

**Waste to Energy (WTE):
Conventional and Plasma-assisted Gasification
Experimental and Modeling Studies**

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

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Waterloo, ON, Canada

Abstract

Ever-increasing amounts of industrial and residential wastes and their environmental footprint dictates the need for effective Waste Management practices. Thermal waste processing technologies play an important role in energy recovery from the waste. Conventional and more importantly Plasma-assisted Gasification, an advanced thermal processing technology, have been introduced as promising and environmentally benign ways for energy utilization from biomass and municipal solid waste (MSW).

This work aims to study the thermal technologies, which result in production of synthesis gas that is useful for heat and power generation; therefore, conventional and plasma-assisted gasification of biomass/MSW are reviewed. In addition, various economic, environmental and policy-related issues are examined in this study.

From the experimental and modeling perspective, this study also reports on the work conducted to characterize the gasification process using a gasification reactor called Gasifier Experimenters Kit (GEK) level IV. Both the syngas quality and quantity have been investigated based on a variety of feedstock, such as wood charcoal, poplar and tamarack wood chips. Moreover, the composition of the gas has been analyzed using a Gas Chromatography (GC) unit and the exact concentrations of carbon monoxide, hydrogen, methane and nitrogen were measured. In this study, a thermochemical model based on the experimental setup (GEK IV) has also been developed in the AspenPlus[®] environment, an established simulation tool in chemical engineering and the energy industry. This model is capable of predicting the syngas composition, the energy required for the gasification reactions. A comparative analysis involving the experimental and simulation results is presented in this study.

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Dedication

To my parents, Hossein and Zahra for their endless love and continued support throughout my life

To my sister and my brother-in-law, Leila and Ehsan for their love and encouragement

To my younger brother, Fazel for being the best bro ever!

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CHAPTER 1

Introduction to Waste-to-Energy (WTE)

This chapter aims to provide background knowledge regarding biomass and Municipal Solid Waste (MSW). Further in this chapter, some fundamental concepts in Waste to Energy (WTE) sector are introduced. At the end of this chapter, objectives of this work are presented.

1 Introduction to Waste-to-Energy (WTE)

Waste to Energy (WTE) technologies use waste to make fuel-like products that could be utilized to produce energy, preferably heat and electricity. The waste or more specifically *Municipal Solid Waste (MSW)* refers to residential waste, construction debris, agricultural, industrial and commercial wastes [1]. In fact, it is possible to produce energy from the waste that has been processed and has converted to fuel in solid form; or from the waste material that has been turned into gaseous fuel, such as syngas; or alternatively, from heat and steam that result from the incineration of the waste. In general, waste-to-energy (WTE) processes have various options for electricity, combined heat and power (CHP) and liquid fuel production. For instance, one is to produce fuels that are rich in methane (CH_4) and carbon dioxide (CO_2), called *biogas*; or produce *syngas* (largely H_2 and CO), which can be used to produce liquid biofuels (ethanol and biodiesel), pure hydrogen and even water, in addition to electricity [4, 5]. *Thermal processes, biological or biochemical processes* and finally *chemical processes* are in fact, the main branches in WTE industry. Waste-to-energy (WTE) in fact, refers to any type of waste processing methods that produces energy from a waste material that otherwise, should have been handled in the landfilling process. Some WTE technologies result in production of usable fuels. In practice, Waste-to-Energy means the use of modern thermal technologies mainly for the purpose of energy recovery, usually in the form of electricity and heat, from variety of sources. These methods can significantly reduce the volume of the waste material - depending on the composition of the input and the desired output - if they are fully commercialized in a particular region. Apart from the nature of the output product (whether it is power, heat or fuel), specific emissions standards must be met by these thermal processes [4].

In this study, the focus will be on the “thermal processes”, mainly on *Conventional Gasification* and its possible extension to the *Plasma-assisted or Plasma Gasification*. Shortly in this chapter, the meaning of WTE is examined and more importantly, the most common thermal processes used for Municipal Solid Waste (MSW) are introduced. Other aspects, such as the technical, economic, environmental, experimental/modeling and policy-related issues will be discussed in the following chapters. The future development and the project conclusions are presented at the end.

1.1 Renewability of Waste-to-Energy (WTE)

The answer depends on the nature and also composition of the waste being fed to the process. In fact, the United States government and some others around the world consider modern WTE processes to be partially a source of renewable energy. In order to determine whether the WTE being utilized in a particular location is considered renewable, a measurement of the biological percentage of the feedstock is needed. In other words, we have to measure the amount of food scraps, paper, fabric, wood, leather (and even some products coming from fossil fuels, such as plastics) in the feedstock to see if the process qualifies for being renewable [4].

In order to further investigate the renewability of the MSW, some experts claim that only the part coming from the living organisms (i.e. biogenic) can be considered as a renewable source. The rationale behind this argument simply comes from the fact that the materials originated from non-biogenic waste are made by fossil fuel resources and are not renewable. Others however, believe that the entire category is renewable, simply because the alternative, i.e. disposal of a large portion of the MSW in the landfills, is actually more environmentally disturbing and except methane extraction, does not give back energy that could be put into any useful process [4, 5].

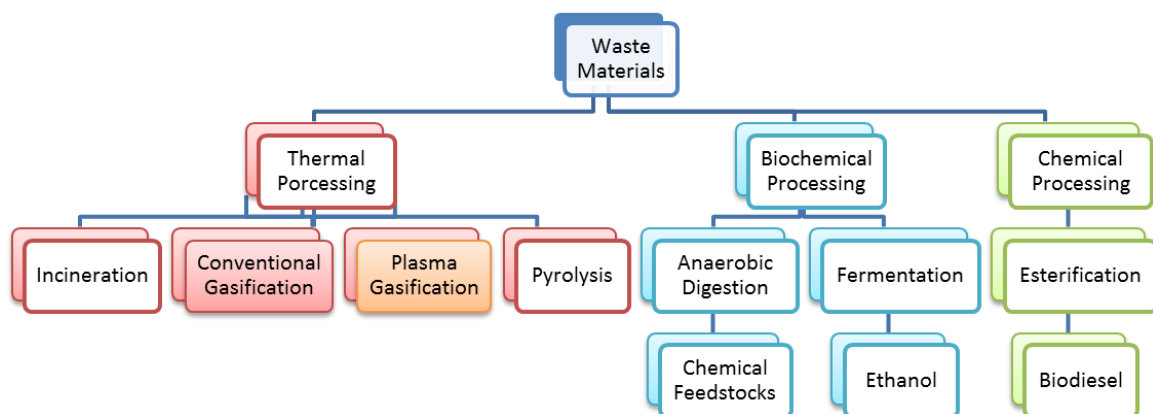


Figure 1: The Map of waste management processes. Data from [6]

As shown in Figure 1, WTE projects in the modern world can be classified as thermal, biochemical/biological or chemical processes. Biochemical or Biological processes are divided into *Anaerobic Digestion*, which leads to production of *chemical feedstock* and *Fermentation*, which results in production of *Ethanol*. Chemical Processing further becomes *Esterification* and that finally gives *biodiesel* [6].

1.2 Sources of Waste-to-Energy (WTE)

In this section, the main sources utilized in the waste to energy technologies will be introduced [7]:

1.2.1 Biomass

“Biomass”, is a category of materials with one important element in common: they are all originated from recently living organisms. Therefore, biomass totally differs from fossil fuels, as the latter requires millions of years to be made, although they are derived from somewhat the same sources, e.g. plants and animal wastes. In today’s global energy market, biomass is not a major fuel for industries; however, still accounts for 15 to 20% of total fuel used worldwide. This issue clearly indicates the significance of energy use in non-industrial and developing economies, which still use biomass as their main energy source. The biomass varieties are briefly explained here:

1.2.1.1 Vegetable biomass

Some data regarding this type of biomass is shown in Table 1. High Heating Values (HHV), Moisture content, Ash, Sulfur and Chlorine content of various sources of biomass, derived from vegetables are available here.

Table 1: Sample of the properties of biomass from vegetable sources. Data from [7]

Biomass	HHV (MJ/Kg)	Moisture (wt. %)	Ash (wt. %)	Sulfur (wt.% dry)	Chlorine (wt.% dry)
Charcoal	25 to ~ 30	1 to 10	0.5 to ~ 6	–	–
Wood	10 to 20	10 to 60	0.2 to ~ 1.7	~ 0.01	~ 0.01
Straw	~15 to 16	10	4 to 5	~ 0.07	~ 0.5
Sawdust	11	35	2	–	–

1.2.1.2 Animal waste

In the literature, the term biomass is mostly used for vegetable biomass; however, animal-derived waste is a type of source that cannot be disregarded. It is worth mentioning that the waste production by poultry is approximately 8 kilograms (kg) per head per year. This number for swine, beef cattle and dairy cattle is 300 kg, 900 to 1200 kg and 1200 to 2000 kg, per year per head, respectively. In the Shell Coal Gasification Process (SCGP) plant in the Netherlands, animal waste has been mixed with coal up to 12% for the gasification process and it has been planned to go up to 30% [7]. Properties of the animal waste vary from type to type. In fact, the literature reports that the poultry litter for instance, has the Higher Heating Value (HHV) of 13 to 14 (MJ/kg), with Moisture content of 63 (wt. %), Volatiles of 25 (wt. %) and finally 20 wt. % Ash [7].

1.2.2 Municipal Solid Waste (MSW)

Municipal Solid Waste (MSW) in fact can be defined as the waste output from households and some other industrial sectors that contain product packaging, clothes, food left overs and some unconventional wastes (e.g. appliances) in some cases. MSW does not include wastes of other types, such as automobile scraps, municipal sludge, ash resulting from combustion and also some industrial wastes that might be disposed in landfilling. The main specification of MSW is that it should originate from either residential, commercial, institutional, or some specific industrial processes [8].

1.2.2.1 Municipal solid waste (MSW) properties

In order to design an applicable process for the waste management and its economic evaluation, access to MSW properties is crucial and can affect the big picture of the waste management practices. Literature suggests that the Low Heating Value (LHV) of the MSW could be as low as 10 MJ per kg; however, evaluating these types of data, is believed to be sensitive to the location and to the local regulations for sorting and recycling of the waste. It is reported that the MSW mainly consists of carbon (with 35.5 wt. %), oxygen (with ~25 wt. %) and moisture (with 26.5 wt. %). Concentration of hydrogen is around 5% and ash accounts for accounts for about 7.5% [9].

