operation.

The first step is to turn on the cooling bath. There is a screen under the control panel which gives information of the temperature of the cooling bath. The temperature should be -10°C, before the operation. Then switch on the feeder, lock the door and start the operation. Make sure all the lights on the right side are green.

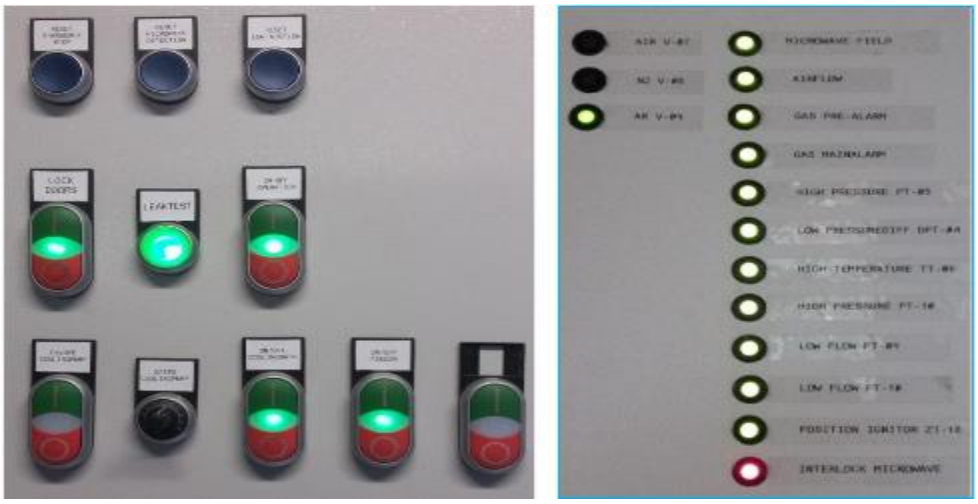

Figure 15 Control panel

Figure 16 Cooling bath control screen

Microwave

It provides the microwave energy to start the plasma, and is located in the right corner. Turn on the black switch. If it appears a Fault in the screen, that means the settings were not done completely correctly. To eliminate the Fault, manually press the rectangular red button next to the microwave generator screen till it disappears and return to the main screen with Back button.

Figure 17 Microwave control screen

This is a good moment to check visually that there are no leaks of cooling water, that the feeder is well connected to the reactor and that the gas sample valve is closed, too. It will avoid future operation problems.

Gas flare

This combustion device is used primarily for burning off flammable syngas generated in the reactor and released through the outlet gas pipe. The flare is in the back outside the building. Turn it on and ensure the flare system ignites correctly. Do not forget to turn it off after all gasification tests.

Figure 18 Gas flare & control panel

Plasma gases Valves

They are placed behind the microwave generator, which need to be opened by hand. There are three valves now for air, nitrogen and argon. The valve for argon is shut down at present, and the other two valves should be open.

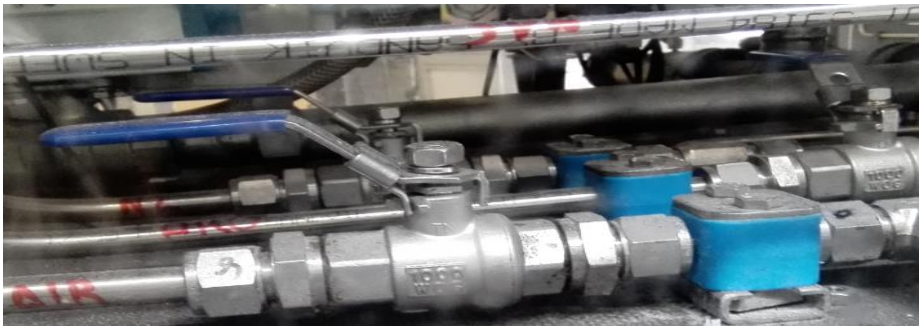

Figure 19 Gas supply valves

Computer controlling system

There are three pages in the controlling window: Control, Manual and Settings. Each page gives different information about the running state and operation settings of this setup.

- **The settings tab:** This page needs to be reviewed before the operation. It contains some important settings for the operation state.