1.2.2.2 MSW production in North America

In the United States for example, the production rate of the MSW, which is the waste generation per capita, has remained relatively constant since 2000. Moreover, the disposal rate per capita that is the trash disposed in the landfills after all the other processes (recycling, energy recovery etc.) per person in that country has remained constant at the rate of 1.13 kg per day since 1960. This is to say that the total rise in generation of waste has been managed by methods other than landfilling [9]. While the MSW management industry claims to have strategic plans in developed countries, the total amount of waste produced worldwide is believed to grow further on, due to population growth and economic prosperity in several parts of the world, especially in China, India and Brazil.

In the United States, production of the MSW has been on the rise over the years and has reached to around 254 million tons in 2007. In that year, more than 63 million tons were sent to recycling, almost 22 million tons were directed for composting and around 32 million tons were incinerated for energy recovery purposes. Hence, the remainder (137 million tons or 54% of total MSW) was disposed in the landfills. As urban areas grow and become more populated, concerns regarding landfill disposal and lack of space rise as well.

In Canada, approximately 30.4 million tons of waste was produced in 2002. In this year, solid waste production per capita reached to 971 kg per person. Moreover, Canadian households produced 12 million tons of waste, which accounted for about 39% of the total waste generation in 2002; or 383 kg per capita, which is about 4.9% more compared to the rate in 2000. The rest of the solid waste came from industrial, commercial and institutional waste producers, as well as construction, renovation and demolition projects. In addition, the provinces of Ontario and Quebec generated about 65% of the residential waste in Canada in 2002. Figure 2 illustrates the composition of the solid waste by weight generated by the Canadian households in 2002. As shown, organics accounted for 40%, paper 26%, plastics 9%, metal 4% and finally glass 3% of the solid waste created by residential sector. Statistics Canada reports that the remaining 18% (other) includes materials, such as animal waste, textile products, tires and wood [12].

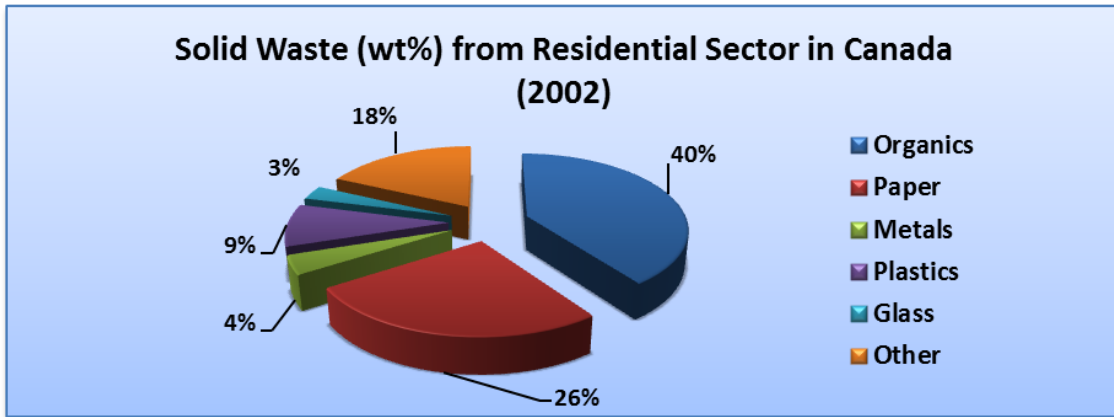


Figure 2: Composition of residential waste in Canada in 2002. Data from [12]

In 2006, Environment Canada reported that 37% of the solid waste originated from residential sector (39% in 2002) and 12% produced by the construction, demolition and renovation sector; however, the majority of the solid waste produced in Canada (51%) came from neither of the sectors mentioned [13]. It is worth mentioning that the total solid waste created in 2002 was 39% and by comparing this value with that of 2006 in Canada, we realize that there is a decrease of 2% (from 39% in 2002 to 37% in 2006) in Canada. In region of Waterloo and Cambridge in the province of Ontario, the total landfill tonnage from 1988 to 2010 has been plotted and it is shown in the figure below.

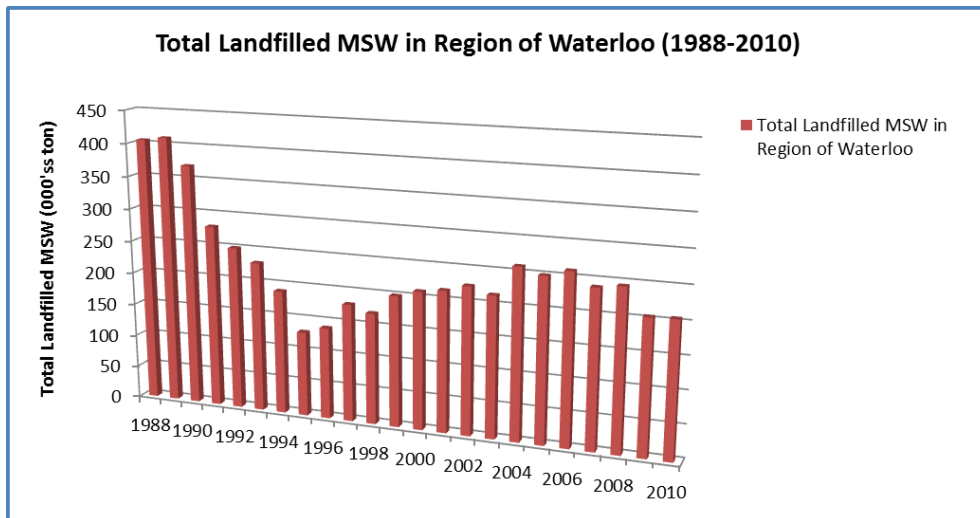


Figure 3: Total landfilled MSW in the region of Waterloo from 1988 to 2010. Data from [14]

As Figure 3 presents, there is a sharp decline in production of the municipal solid waste in the region in 1995. In that year, new programs for recycling and composting were implemented and therefore, reduced the amount of solid waste going into the landfills. In fact in 1995, 22,000 tons of the MSW were recycled and another 8,400 tons were composted. The increase from 1995 to 2006 is believed to be related to the growth in the population and economy of the region [14]. As we have learned about the waste material, in chapter 2 the focus will be on the thermal processes of the WTE technologies.

1.3 Research Objectives

This work aims to study the conventional and plasma-assisted gasification of biomass/MSW. In terms of objectives, this work focuses on the literature review on the technical, economic and environmental aspects of these thermal processes, while research contribution is done in the area of experimental, modeling and policy-related studies, presented in chapters 4, 5 and 6 of this paper, respectively.

From the experimental and modeling perspective, this study reports on the work conducted to characterize the gasification process using a gasification reactor called Gasifier Experimenters Kit (GEK) level IV. Both the syngas quality and quantity have been investigated based on sugar maple wood charcoal, poplar and tamarack wood chips, as the feedstock. Moreover, the composition of the gas has been analyzed using a Gas Chromatography (GC) unit and the exact concentrations of carbon monoxide, hydrogen, methane and nitrogen were measured. In this study, a thermochemical model based on the experimental setup (GEK IV) has also been developed in the AspenPlus[®] environment. This model is capable of predicting the syngas composition and the energy required for the gasification reactions. A comparative analysis along with a sensitivity analysis is presented in this study, as well.

Ultimately, the conventional and plasma-assisted gasification technologies are investigated from the strategic point of view. In this part, some significant drivers, barriers and other policy related issues are examined and the author's recommendations for the promotion of this industry are presented.

CHAPTER 2

Literature Review of the Technical Aspects of WTE

The objective of this chapter is to briefly explain the technical aspects of the Waste to Energy (WTE) thermal processing technologies. Here, the focus is mainly on the conventional and the plasma-assisted gasification processes.

2 Literature Review of the Technical Aspects of WTE

Thermal processing of the Municipal Solid Waste (MSW) could potentially produce heat or a number of liquid or gaseous fuels that have the potential to be converted to electricity. Four different technologies are introduced here, that are

- Mass burn, direct combustion or incineration of the MSW
- Pyrolysis of the MSW
- Conventional Gasification of the MSW, and
- Plasma-assisted Gasification of the MSW.

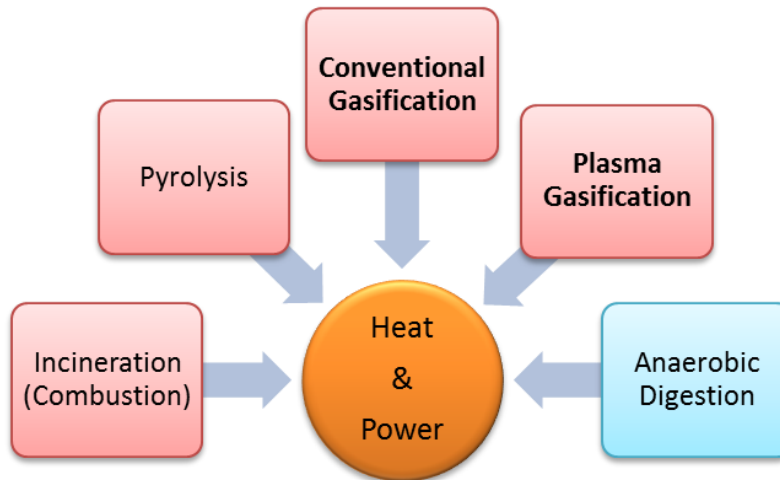


Figure 4: Ways to get heat and power as the output from MSW

The figure above illustrates the common energy recovery technologies in the waste management industry. In other words, there are mainly five common approaches to produce heat and / or power from the MSW, in which, four out of five are in the thermal processing category and one (Anaerobic Digestion) is from biochemical/biological category.

2.1 Direct Combustion or Incineration

One of the reasons that the incineration or direct combustion of the MSW has been around is because it requires minimal processing of the MSW. The heat from this process is therefore, used to produce steam from water to run a steam turbine to eventually produce electricity. In the waste management or energy recovery context, the term “incineration” refers to the burning of waste without recovery of materials. The most important challenge facing this technology is the amount of emissions to the atmosphere. New incinerators currently utilize pollution control systems for air, although ash or other pollutants trapped in this method should still be disposed to the atmosphere. There are several other emerging combustion technologies that are capable of extracting energy from the waste with controlled amount of emissions. These advanced technologies are expected to be more publicly acceptable than the conventional incineration processes [4,15].

2.2 Pyrolysis

Pyrolysis is known to be the chemical decomposition of organic materials in an oxygen-free environment to break down the bonds in the material. This process mainly results in the production of a gaseous mixture, rich in CH_4 (methane), H_2 (hydrogen) and CO (carbon monoxide), which produces some tars and solids as well. The gas produced here can be directly fed into the boilers to provide heat. In fact, incineration converts the waste into useful energy; however pyrolysis produces fuel that can be transported from one location to another [4,15].

2.3 Conventional or Thermal Gasification

In conventional gasification an oxygen or air-starved environment is created, so that the carbon in the material, such as the MSW is converted into synthesis gas or syngas. The operating temperatures are reported to be between 750°C and 1200°C. In order to enhance the performance of the gasifier, steam is injected into it. The primary result of the gasification is the production of a fuel, rich in carbon monoxide and hydrogen [15]. Gasification is not a new technology and has been used since the 18th century. Some historical developments of this process are highlighted here.

2.3.1 History of Gasification

The first fuel that has been used by mankind is wood and still is in use throughout the world for cooking and heating purposes. Moreover, wood in the form of charcoal and coal, has been widely used in the industry and has played a significant role in the industrial revolution.

In 1812, *London Gas Light and Coke Company* was established and that was the beginning of the commercialization of the gasification, where town gas was the direct outcome of this process. At the beginning, this production was expensive and therefore, it was mainly used for lighting and cooking. It was then in the beginning of the 20th century that the gas became the primary source for space heating. The most important limitation of the town gas was its low heating value and that made the transportation of the town costly [16].

From 1900 onwards, gasification became a source of lighting and heating, and produced almost equal amount of hydrogen and carbon monoxide; thus, became important for the chemical industries. There were many gasification-engine units for power generation purposes [16].

In 1930s Nazi Germany started to use gasification for vehicles as part of their national security road map to significantly reduce their dependency to the imported foreign oil. British and French at same time came to the conclusion that vehicles powered with producer gas is more beneficial for the regions that have limited access to gasoline but, easy access to plenty of wood. In Sweden, 90% of the vehicles were converted to charcoal gas producer compatible. 20,000 tractors were also operating using producer gas, where approximately 40% of the fuel came from wood and the rest from charcoal [16].

In fact, when World War II ended in 1945, diesel and gasoline were readily available at a reasonable price and therefore, gasification was not the favorite technology any more. From 1950 to 1970, gasification could be referred to as the “Forgotten Technology” and many governments felt that this technology will damage the forests and will cause various environmental problems [16].



Figure 5: Vehicles with a gasifier during the second world war [16]

After 1970, power generation at small scale seemed promising and thus, this technology gained some considerable attention again. Since then, this field is expanding and use of other fuels other than wood and charcoal is being researched [16].

2.3.2 Today's Status of Gasification

One of the major events in the history of gasification is in 1973, when the Organization of Petroleum Exporting Countries (OPEC) sanctioned the U.S. and some of its allies, which were dependent on oil from the Middle East. This issue resulted in somewhat a sudden comeback to processes, such as gasification to reduce the negative impacts of the oil embargo. Moreover, some countries decided to support the idea of building the *Integrated Gasification Combined Cycle (IGCC)* plants, which positively contributed to the expansion of the technology [16]. Since 2001 issues such as, climate change, unrest in some oil-producing countries and thus instability in oil prices, have justified further development of gasification technology. Renewable sources of energy are widely promoted throughout the world and there is a momentum for using less of fossil fuels, which in fact paves the way for technologies such as gasification to play a more important role in today's energy market [16].

Figure 6, summarizes the key events in the history of gasification technology.

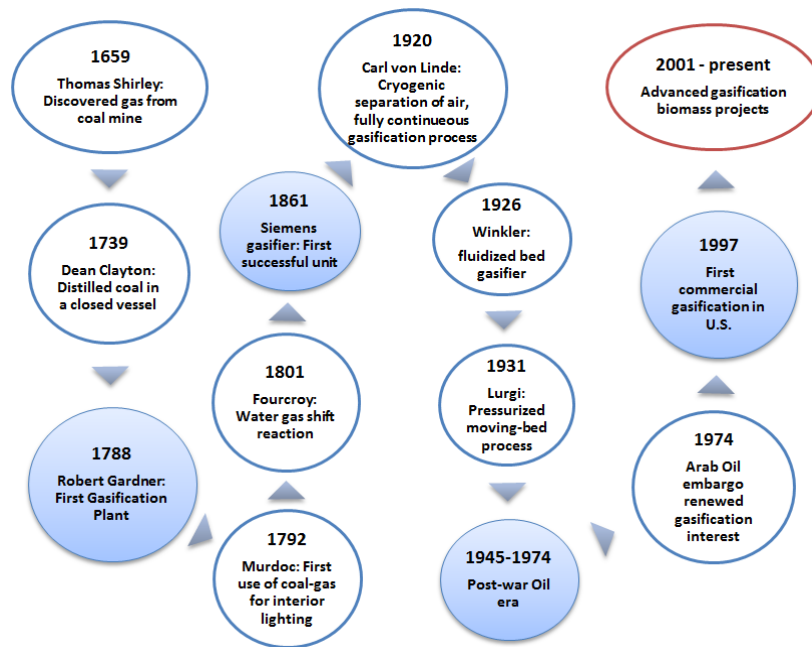


Figure 6: Major historical events in the development of gasification. Data from [16]

As explained before, the last 15 years have been extremely prosperous for gasification industry and that is clearly visible in Figure 7, where syngas capacity (GW thermal) is plotted against time. This figure shows real and projected capacities combined over the years from 1964 to 2016 in the world.

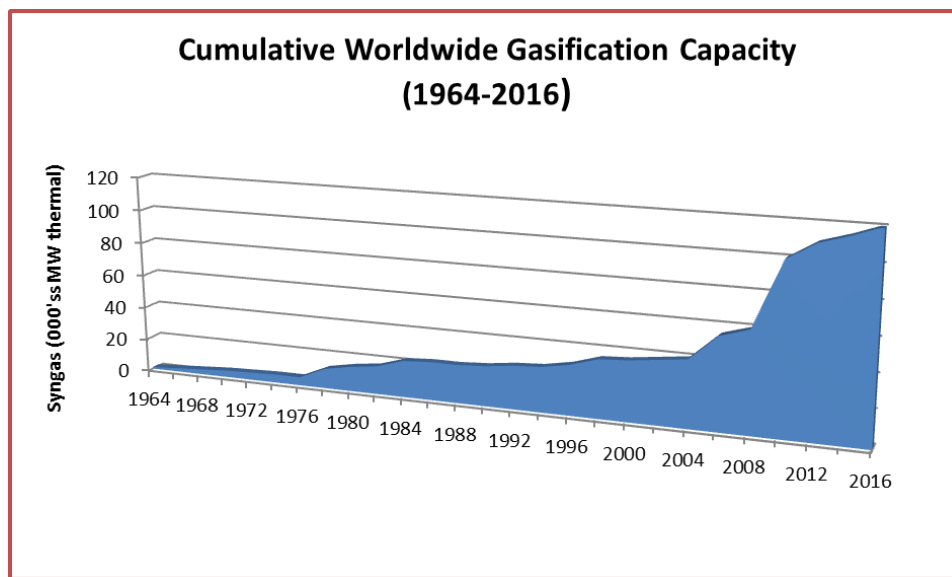


Figure 7: Cumulative worldwide gasification capacity. Data from [17]

2.3.3 Practical Advantages of Gasification Technology in Power Sector

There are several advantages and benefits in gasification utilization. One of the most important features of this thermal process is the conversion of waste or biomass (relatively inexpensive) into expensive and high value chemicals. Although, there are numerous advantages for the gasification, some related to power generation industry are summarized here [16-18]:

- **Cost:** Gas cleaning is less expensive in gasification plants compared to coal-fired plants.
- **Product Variety:** In gasification, multiple products could be delivered. It could be modified to produce steam or electricity for the grid and gas for synthesis and the chemical industries. Moreover, by-products of gasification plant could be sold; for example, the slag can be used for cement manufacturing, road and building constructions.
- **Efficiency:** Overall efficiency of gasification plants designed for power generation can be between 38 to 41%; therefore, this technology has relatively low power generation costs.
- **Carbon Dioxide Capture & Sequestration (CCS) Compatible:** In an Integrated Gasification Combined Cycle (IGCC), the plant is capable of capturing and sequestering CO_2 in a feasible way.
- **Environmental Benefits:** Gasification offers some benefits in comparison with other competing technologies. These features are introduced in the next chapter. It is estimated that the gasification power plants are as clean as natural-gas-fired ones.
- **Water Consumption:** Water consumption is an important parameter for any industrial plant. In fact, gasification plants use much less water than conventional power plants do.

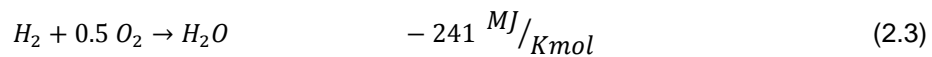
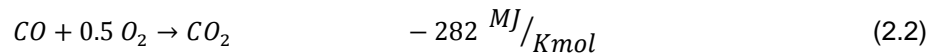
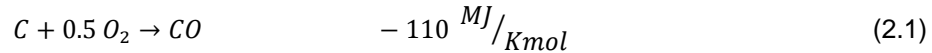
2.3.4 Thermodynamics of Gasification

In order to understand this thermal process better, it is necessary to provide some information regarding the thermodynamics of this technology.

In gasification reactions, the key players are fixed-carbon, carbon monoxide, hydrogen, carbon dioxide, water (moisture and steam) and methane. Gasification in fact, has various phases. Some of the simple chemical reactions that occur in different phases of the gasification are as follows [19]:

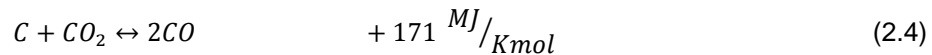
- **Drying** (moisture is removed from the biomass or feedstock)
- **Pyrolysis** (heating the feedstock with absence of air/oxygen; complex chemical reactions)
- **Combustion** (injection of air/oxygen to produce required heat from combustion to move the endothermic reduction reactions forward)

- Combustion reactions [19]:

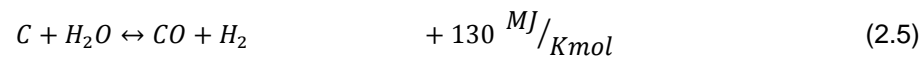


- **Reduction** (production of syngas) [19]:

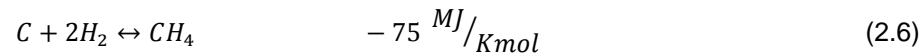
- Boudouard reaction:



- Water-gas shift reaction:

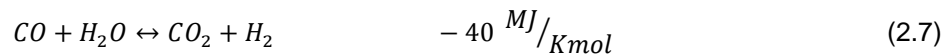


- Methanation reaction:

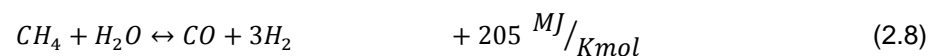


Reactions (2.1) to (2.3) occur in combustion and are all exothermic to provide heat for the endothermic reactions. By occurrence of the complete carbon conversion, the heterogeneous reactions (2.4) to (2.6) could be modified to the homogeneous reactions shown below [19]:

- Carbon monoxide shift reaction:



- Steam methane reforming reaction:



2.3.5 Gasification Systems

In gasification systems a limited amount of air or oxygen enters the gasifier and reacts with materials inside the reactor. The synthesis gas or syngas leaves the gasifier and enters the cleaning/quenching section; then the syngas is delivered to the power plant. As the gasification system requires energy itself, the electricity generated is used for the systems first and the remainder can be sold to the grid. Finally, ash is removed from the reactor and is usually disposed, which is one of the environmental drawbacks of this technology.