Figure 20 Setting tab

Settings	Function	Settings
Power Settings		
MPS Max Power	The maximum power can be supplied by microwave	6000W
Netto Power SP	The limit of the power supply during operation	2200W
MPS Startpower	The power used to start the plasma	2400W
Start Gas		
StartFlow TOP	The gas is used to start the plasma	10l/min
StartFlow SWIRL	Need to be set as 0, prevent the plasma to be disturbed	0l/min
Air Flow	Pure air is used as starting gas	10l/min
Process Gas		
ProcessFlow TOP	The gas used to sustain the plasma and carry the feed stock	Base on the experimental plan
ProcessFlow SWIRL	The gas centers the plasma and protect the reactor wall	
Air Flow	The air feeding rate	
Others		
Flush Time	The time takes for the system to flush itself after operation	15s
TR-06 REF	The temperature of the reactor wall	Maximum at 500^0C
Feeder Opp Speed	The rotating speed of the feeder	Start with 0, then change

Table 2 Setting tab parameters

- **The Manual tab:** This tab is used in cased something is not working properly.

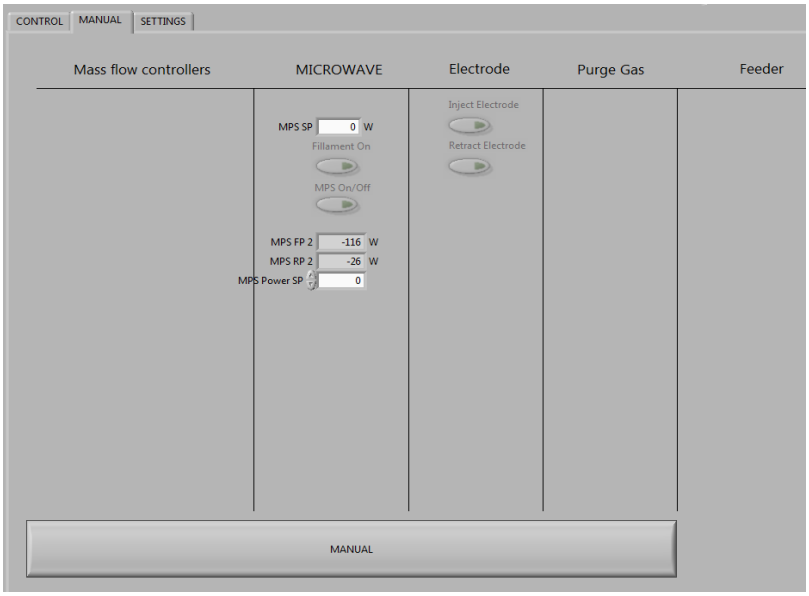

Figure 21 Manual tab

Microwave column: Manual control of the parameters that controls the microwave system.
Electrode column: Manual control of the injection/retraction of the electrode used for turning on the plasma.

- **The Control tab:** This tab gives information of the running state of this setup. Adjustment for process gas flows can be made here. There are buttons on the left where adjustments can be made. Column on the right gives information of flow, pressure and temperature. The two graphs give the information of temperature and power change during the operation time.