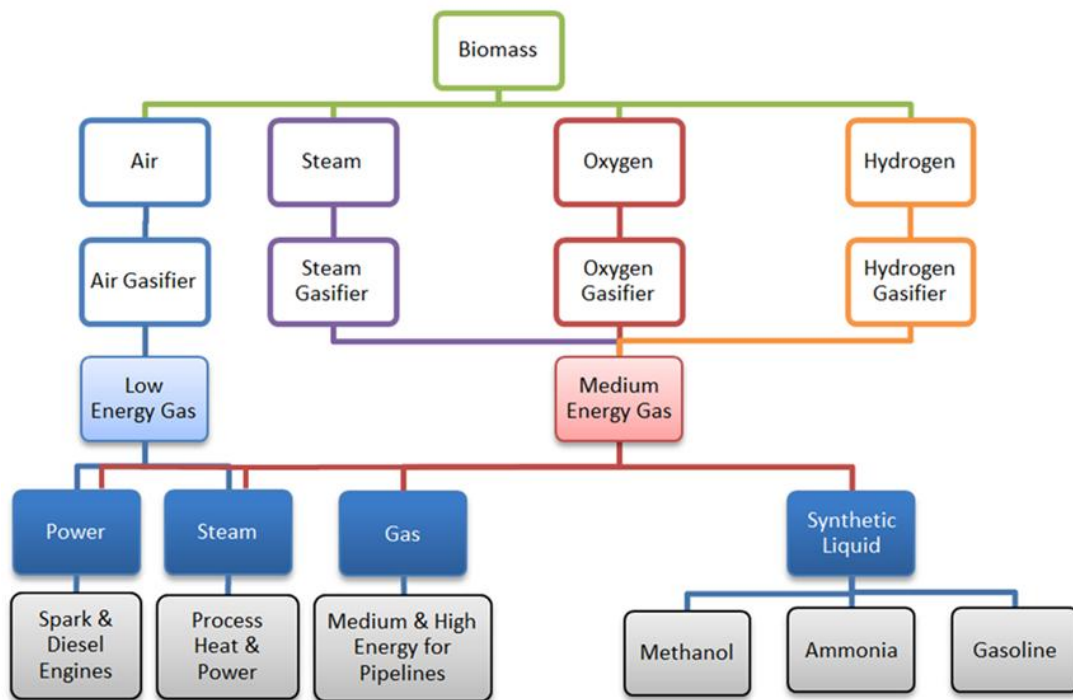


Figure 8: Gasification processes and their products. Data from [22]

In order to understand the overall system, it is necessary to classify various stages from biomass to final products. Various levels, such as inputs, media, intermediate products and final products are shown in Figure 8. It could be seen here that although air is inexpensive to use as the gasification medium (agent), it results in production of low energy syngas. On the other hand, if steam, oxygen or hydrogen is used as the gasification agent, the cost of the system increases significantly, so does the quality and energy content of the syngas.

2.3.6 Types of Gasification Reactors (Gasifiers)

The most important component of a gasification system is the gasification reactor or the gasifier. Typically in gasification, the *fixed-bed gasifiers*, the *fluidized-bed gasifiers* and the *entrained-flow gasifiers* are used. Literature reports that downdraft gasifiers are the most popular ones in the industry in western countries, such as U.S. and Canada. It also claims that the majority of the gasifiers are of downdraft type and only 20% are fluidized-bed type. It also mentions that 5% have other designs [18].

2.3.6.1 Fixed-bed reactors: updraft gasifiers

Generally, in an *updraft gasifier* the feedstock enters from the top, where syngas also leaves the gasifier. The gasifying agents (could be air, steam or even a gaseous mixture) are pre-heated and are fed into the gasifier at the lower part or bottom. The produced syngas then goes up through a bed of biomass that moves downwards [24]. The temperature in the bottom section of the gasifier is much higher than the ignition temperature of carbon; therefore, combustion with exothermic reactions occurs with sufficient amount of oxygen. In fact, produced heat moves upwards and meets the gas and the descending solids; hence reduction reactions take place. Figure 9 shows an updraft gasifier [24].

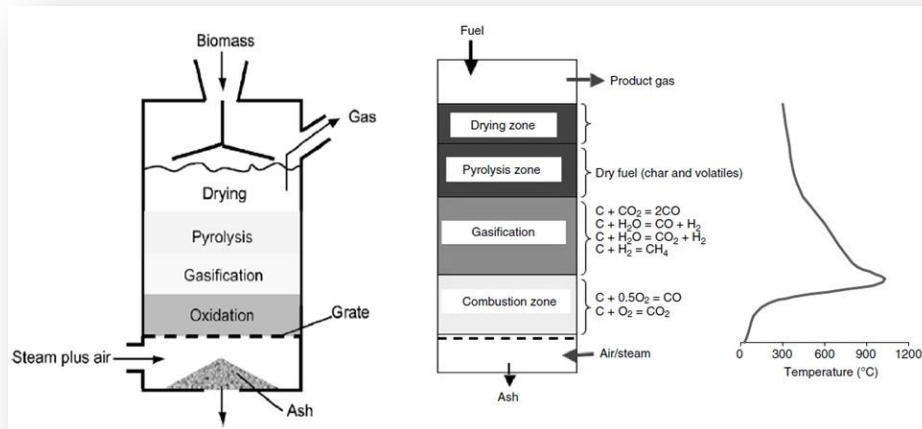


Figure 9: Various zones and the mechanism in the updraft gasifier [24]

2.3.6.2 Fixed-bed reactors: downdraft gasifiers

The sequence of reaction zones in the *downdraft gasifiers* is different from those in the updraft ones. In this type, the fuel enters the system from the top and travels all the way down in the chamber. The first zone is actually drying followed by pyrolysis and combustion. The pyrolysis and combustion products flow downwards and reach reduction zone, where the gasification reactions take place. The main advantage of a downdraft gasifier is that the produced syngas is somewhat tar-free; however, the energy content of it is relatively low [25]. Some of the key advantages and disadvantages of the downdraft gasifiers are summarized in Table 2.

Table 2: Advantages and disadvantages of downdraft gasifiers. Data from [25]

Downdraft Gasifier	
Advantage	Disadvantage
99% of tars are consumed; thus minimal need for tar clean-up	Requires feedstock drying to low moisture content (less than 20%)
Minerals remain with ash/char; thus, minimized the use of an advanced cyclone	Syngas is at high temperature; may require a secondary cooling system
Benefits from a technically proven, simple and low cost process	4 to 7% of the carbon remains unconverted

2.3.6.3 Fixed-bed reactors: crossdraft gasifiers

In *crossdraft gasifiers*, the feedstock comes to the reactor from the top and air is fed into the system via a nozzle on the side, as shown in Figure 10. The primary application of the crossdraft gasifiers is to gasify charcoal that has low ash content [26]. One of the differences between this type of gasifier and the previous two (updraft and downdraft) is that the product is released from the side, which is exactly parallel with the stream of air. Crossdraft gasifier is normally used in small projects and pilot plants. Here, the reaction zone is quite small and the thermal capacity is also low; this makes this system, however, faster in terms of response time, comparing to the other fixed bed reactors. Moreover, the tar formation in this type is low and therefore, the crossdraft gasifier should be connected to a gas-cleaning system [26].

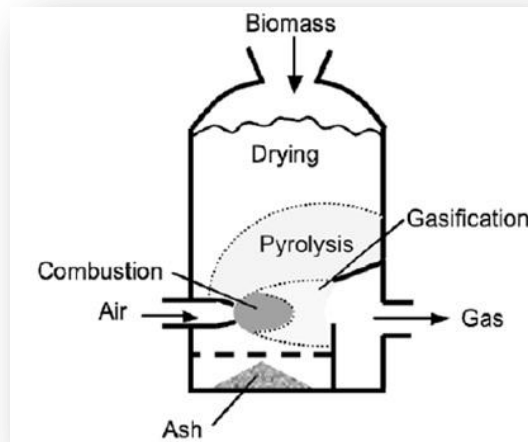


Figure 10: A crossdraft gasifier [26]

In the crossdraft gasifiers, the limitation arises when the fuel contains considerable amount of ash or high levels of tar; however, high level of moisture does not affect the system that much. Thus, this design is capable of handling that type of fuel. In fact, if the top of the gasifier is open, the moisture evaporates and leaves the system from the top. The size of the fuel should be controlled to avoid problems, such as bridging and channeling. Table 3, summarizes some of the information regarding the fixed-bed gasifiers and basically compares the Updraft, Downdraft and Crossdraft gasifiers with each other by considering various parameters [26].

Table 3: Characteristics of fixed-bed gasifiers. Data from [23]

	Wood	Updraft	Downdraft	Crossdraft
Moisture (%)		< 60	< 25	10 to 20
Ash (%)		< 25	< 6	0.5 to 1.0
Feedstock Size (cm)		0.5 to 7	2 to 7	0.5 to 2
Gas Exit Temperature (°C)		200 to 400	700	1250
Tar (g/Nm^3)		30 to 150	0.015 to 3.0	0.01 to 0.1
Gas LHV (MJ/Nm^3)		5 to 6	4.5 to 5.0	4.0 to 4.5

2.3.6.4 Fluidized-bed reactors: bubbling fluidized-bed gasifiers

The operating temperature in the *fluidized-bed gasifiers* are generally between 800 to 1000°C. This range is suitable to use biomass and the MSW. This feature is essentially important for wood and agricultural waste; thus, large-scale biomass gasification systems use fluidized-bed gasifiers. In a bubbling fluidized bed reactor, the feedstock can enter the system from the top or the side in a somewhat short period of time over the whole surface of the fluid bed. In fact, the gasification agents serve as the fluidizing gas and thus, are channeled to pass through the bottom of the reactor. In a general type of this gasifier, new solid fuel particles meet with solids that are hot and located on the bed; therefore, particles will heat up quite fast and subsequently, go through drying and pyrolysis and eventually produce char and syngas, in a short period of time. The fluidizing gas enters the gasifier from underneath and exits from the top of the reactor. When the oxygen enters the bottom of the chamber, it reacts with charcoal in an exothermic manner. As the gas travels upwards, the reduction reactions take place. The bubbles act as a channel to the top of the gasifier. One of the issues in the bubbling fluidized bed gasifier is the fact that the complete conversion of the char does not occur. Therefore it is essential to have a good mixing of solids to guarantee the temperature uniformity in all parts of the gasifier, although the ideal case can never be achieved in this matter. [26].