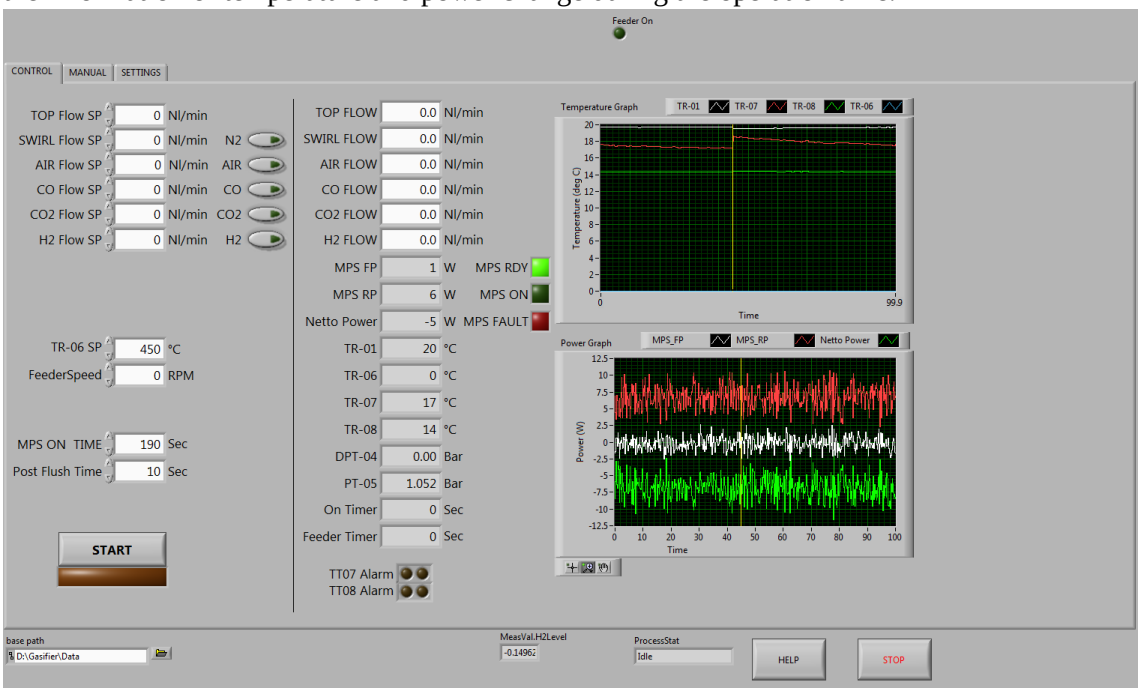

Figure 22 controlling tab

Buttons	Function

Gas valves	Open/Close the gas valves
Flow SP	The process gas flows can be adjusted here
TR-06 SP	Adjust the reactor wall temperature setting
Feeder Speed	Need to be adjusted in Setting tab
MPS ON time	The operation time of the microwave plasma

Table 3 Control tab settings

It takes some time before the plasma is stabilized after it is started. When the graphs of power and temperature start to give stable lines, adjustments can be made to process flow settings and power settings. There are several points need to be taken care of:

- **Adjustment of process flows:** Make sure only increase the total flow rate (top flow + swirl flow) instead of decreasing. Also, the air flow needs to be increase gradually with interval of 2l/min to avoid any large thermal impact. The decreased process gas flow and suddenly increased air flow would both bring the risk of melting the reactor. It is easy to understand that a smaller process gas flow requires less energy to form plasma, so the excessive microwave power might be absorbed by the reactor wall and heat it up. A suddenly increased air flow would bring the same problem because comparing with pure nitrogen, the energy requirement for plasma formation is also smaller.**[6]**

- **Adjustment of power:** When the temperature is much lower than the set point, the Netto Power SP can be increased by 200W each time, until it reaches the required temperature. The maximum power that the reactor can stand is 3000W at present.
- **Adjustment of feeding:** After the plasma is stabilized with the required gas flows, the feeder can be switched to the needed rotating speed in setting tab.

After the operation is started, samples can be taken with sample bags from the opening after the gas cleaning system. The sample bags should be able to collect enough gas for GC analysis within 5 seconds.

2.4 Analysis Method

2.4.1 GC Analysis

The offline analysis was done by a gas chromatographer with two columns (CP-molesieve 5Å and PPU-molesieve) via Tedlar sample bags. The molesive column is sensitive to carbon dioxide, so the gas would first pass by a pre-treatment column, and carbon dioxide would be held and analysed there. This machine can give a composition analysis of the gas sample. To carry out the GC analysis is relatively simple.

Procedure:

1) Open the GC analysis software, and choose “open” on the top of the screen. Choose “open method”, then, in the pop up window you can choose the needed method. Then, click the “control” button, and choose “download method”. The method loading takes around 10 min, when the three symbols at the bottom of the window become green, the analysis can be started.