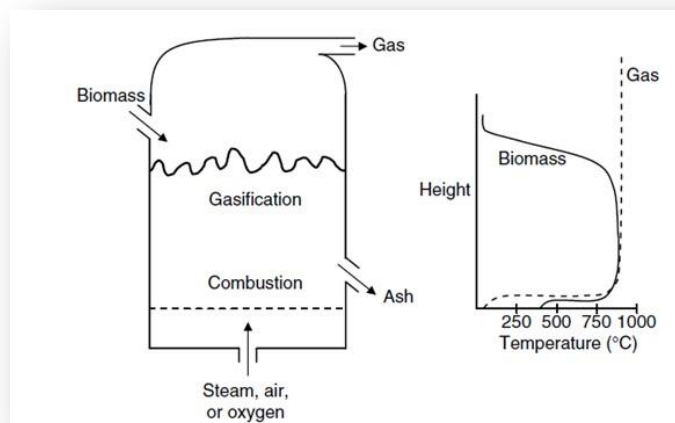


Figure 11: A bubbling fluidized-bed gasifier [26]

2.3.6.5 Fluidized-bed reactors: circulation fluidized-bed (CFB) gasifiers

The mechanism in the *circulating fluidized-bed gasifier (CFB)* is in a way that solids go on a circular path that benefits from extreme mixing conditions, as well as longer time periods for its circulation of solids. As there are no bubbles in this type of fluidized-bed gasifier, the gas-bypassing problem that exists in the fluidized beds does not occur here [26].

2.3.6.6 Fluidized-bed reactors: twin (dual) fluidized-bed gasifiers

One of the other types of the fluidized-Bed gasifiers is called *Twin or Dual type*. This design is important, as it physically separates the combustion zone from gasification zone. It is in fact well known that one of the most challenging issues in air gasification of biomass is the dilution of the syngas by the high concentration of nitrogen content of air, which is used for the heat releasing reactions in the combustion zone. It is possible to overcome this problem by introducing oxygen, as the gasification agent; however, this solution is expensive and increases the required energy significantly. In twin fluidized-bed gasifier, combustion chamber is separated from the gasification reactor. The reason for such a design is to prevent the nitrogen content of the air that is supplied to the combustion chamber from mixing with the product gas in the gasification reactor.

This design has its own limitations though [26]:

- As we know, there is less char in biomass compared to coal and if the char used for the gasification purpose is not sufficient to provide heat for gasification reactions to take place, then external heating should be supplied to keep the temperature above 900°C.
- In case the gasifier is running on steam, just a small percentage (less than 9%) of the steam contributes to the gasification reaction and majority of it actually leaves the system, which means considerable amount of heat is wasted and the gas is diluted.

2.3.6.7 Entrained-flow gasifiers

The most suitable type of gasifier for IGCC plants is the entrained-flow gasifier. The temperature in this type reaches approximately 1400°C. Entrained-flow gasifiers are in two types: (a) side-fed and (b) top-fed. The gasification agent and the fuel that has been pulverized (less than 75 microns) enter from the side of the reactor; in the second type (b), they enter from the top. The concept in this design is to mix the pulverized feedstock with water to improve the efficiency. The gas velocity in this type of reactor is high, which results in entraining the fuel particles. This phenomenon increases the temperature in the gasifier far above the melting point of the produced ash; therefore, any remaining carbon will be converted [26].

Entrained-flow reactors are somewhat superior to the other types. Some of the reasons are [26]:

- Low levels of tar in the process
- Flexibility over material feed
- No ash (conversion of ash to slag)
- High temperature and pressure
- High conversion rate of carbon
- Low level of methane

From the thermal input perspective, downdraft gasifiers have the lowest power (10 kW to 1 MW), where entrained-bed gasifiers could go up to 1000 MW. The range for fluidized-bed also varies from about 1 MW to 100 MW [23].

Table 4 compares some of the commercial gasifiers with each other. It can be shown that the challenge in the fixed bed gasifiers is the tar production and the use of fine particles; however, in the fluidized-bed gasifier the problem arises from the carbon conversion issue and finally in the entrained-bed, the problem is in the area of syngas cooling [23].

Table 4: Comparing some key factors in some commercial gasifiers [23]

Factor/gasifier type	Fixed-Bed	Fluidized-Bed	Entrained-Bed
Feed Size	Less than 50 mm	Less than 6 mm	Less than 0.15 mm
Gas Temp. (exit)	450 to 650 °C	800 to 1000 °C	above 1260 °C
Feedstock Type	Coal	Coal and Excellent for Biomass	Coal but no biomass
Need for Oxidizer	Not much	Fair	Very much
Reaction Zone Temp.	1090 °C	800 to 1000 °C	1990 °C
Cold-Gas Efficiency	~ 80%	~ 90%	~ 80%
Applications	Small-scale units	Medium-scale units	Large-scale units
Challenges	Tar Formation Fine Particles	Carbon Conversion	Syngas cooling

2.4 Plasma-assisted Gasification (Plasma Gasification)

By definition, *plasma* is in fact an extremely high-temperature ionized gas that has been produced using a source, which is a good conduction of heat and electrically. When this source is utilized in the gasification, the process is referred as *the plasma gasification*. In this technology, the organic materials in the MSW form a fuel that is called syngas. On the other hand, the inorganic compounds create a brittle solid that is labeled as slag. A high quality syngas should mainly consist of hydrogen and carbon monoxide. Electric sparks in the plasma torch create extremely high temperatures, which form plasma. Thus, in this process a reactor is equipped with the plasma torches to thermally process organics materials of the MSW. The operating temperature of the plasma gasification reactor is usually between 4000°C and 7000°C. The utilization of the plasma torches is not new. In fact, *Westinghouse Plasma Corporation (WPC)* started manufacturing these torches for *NASA*, specifically for the Apollo Space Program in 1960s; however, the use of plasma torches in the large-scale waste processing facilities is fairly new. In fact, the plasma gasification of the MSW is a novel approach that integrates some of the well-established processes into a new one. Such processes are waste pre-treatment, plasma conditioning, cooling/cleaning, and more importantly power production [15, 27, 28].

In some methods, coal or coke is fed into the reactor. By adding these materials to the gasifier, fast reactions with oxygen occur, which results in heat generation for the chemical reactions to go forwards. In addition to that, sometimes steam is injected into the plasma gasifier for the syngas reactions to take place more effectively. Since the operating temperature is very high (4000°C to 7000°C.), the inorganics in the MSW are converted into a vitrified slag which will be largely formed by metals and glass. Metals also could be recovered from any type of waste in the system [15].

2.4.1 Advantages/Disadvantages of Plasma Gasification over Other Processes

Plasma gasification or plasma-assisted gasification in general has some advantages over non-plasma methods, especially conventional gasification. Some of the major advantages are listed below [29]:

- In plasma gasification the energy required for reduction reactions comes from the plasma rather than a combustion zone. This results in a better process controlling.
- As there is no combustion phase in plasma gasification, no combustion gas will also be in the system; therefore, emissions and environmental pollutants are significantly lower.
- The temperature in the plasma reactor is easily controlled, as the power of the plasma and the feedstock feeding rate could be easily controlled.
- By optimizing the location and power of the plasma torches in the reactor, high temperatures and also the temperature uniformity can be easily maintained. This, therefore results in the minimization of tar production in the system.
- Plasma gasification claims to provide higher energy density and higher efficiency, compared to other thermal processes, which results in handling of larger loads of feedstock.
- As the operating conditions and composition of the products could be controlled, plasma facility can produce variety of products, such as electricity, liquid fuels and chemicals.
- In plasma gasification, syngas dilution is minimized. Moreover, energy loss is significantly lower than the loss in the conventional gasification.

In most of the advanced plasma gasification processes today, the produced syngas could be used to produce steam by exchanging heat with water for electricity generation using steam turbines, as well as cleaning and filtration of it to be fed into a gas turbine. Table 5 summarizes the fundamental distinctions between plasma gasification and incineration technologies.

Table 5: Differences between plasma gasification and incineration. Data from [28, 30]

Plasma-assisted Gasification	Incineration
Presence of very small amount of Oxygen, preventing from combustion	Presence of excess air, complete combustion
Syngas is formed and energy and industrial chemicals are then produced	Energy is all converted to heat
Non-organic materials are mainly converted to slag (6 to 15% of the original waste volume)	Inevitable production of hazardous ash
Emissions are much lower	Far more emissions of Greenhouse Gases (GHGs) and other pollutants

As discussed, Figure 12 clearly summarizes the difference in the operating temperature of each of these technologies. As shown, incineration has the lowest operating temperature. Pyrolysis and conventional gasification are quite similar in this aspect; however, the plasma gasification benefits from the highest range of temperature among the thermal technologies. Moreover, the difference between the lowest and highest operating temperature is 3000°C, far more than other technologies. That is in fact, due to utilization of different plasma torches and reactor designs, which have been developed by various companies. Some more information regarding these designs will be given shortly in this chapter. It is necessary to mention that one could use plasma-assisted gasification for metal separation, as metals can be separated from the slag. In addition, the vitrified and metal-free slag can be utilized to create materials that are useful in road and building construction, landscaping and gardening [31]. Furthermore, the research and development has improved the design of the plasma-assisted gasification reactors in recent years and these progresses have almost removed the need for pre-treatment and pre-processing of the MSW before feeding into the plasma gasifier [32].