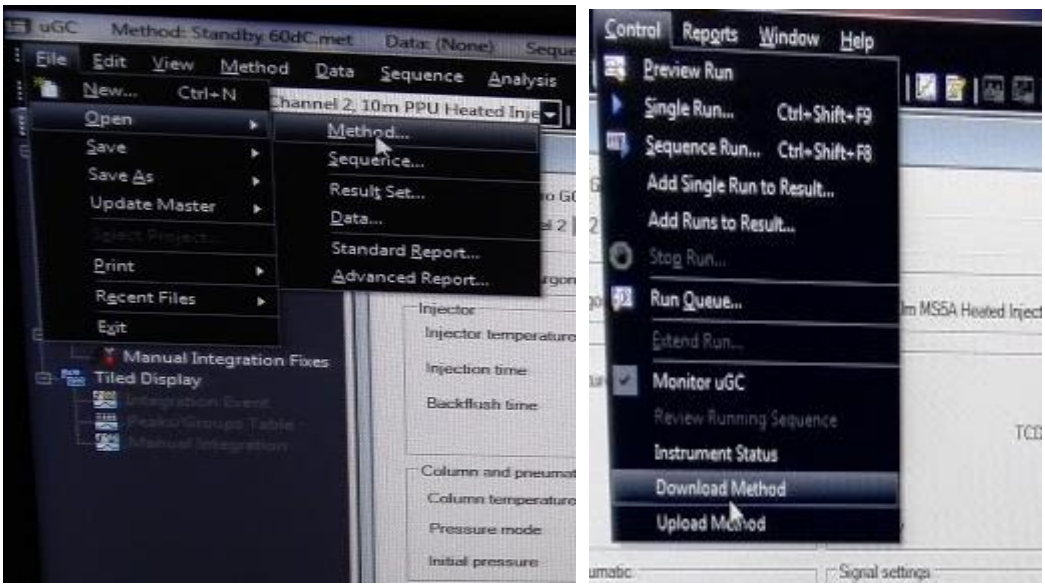

Figure 23 GC method loading

2) Open the sample bag and connect it tightly to the GC gas taking point. Make sure the gasket is correctly located before start.

Figure 24 GC sample taking point

Figure 25 Sample bag

3) Click the "control" button, and choose "single run". Then in the window shows up, the name of the file can be typed in.
4) The sample taking and analysis takes between 3 and 5 minutes. Then two graphs with peaks indicate different gases will be given. After the running is finished, go to the left column, click on "report", a report of gas composition will show up, and can be saved as PDF file by clicking on the printing button.

2.4.2 Data Analysis

The collected data include the gas composition results given by GC and power use from the gasifier logbook. These data were normalized and used for calculating the carbon conversion and cold gas efficiency. The data from the same group of experiments are plotted to give a clear idea of the changing trend of the results for different factors.

Calculations

Data normalizing: As the GC gives gas composition in estimated concentration; the sum of all gas composition is not accurately 100%. So the normalization needs to be conducted by:

$$\text{Normalized number for X} = \frac{Result\ from\ GC\ for\ X}{\sum Ressult\ from\ GC}$$

Carbon conversion (CC %): With help of analysis results for the feed stock, we can know the carbon concentration in the feeding material. Then the input of carbon can be get:

$$\text{Carbon input} = \text{Carbon concentration} \times \text{Feeding rate} \times \text{Operating time}$$

It is roughly assumed that the amount of nitrogen is the same for input and output, so the amount of each gas output can be figured out:

$$\text{Gas X output} = \frac{N_2\ output}{N_2\ concentration} \times X\ Concentration\ in\ output$$

Methane, carbon monoxide and carbon dioxide all contains carbon, so the total output of carbon can be found. Then the carbon conversion is simply obtained:

$$\text{CC\%} = \frac{Total\ carbon\ input}{Total\ carbon\ output} \times 100\%$$

Cold gas efficiency (CGE%):this parameter is an important reference for the operation efficiency. This can be calculated by dividing the total low heating value (LHV) of the produced fuel gas with the total heat input. In our case, the produced fuel gases are hydrogen, carbon monoxide and methane. The total heat input includes the low heating value of the feeding and power supplied by microwave. [7]

$$CGE\% = \frac{m_{fuel\ gas} \times LHV_{Fuelgas}}{m_{feeding} \times LHV_{feeding} + Netto\ Power}$$

---m refers to mass flow

Chapter 3 Result

3.1 Research pathway

This project selected the gas feeding settings as the main study aspect which would influence the gasification result. So experiments with verified gas feeding conditions were planned.

To make sure the experimental settings would be within the capacity of the setup and obtain some comparable results. A base case should be selected based on results of experiments that have been carried out with this certain setup.

This time, the base case was chosen from experiments carried out by A. Chandrasekar. [8]The settings can be seen in the table below:

Feed	0,13g
Top flow	5lmin
Swirl Flow	30l/min
Air flow	10/min
Temperature	500˚C

Table 4 Base case settings

After defining the base case, series of experiments can be planned. According to the researching purpose, find the settings which are manipulatable within this factor and design at least five experiments for each changing setting; at the same time, keep other influencing factors the same. In this case, the feeding gas condition was studied, so the settings of top/swirl flow rate and air/nitrogen flow rate were verified. The total gas feeding was kept constant, only the ratio of top/swirl flow rate and that of air/nitrogen feeding rate were changed.

In experimental trials, it is important to be careful with the limit of parameter changing. As happened in this experimental section, when the top/swirl flow ratio was set at 0.75 the reactor got melted after running for 6 minutes. This indicates that a too high top flow ratio might lead to higher chance of contact between the plasma and reactor pipe, which is dangerous, for the temperature of plasma is much higher than what the reactor pipe can stand. In order to prevent this kind of situation, it is important to give a close look at the temperature graph on the control tab, when a sudden large temperature growth is observed, shut the system immediately. This can also be noticed when the watching windows on the reactor gives a super bright white light.

3.2 Possible Problems & Solutions

Since the setup in not optimized yet, a bunch of problems may show up during the operation. For each problem there could be multiple reasons. When the problems are defined, solutions can be found accordingly as well.

- **Pressure building up**: before starting the operation, a top process flow of 20l/min need to be fed to the system, and the pressure increase should not be higher than 50mbar. If the over pressure is much higher than this, several steps can be taken to find and solve the problem.
    1) Check if the valve behind the sampling point is open, if not, open it till it's parallel to the pipe and try again.
    2) If the valve is open and the problem is still not solved, that means the system requires a cleaning. The cleaning steps can be found in the appendix 2.
- **Sampling problem**: Mostly two types of problem can happen to the sampling step: inadequate sampling and impure sampling. Normally takes 4 or 5 seconds. Within this time, an obvious increase in volume of the sample bag should be observed. If a clear gasification can be observed in the watching window, but the sample analysis only gives result of pure air or very diluted product gas, that means the sample is mixed with air. These problems can be caused by a leakage or blockage in the system. The instruction below will explain how to locate the problem and solve it.
    1) If clear noise of gas leakage is heard, the leaking point can be found by leakage tracer. Just apply some leakage tracer onto the connection joints, and run an air flow of 5l/min in the system. If big bubbles are seen, that means a leakage exists.
    2) A pressure meter can be used to locate the blockage point and check joints where leakage tracer cannot be applied. To use it, the system needs to be partially resembled and connects to the pressure meter. Then apply a process air flow of 20l/min, a fast pressure build up need to be observed, otherwise a blockage or leakage spot can be located before the connecting point. After the flow is shut, if the pressure drops, that means a leakage point is found before the connecting point.
- **Plasma maintaining problem:** Plasma gasification is a delicate process which needs lots of attention to be maintained and stabilized. When the plasma cannot be maintained or even started, several things needs to be taken care of:

1) If the microwave generator gives a signal of FAULT, recheck everything, and try to reset the microwave. Before the microwave is started, all the lights on the control panel need to be green.
2) Open the reactor from the top and check if it needs to be cleaned. Too much particles and tar on the reactor wall would absorb the microwave power which weakens the plasma and heat up the reactor wall. When there is not enough power supplied to the plasma or the pipe is over heated, the plasma cannot be maintained or started.
3) Look at the temperature and power graphs, if large sudden changes appear, that could be from the sudden changes in gas feeding or power settings. A suddenly increased swirl flow might disturb the plasma and the instability would stop the process; if the top flow is increased quickly without adjusting the power limit higher, the plasma would also fail; in case of adequate power supply, a sudden increase in top flow and air flow might also bring the problem of the sudden temperature change which would give alarm to the system to stop the plasma.
4) Since the plasma gasification is operated at very high temperature, the reactor can be easily damaged. So when the plasma cannot be started, a carefully check need to be given to the reactor with a torch. If the reactor pipe is melted, the replacing procedure can be found in the appendix 3.

- **Analysis problem:** The GC columns applied are very sensitive to moisture, so after being used for some time the result given by GC would be inaccurate. This can be recognized when a shift of peaks in the graphs are observed. To solve this problem, two methods can be taken:
    1) Open the method named as "conditioning" and let it stand for 10h or longer. This will heat the columns up to 180°C, then, the pollution can be burnt and evaporated.
    2) Recalibrate the column with calibration gas. The supervisor (G.S.J.Sturm) and technician need to be contacted to finish this step.

A summarised table for problem shooting and solution is listed in Appendix 5.