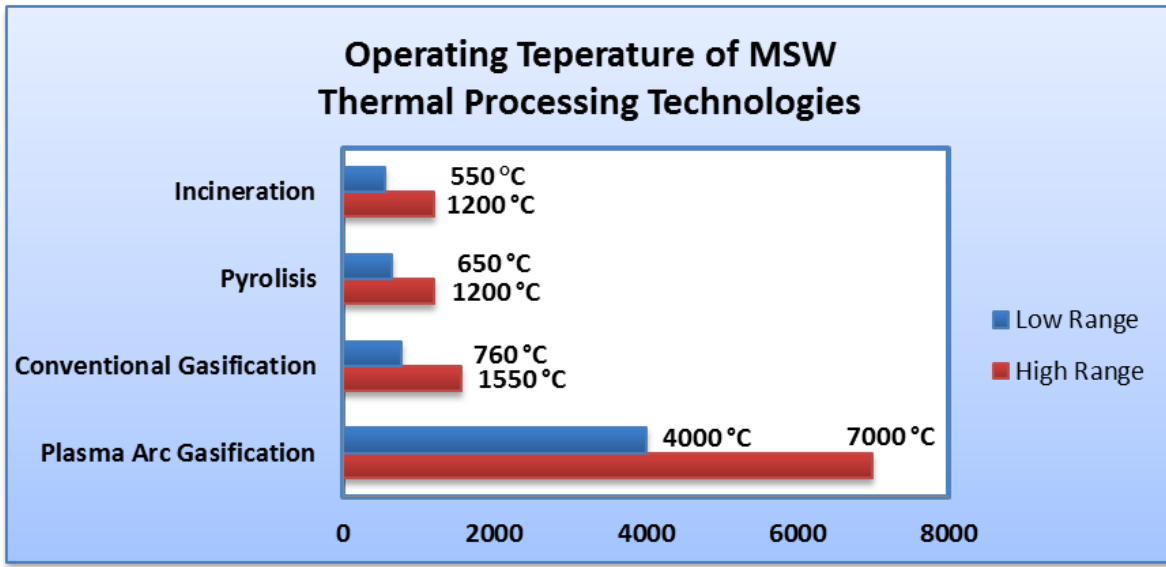


Figure 12: Operating temperature range in various thermal processing technologies. Data from [4-6]

Although plasma gasification has many advantages over the other thermal processing technologies, it shows some drawbacks in some points. These points are as follows:

- Plasma gasification reactors require continuous supply of high voltage/current electricity to the plasma torches. If this supply is disrupted, the process cannot continue.
- Due to the limitations in supply of electricity, this technology cannot be developed everywhere and few countries and regions can benefit from it.
- Plasma gasification is new and very few of these plants are currently operating. Therefore, the industrial and technical experience is far lower than that of incineration or gasification.
- Large amount of MSW or biomass is needed to make the plant economically feasible to operate. In most cases, long-term arrangements and contracts have been made between municipalities and other plants using other technologies. Also, feedstock sorting is needed.
- Due to financial issues and high capital cost for these plants, this technology has not been fully commercialized.

Regarding the technical limitations and concerns about plasma gasification, it is necessary to mention that one of the main concerns is to ensure that gaseous emissions are minimized and cleaned before being released into the atmosphere. If this is not done properly, then this technology will face the same opposition, as has happened to the incineration. Moreover, because it is relatively a new system, still there are significant transportation and infrastructure issues that require consideration. Finally, due to the fact that very few large and commercial facilities have been constructed around the world, it is not yet a proven technology on very large and fully commercial scales; therefore, there is a tremendous need for various testing experiments and pilot plants which are currently happening [33]. “*Feedstock Source Separation*” is highly recommended for a plasma gasification plant and that is due to the following reasons:

- Metals and inorganic content of the MSW do not have any contribution to the energy content of the system and therefore, it is more beneficial to separate them at the source.
- Sorting the MSW to recover recyclables, such as paper, metals, and high quality plastics can be more advantageous than using them in the energy recovery process.
- Revenue can be generated by collecting these recyclables.
- Finally, the use of waste that contains considerable amount of halogen can result in emissions of elements that are very complicated to capture, such as hydrogen sulfide.

2.4.2 Development of Plasma Gasification Systems

In this section, some of the well-known plasma gasification systems that are widely used in today's waste to energy (WTE) market are briefly introduced. The plasma gasification technology is now being developed and tested in North America, Asia and Europe. In Europe, almost 50% of the waste is thermally treated; however, this conversion rate is less than 5% in North America [34].

It is interesting to see in Japan, due to their lack of space that has forced them to find other options instead of landfilling. That is probably why we see the only commercial plasma gasification plants (Utashinai and Mihama-Mikata) in Japan that are run by Hitachi Metals Ltd. and Alter NRG. In fact, 95% of the waste in Japan is thermally treated [27].

2.4.2.1 EUROPLASMA - plasma arc gasification system

EUROPLASMA, a French company, is specialized in industrial thermal processes, specifically plasma processing. They have developed variety of torches for their objectives and in fact one of the advantages of their plasma torch is the flexibility that enables the operators to use it from 25% to 100% of its power range. The power range for *EUROPLASMA* torches vary from 100 kW to 4 MW. Moreover, this company has developed a type of plasma torch to breakdown the syngas after production in the gasification process and is called "*TurboPlasma*". The process designed by *EUROPLASMA* does not rely on the full use of plasma torches for gasification. Gasification is performed by using the recycled heat of combustion. Plasma torches are used only for the thermal cracking of the syngas and for the slag vitrification. This gasifier benefits from a heat exchanger that recovers the sensible heat of the gasification gas and feeds the gas to the engines to produce electricity from the syngas. *EUROPLASMA* is currently launching the construction of their first plant CHO-power in Morcenx, France. The plant capacity will be 50,000 tons of waste per year, corresponding to a net electrical output of 12 MW of electricity [27, 35].

2.4.2.2 Phoenix Solutions Co. (PSC) – plasma torch technology

Phoenix Solutions Company (PSC) is a leading firm in plasma heating systems that are relatively large in size. In fact, one of the areas in which their technology has been used is the gasification of low-level nuclear waste. This company's plasma torches are capable of operating on argon, nitrogen, helium, hydrogen, air, methane, propane or oxygen and their power range is from 50 kW to 3 MW. It is necessary to mention that Poenix Solutions technology has been installed on Plasco Energy Group's conversion process to generate electricity in their pilot plant in Ottawa, Canada. Moreover, a Japanese company called Kobelco Eco-Solutions Ltd. Utilizes this technology to reduce the size and toxicity of their ash waste produced in their incineration process [35].

2.4.2.3 Plasco Energy Group

Plasco Energy Group is a private Canadian company based in Ottawa, Canada that has a pilot plant in that city. Their “Plasco Conversion Process” is their recipe for extracting energy from the municipal solid waste. In their system, everything starts with a pre-treating process. In the gasification reactor, waste material is converted to raw syngas and then the gas is further treated using two plasma torches. Pollution control is the next step in their design, where harmful elements, such as sulfur and metals are removed. At this point, the syngas is ready to be used for electricity production. Steam is also produced by recovering the generated heat in the electricity production part, which could be used in steam turbines for more electricity production or heating purposes. Another plasma torch is used to treat the ash and converts that to a vitrified slag. This way, any remaining fixed carbon could be converted to syngas, which is sent back to the conversion chamber. Their vitrified slag is reported to be compliant with US EPA standards. Plasco’s 94 tons per day plant in Ottawa, received a green light in 2008. It is estimated that \$25 million has been spent for this plant since then. It is worth mentioning that they have another plant in Castellgali, Spain [27, 35].

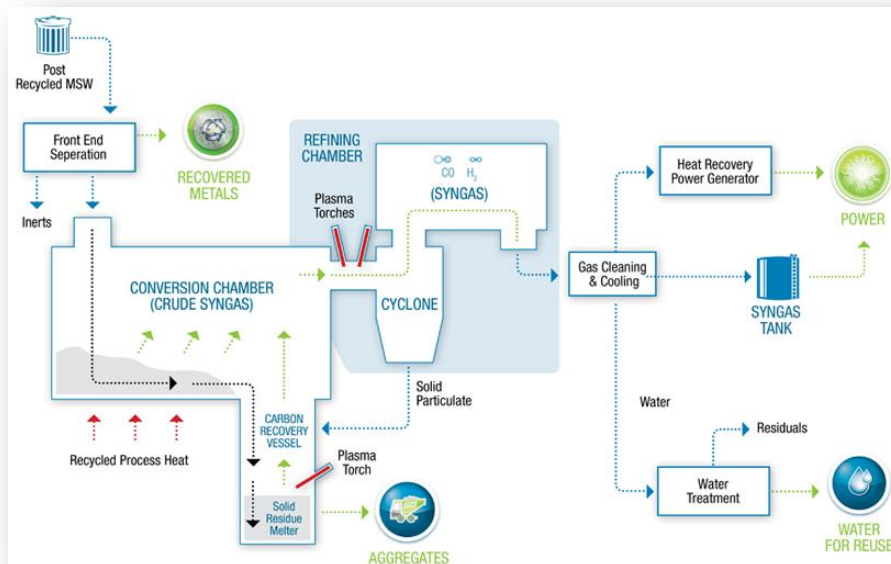


Figure 13: Plasco Energy Group’s plasma gasification plant [36]

2.4.2.4 *PyroGenesis Canada Inc. plasma-based waste to energy*

PyroGenesis Canada Inc. is a Montreal-based company that is involved in plasma waste treatment systems and has the capability to design their own plasma torches. These torches use approximately 50 kW to 500 kW of power for operation and heat up the reactor up to around 5000°C. PyroGenesis has developed a system to be used in marine industry. In fact, they use their non-hazardous “*Plasma Arc Waste Destruction System (PAWDS)*” to treat waste on ships. For the MSW and also hazardous wastes, this company has developed a system called, “*Plasma Resource Recovery System (PRRS)*” [27, 35].

2.4.2.5 *Integrated Environmental Technologies (InEnTec)*

Integrated Environmental Technologies (InEnTec) has been established primarily based on the work that resulted in creation of a system, called *Plasma Enhanced Melter (PEM)* in the United States. In 1998, this company built two pilot plants to test the technology, but due to some technical issues in the plasma section of the system, both of the plants were shut down. The system is capable of treating solids but not gaseous wastes [27, 35]. This company has a demonstration plant in Richland, Washington, USA with a capacity of 25 tons per day for various types of feedstock, including biomass and MSW.

2.4.2.6 *Alter NRG / Westinghouse Plasma Corporation (WPC) system*

Westinghouse Plasma Corporation is a leader in the field of plasma and has joined Alter NRG, since 2006. One of the applications of the plasma torches is to vitrify ash, which has been popular in recent years, specifically in Japan. It is reported that the thermal efficiency of the plasma torches developed by Westinghouse Plasma Corporation (WPC) varies from 60% to 75%. In fact, Alter NRG has incorporated the plasma torch developed by WPC and has used it in their plasma gasification chamber to make it a reliable and commercialized technology. One of the main differences between this system and the other's is the location of the plasma torches, which are placed at the bottom of their reactor. The maximum number of plasma torches in their design is 6 [27, 35].