3.3 Experimental results

Three groups of experiments were carried out with different purposes:

I. Cellulose (Sigma-Aldrich) gasification tests to define the influence of TOP/SWIRL flow. The setup was running at 475^{0}C. The results and TOP/SWIRL flow settings are shown in the table below:

Cellulose	**Particle size 50µm**								
top flow l/min	Swirl flow l/min	Top/Swirl	H_2 %	CH_4%	CO%	CO_2%	feed g/s	CC%	CGE%
5	30	0,166667	2,939	0	4,303	3,822	0,13	41	12
7,5	27,5	0,272727	3,083	0	4,431	3,346	0,13	39	10
10	25	0,4	2,451	0,01	3,747	3,862	0,13	40	12
12	23	0,521739	2,865	0	4,394	3,689	0,13	42	12
15	20	0,75	3,055	0,01	4,592	4,27	0,13	47	12

Table 5 Cellulose gasification test result with verified Top/Swirl flow

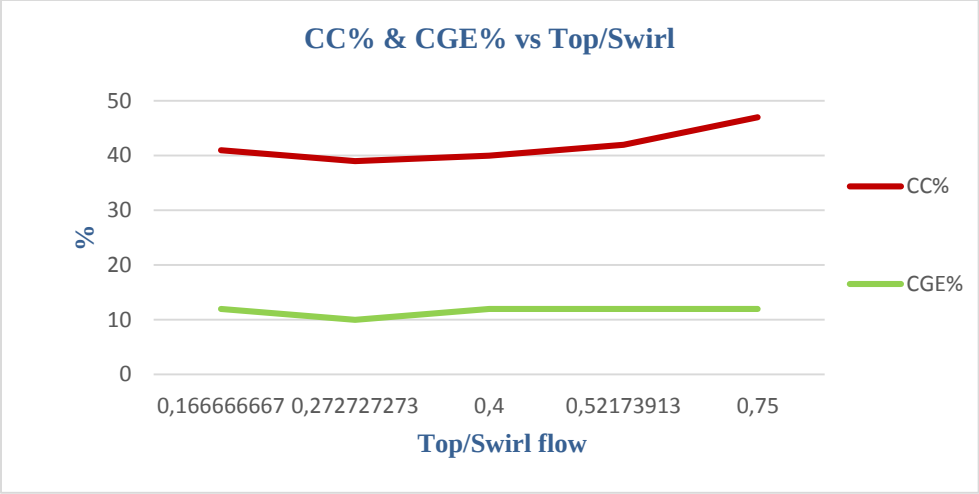

Figure 26 Carbon conversion & Cold gas efficiency vs Top/Swirl flow

From the table we can see that when top flow increases the carbon conversion increases obviously while the cold gas efficiency does not seem to be influenced significantly. This phenomenon can prove our assumption that: the larger top/swirl flow ratio can bring a better contact between the particles and the plasma which makes the gasification more effective. Which has been confirmed by experiments carried out by another research group.[9]However, with this specific setup we could not increase the top flow ratio anymore for after running the setup at the top/swirl flow ratio at 0.75, the reactor was melted. So in order to have good carbon conversion and avoid the reactor melting problem, we selected 10 l/min as top flow and 25 as swirl flow for the air ratio study experiments.

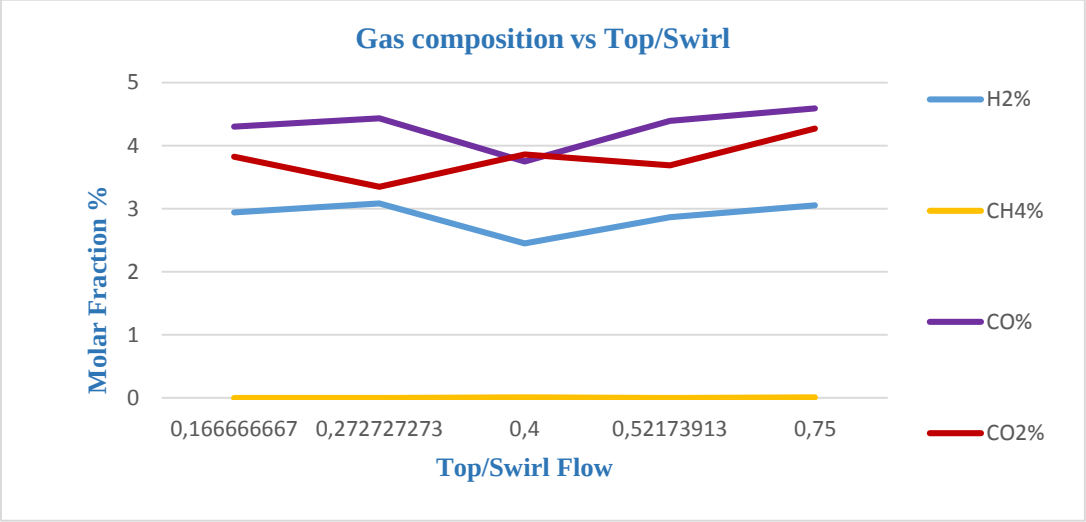

Figure 27 Product gas composition vs Top/Swirl flow

The gas composition changing graph hardly gives any clear trend. The very low concentration of syngas in the final product could bring much inaccuracy to the analysis step, also limited experimental data might still be inadequate for defining the gas composition changing rate. This requires further study by comparing more experimental results.