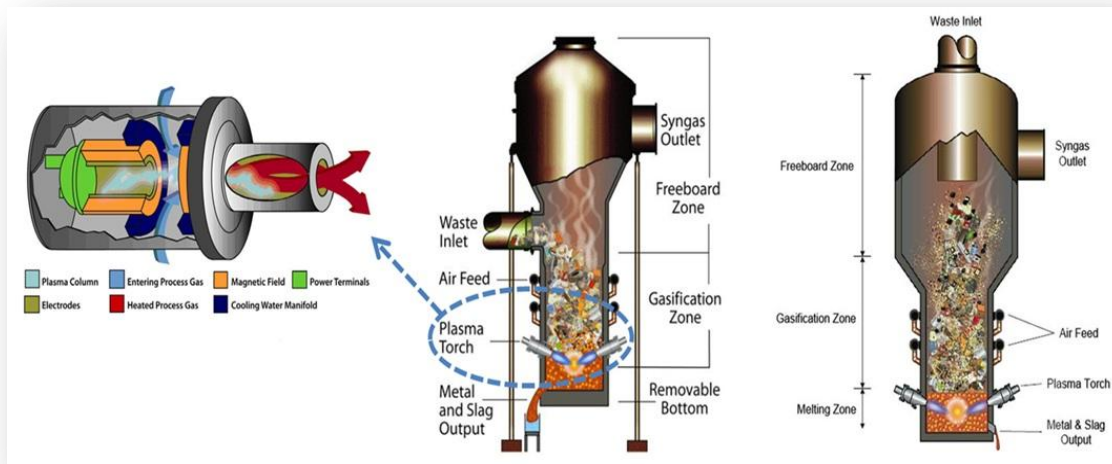


Figure 14: Westinghouse plasma corporation plasma torch [27, 35]

The optimum size of the feedstock is 10 inches in length and the gasifier is capable of handling the feedstock with any moisture content. As shown in the figure above, the feedstock inlet was initially designed to be on the side of the reactor; however, Alter NRG has moved the inlet to the very top of the gasifier. In this design, torches are working continuously and the power supply for each plasma torch is separate, which enables the system to have flexibility over the torches; thus, it is possible to switch off a plasma torch without disturbing the entire system [27, 35].

The other feature of this system is about the internal pressure of this gasifier. The reactor is actually operating under negative pressure. This means that if in case there is a leak in the system, syngas or any other gaseous element is not leaking out of the system. Instead, air will enter the gasifier from the leaking point. Inside the gasifier is insulated to minimize the heat loss from the gasifier to the surrounding area. In the best case scenario, the syngas produced in Alter NRG's system will have one third of the energy content of the natural gas. This company is currently collaborating with a turbine manufacturer (Solar Turbine) to eventually design and make a turbine that primarily operates by the produced syngas. The other solution is to mix the syngas with natural gas and use this mixture for the turbines [27, 35].

There are various ways of combining the plasma gasification with conventional waste to energy technologies. For instance, the IGCC is one of the unique ways of utilizing plasma gasification in line with other methods. In fact, designing an IGCC that works entirely on MSW is believed to be the ultimate goal of Alter NRG [27]. Table 6, finally summarizes the information regarding the plasma plants (commercial, pilot and research plants) in North America, Europe and Asia. This table does not include the plants that are under construction or the ones that will be built in the future. It is necessary to mention that only Mihama-Mikata and Utashinai plants in Eco-Valley, both located in Japan are commercially operating.

Table 6: Plasma waste processing plants in the world. Data from [28]

North America			
Location	Feeding Material	Max. Capacity (ton per day)	Start Date
Jonquiere, Alberta, Canada	Aluminum Dross	50	1991
Ottawa, Ontario, Canada	MSW	94	2007
Madison, Pennsylvania, USA	Biomass, Waste	48	2009
Richland, Washington, USA	Hazardous Waste	25	2001
Europe			
Bordeaux, France	Ash from MSW	10	1998
Asia			
Mihama-Mikata, Japan	MSW, Sewage	MSW	2002
Utashinai, Japan	28	300	2002
Kinura, Japan	MSW	50	1995
Kakogawa, Japan	MSW	30	2003
Shimonoseki, Japan	MSW	41	2002
Imizu, Japan	MSW	12	2002

CHAPTER 3

Literature Review of the Economic, Environmental and Emission Aspects of WTE

The purpose of this chapter is to briefly discuss some of the key points regarding the economics of the Waste to Energy (WTE) thermal processes. Moreover, some environmental aspects and issues related to emissions of these processes are discussed.

3 Literature Review of the Economic, Environmental and Emission Aspects of WTE

3.1 Economic Comparison for Thermal Processes in WTE

In this section a preliminary analysis on the economics is presented and each of the thermal processes discussed previously are economically compared against each other. The starting point of this economic analysis could be the net energy output from these thermal processes, as the main objective. By considering four WTE thermal processes (incineration, plasma gasification, conventional gasification and pyrolysis) with the daily handling capacity of 500 ton MSW (500 ton MSW/day), the one utilizing plasma gasification generates the highest level of energy (816 kWh). As the operating temperature ranges decrease, conversion thermal efficiency of the MSW to Energy declines as well. That means conventional gasification, pyrolysis, and incineration could generate 685, 571 and 544 kWh per ton, respectively. Table 7 summarizes the brief economic analysis that has been done by [15] for four thermal processes discussed in this paper.

Table 7: Factors affecting the economics of the thermal processes (US\$) [15]

Factor	Technologies			
	Incineration	Pyrolysis	Gasification	Plasma Gasification
Investment @ 6% in 20 yrs.	~ \$116,000,000	~ \$87,000,000	~ \$80,338,000	~ \$101,584,000
MSW Capacity (tons per day)	~ 500	~ 500	~ 500	~ 500
Power Generation (kWh per ton)	~ 545	570	~ 685	~ 815
Operation & Maintenance	~ \$8,217,000	~ \$7,194,000	~ \$6,872,000	~ \$7,483,500
MSW Tipping Fee (US \$ per ton)	\$35	\$35	\$35	\$35
Green Tags	\$0.02 per kWh	\$0.02 per kWh	\$0.02 per kWh	\$0.02 per kWh
Energy Sales	\$0.065 per kWh	\$0.065 per kWh	\$0.065 per kWh	\$0.065 per kWh
By-Products	~ \$0.2	~ \$0.2	~ \$0.2	~ \$0.2
Residue	Ash	Ash and Char	Ash and Slag	Slag

As shown in Table 7, thermal processing technologies have been compared with each other in variety of factors. The figures estimate the economic evaluation of a facility with an operating capacity of 500 ton MSW per day. As shown, incineration requires the highest capital investment of about \$116 million and then plasma-assisted gasification is in the second place with the capital investment of around \$101,584,000. Operation and maintenance costs are also shown in the table. Incineration again is the least favored technology from this perspective and plasma-assisted gasification is in the second place. As discussed before in terms of electricity generation (kWh per ton MSW), plasma-assisted gasification claims to be the most thermally efficient technology among thermal processes in conversion to electricity.

The green section in Table 7 shows the revenue for these technologies. That section consists of tipping fee (\$/ton MSW), which has been considered to be \$35 for all the technologies; Green tags (Renewable Energy Credit, CO_2 Credits and Credits for Emission Reduction) to be 2 cents per kWh, which has been considered to be the same in all the technologies here; and finally revenue generated from sales of energy from these plants. The price of 6.5 cents per kWh has been used in this comparison, as all of these technologies are in the waste to Energy (WTE) category.

It is also necessary to mention that the residue has some economic impact, which could be positive or negative. As discussed before, in case of plasma gasification this factor contribute positively, as the vitrified slag is a safe, sealable and environmentally sound by-product and has applications in road and building construction; however, in the case of incineration, pyrolysis and conventional gasification, ash coming out of the process needs to be removed and thus contributes negatively to the economic picture of these processes. This economic analysis using these parameters gives us the ability to calculate the total revenue of the desired thermal process. In fact, incineration (mass burning) technology presents negative total annual revenue; however, other thermal processes such as, pyrolysis, conventional gasification and plasma-assisted gasification have positive total annual revenues. In fact, plasma gasification technology benefits from the highest net annual revenue, which is equal to \$3,350,000 per year.

In addition to this economic advantage, plasma-assisted gasification produces a sealable, safe and non-toxic slag, which has applications in road and building construction and positively contributes to the technologies economic picture at a rate of about \$15.00 per ton. One of the major drawbacks of incineration, pyrolysis and conventional gasification is that their by-product, i.e. ash is disposed in a landfill, as there is no other way yet to remove ash from environment (except plasma processing it) [39, 40].

In general, it can be suggested that industries and municipalities that are interested in pursuing a plasma gasification facility conduct their own analyses based on their specific information and modify the key parameters to match them to their scenario. In fact, cost is not the only issue. It goes beyond the budget and funding challenges. Co-operation between the governments and industries is essential and both sides are expected to show a clear objective in preparation of their final economic analysis. Regarding other economic benefits, it is necessary to mention that job creation of plasma gasification plants can play key roles in improving a region's economy. In fact, construction of the plant and permanent jobs to run the plant are some of the benefits of having one of these facilities in a specific location. These jobs cannot be outsourced by any means.

3.2 Environmental Comparison for Thermal Processes in WTE

Environmental aspects of any technology have been extremely important as the evidences of climate change are on the rise. Therefore, the need to decrease pollutions originated from industry has been globally recognized. In this section, some explanation regarding significant environmental elements in WTE industry, such as carbon dioxide, sulfur, nitrogen and dust is presented. We start with environmental benefits of such technologies.

3.2.1 Carbon Dioxide

In the case of combustion of biomass in general, carbon dioxide that had been absorbed from the atmosphere by the plant is released. In conventional and plasma gasification of biomass however, based on the unit of heat release, emissions of carbon dioxide to the atmosphere is considerably lower. In Figure 15, the carbon dioxide emissions of the plasma gasification of the MSW is compared with coal, oil and natural gas. In fact, the results show that for generation of 1 MWh of energy, coal has the highest amount of emissions. Emission in the plasma gasification of the MSW lies between oil and natural gas. The plasma gasification has shown to be emitting 644 kg of carbon dioxide for generation of 1 MWh, where the emission from oil is 759 kg [41, 42].