II. Cellulose gasification tests to define the influence of Air/N_2 flow. The setup was running at 475^{0}C. The feeding rate was 0.13g/min. The results and TOP/SWIRL flow settings are shown in the table below:

Cellulose	Particle size 50 µm								
top l/min	swirl l/min	O_2/N_2	air l/min	H_2%	CH_4%	CO%	CO_2%	CC%	CGE %
10	25	0,05422	6	3,17	0,395	5,692	2,24	43	16
10	25	0,07362	8	2,594	0,103	4,689	3,461	42	12
10	25	0,09375	10	2,451	0,008	3,747	3,862	40	12
10	25	0,11465	12	0,984	0,037	2,629	5,605	42	6
10	25	0,13636	14	1,119	0,074	2,737	6,489	47	7

Table 6 Cellulose gasification test result with verified O_2/N_2 flow

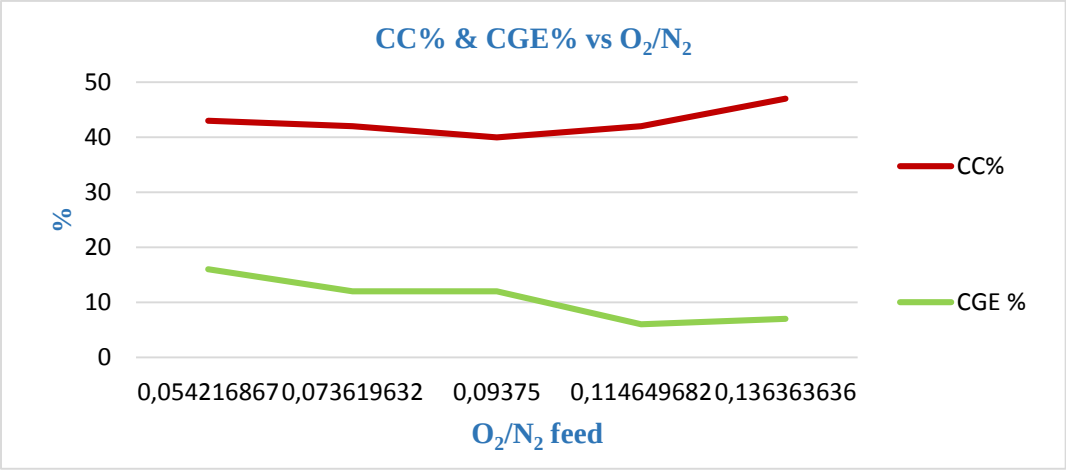

Figure 28 Carbon conversion & Cold gas efficiency vs O_2/N_2 flow

From the results we can see that increasing amount of oxygen in the feeding helps converts more carbon but would lower down the cold gas efficiency. So base on different purposes the amount of oxygen in the feeding gas can be adjusted.

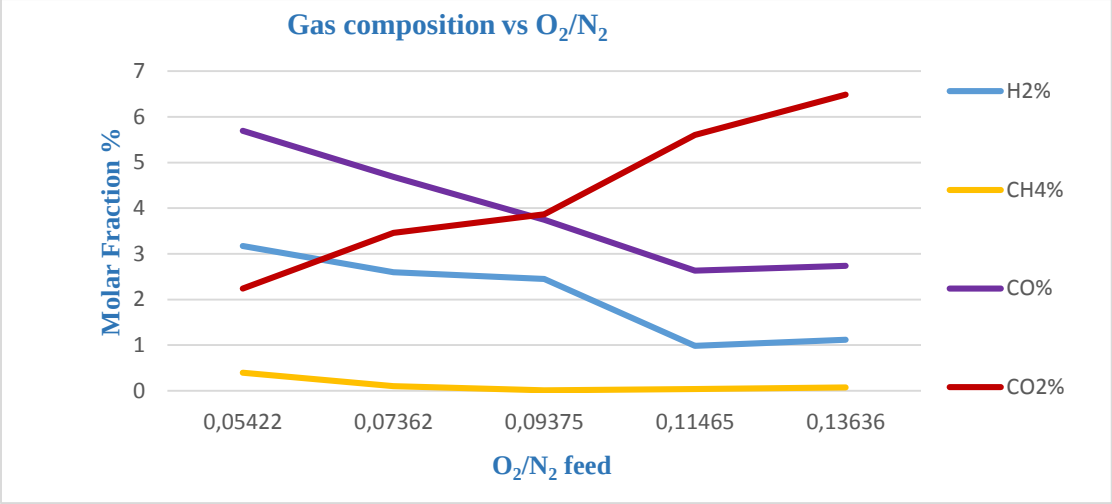

Figure 29 Product gas composition vs O_2/N_2 flow

In this graph, an obvious growth of carbon dioxide concentration is observed when the oxygen feeding is increased. Meanwhile, the syngas concentration and methane amount drops with

growing oxygen feeding. Combustion of fuel gases with excessive oxygen in the process flow could be an explanation for this result.[10]

III. Pure lignin gasification experiment was done to compare the influence of different feed stock. This feeding material was bought from TCI. This is a black coloured fine powder with typical particle size of 74μm. Experimental settings and results are attached below:

Feed	0,13g
Top flow	5lmin
Swirl Flow	30l/min
Air flow	10/min
Temperature	475˚C
H2%	1,06
CO%	2,58
CO2%	3,12
CH4%	0,22
Carbon conversion	0,33
Cold gas efficiency	0,09

Table 7 Pure lignin gasification results

Compared with the result of same experiment done with cellulose, the gasifier used less power (1.7kw) to reach the set temperature and both the carbon conversion and cold gas efficiency are lower than those of cellulose. This result was out of expectation, the carbon conversion at least is expected to be higher than cellulose, because of its darker colour and smaller particle size, the absorption of optical radiation and contact with plasma should be enhanced. However, there is also a reasonable explanation for this result. The finer powder is easier to be pushed by swirl flow and adhesive on the reactor wall, at the same time, the darker colour helps it to absorb a lot of optical radiation, so the reactor wall is heated up quickly and the temperature signal sent to the controller of the microwave would lead to a reduction in power supply from the microwave. As the result, the plasma gets less power and its intensity is weakened which lead to a less effective gasification process.

Chapter 4 Discussion & Recommendation

The system, as stated already, operates unstably and with plenty of problems. The instability is mostly observed after feeding in the bio-mass. The feed stock particles would bring changes to the temperature significantly, as they will absorb the microwave energy, undergo the phase change and chemical reactions, these all cause complex energy changes in the reactor. The instable temperature signal then leads to an instable power supply from the microwave generator, and it would switch off the system when any large temperature shooting up is detected. The experimental results from the gasification tests till now all give low value in carbon conversion and cold gas efficiency. While according to the previous researches on this topic, the expected value should be much higher. [11] Reactor pollution and bad contact between the feed stock and plasma are mainly responsible for this.

According to the results of the experiments, it is recommended that the application of the product gas from the process need to be specified before optimize the process. When the main purpose is to destruct the waste, more oxygen can be introduced to the system to bring a higher conversion, though it leads to

lower cold gas efficiency and larger emission of the carbon dioxide. While a higher energy recovery is wanted, the oxygen feeding need to be reduced to increase the methane concentration in the product gas.

Chapter 5 Conclusion

Supported by the experiments carried out during the research and related literature study, main conclusions can be drawn.

The plasma gasification is not a stable process yet, because the plasma is so delicate that can be intensively influence by many factors. Thermal impact, flow disturbance and reactor pollution can all lead to a failure in plasma functioning. So an operation procedure was carefully described with safety notifications and setting suggestions to bring a relatively stable process.

According to the observations and theoretical knowledge about the setup, problems that might happen during the experiment are listed and accordingly guideline was given for problem shooting and solving.

The experimental results data analysis has implied that when other factors are kept constant, higher the top flow ratio is, higher carbon conversion can be obtained while no obvious changing trend was found for gas composition change and cold gas efficiency change. On the other hand, more oxygen in the feeding gas would give a higher carbon conversion and lower cold gas efficiency. Also outcome gas with higher carbon dioxide concentration and lower syngas concentration would be produced.

In order to optimize the process of plasma gasification with this certain setup by settings adjustment, the application need to be specified to clarify what would be the wanted result. Due to the fact that the carbon conversion and cold gas efficiency change oppositely against the oxygen feeding ratio , a compromise need to be made when conducting plasma gasification with bio-waste for energy recovery.

Appendix

See attached file

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