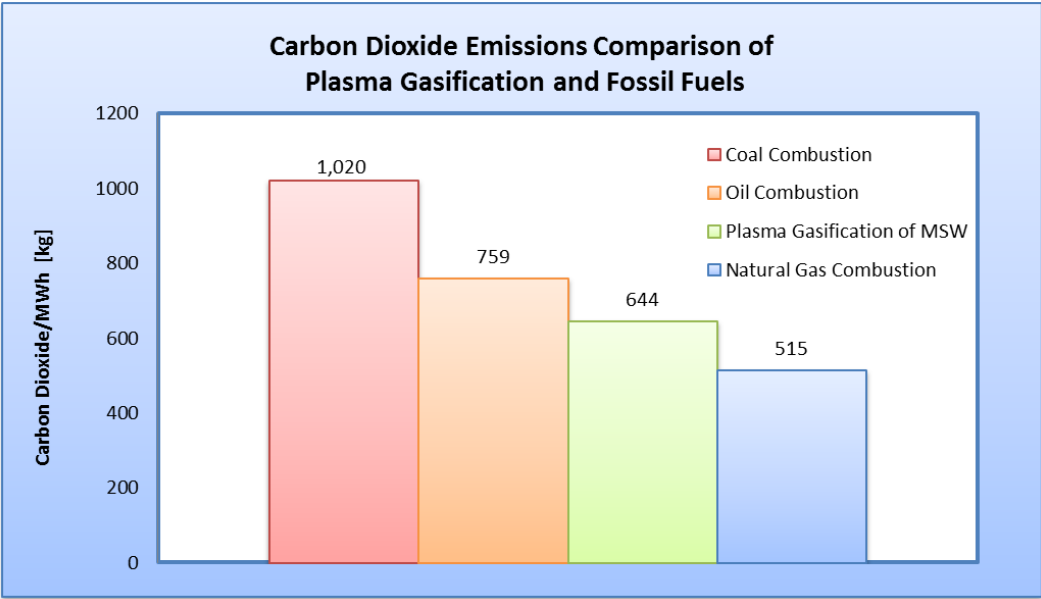


Figure 15: Carbon dioxide emissions comparison of MSW. Data from [41, 42]

3.2.2 Sulfur-based Content

Sulfur content of the biomass itself varies based on the type and age of the material and is not significant; however, the Municipal Solid Waste (MSW) does include some significant level of sulfur. Surprisingly, MSW contains considerable amount of calcium that contributes to the sulfur capturing and removal [18].

In combustion (or incineration), sulfur content of fuel forms SO_2 which is difficult to remove. On the other hand, in gasification almost all of the sulfur content (up to 96%) appears as H_2S which is relatively easier to remove from the syngas. Moreover in the gasification process, sulfur can be extracted and form a valuable by-product [18].

3.2.3 Nitrogen-based Content

In a gasification plant, most of the nitrogen-based contents appear as N_2 or NH_3 , which can be removed by adding a syngas cleaning phase after the production phase [18].

3.2.4 Particulate Matter (PM) and Other Hazardous Gases

Although there are some disagreements between the scientific and industrial bodies, toxic gases such as furan and dioxin are believed not to be generated (at least not in significant amount) in a gasification process, as the gasifier is supplied with limited amount of oxygen (oxygen-starvation). Particulate Matter (PM) content of the gas also can be removed using typical gas cleaning techniques [18].

Figure 16, presents some information regarding the emissions in gasification, combustion (Incineration) and landfilling processes. Based on the results shown in Figure 16, we can conclude that incineration has the highest emissions in all categories, especially in the emission of NO_x . Gasification however, shows the lowest amount of emissions, although in emissions of particulate matter (PM), landfilling wins over gasification by only 1 gram per ton difference [18, 43].

This figure also, compares the emissions for various WTE technologies, in which all of these technologies are compared to the emission levels specified in the Ontario Guideline A-7, 2010.

Conventional Gasification in fact, meets all the emission requirements for the province of Ontario. Therefore, plasma gasification technology meets the requirements, as this technology is the advanced version of the gasification and has shown significant improvements in all the aspects.

It is interesting to see that incineration (burning the MSW) exceeds almost all of these limits set by the Ontario guideline. In NO_x formation in fact, this technology marginally meets the requirement.

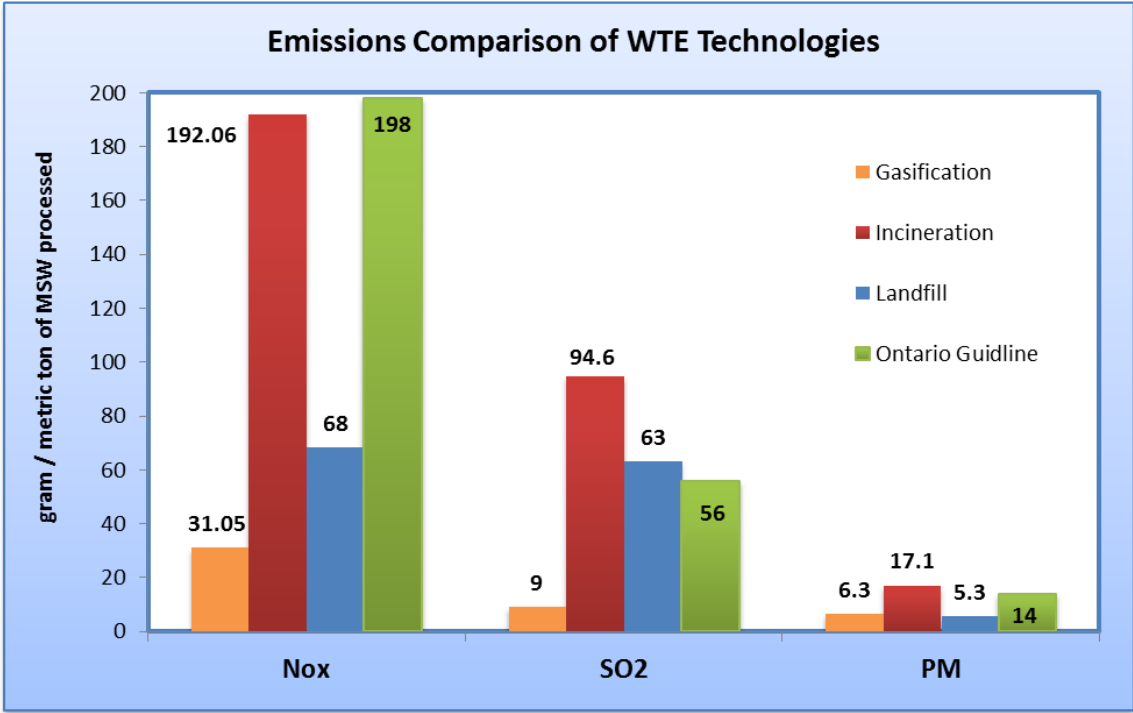


Figure 16: Comparison of WTE processes in terms of emissions. Data from [42, 43]

Figure 17 on the next page, summarizes the emissions information for electricity generation from waste using thermal processing. Carbon dioxide content, water usage, sulfur and nitrogen-based contents and the amount of total solids for a typical pulverized-coal and combined natural gas combustion processes with a gasification process are compared with each other in this case.

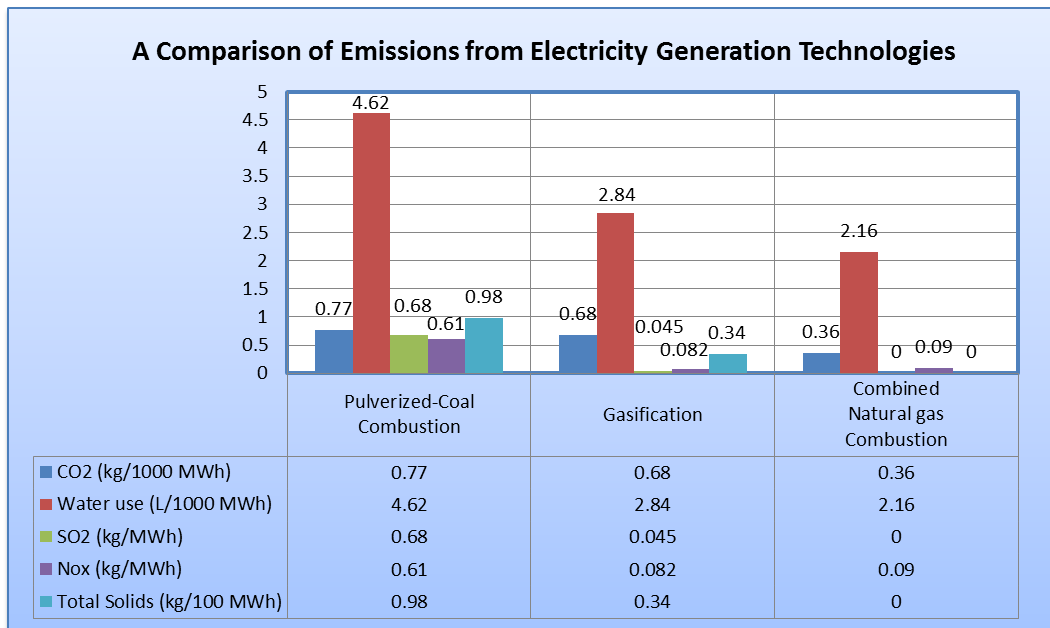


Figure 17: Comparison in terms of emissions. Data from [42]

In the table shown here, various environmental standards are compared. These standards are the Ontario standards defined in the A-7 guideline, US EPA standard, California standard and EU standards. Plasma gasification in fact, meets all the emission requirements regardless of the type.

Table 8: Summary of various environmental standards. Data from [43]

Emissions	Ontario standards A-7 Limits (Oct. 2010)	US. EPA Standard	California Standards	EU Standards
Particulate Matter (PM)	14	11	16	9
Cadmium	0.007	0.01	0.01	0.046
Lead	0.06	0.14	0.14	-
Mercury	0.02	0.05	0.05	0.046
Dioxins and Furans *	0.08	0.14	0.09	0.092
Hydrochloric Acid (HCl)	27	29	27	9
Sulfur Dioxide (SO₂)	56	63	56	46
Nitrogen Oxides (NO_x)	198	264	202	183

Units: mg/Nm³, * reported in ng/m³

In plasma gasification, emission values measured in InEnTec plasma facility were compared to the ones specified in the US EPA standard. In fact, US EPA verification testing results were obtained in 2000 for InEnTec plasma gasification for their pilot plant in Richland, Washington, USA. The capacity of the plant was reported to be 10 tons per day at that time. The values (in mg/Nm^3) for the particulate matter, mercury, hydrochloric acid and sulfur dioxide were, 3.3 (11 in US EPA), 0.00067 (0.05 in US EPA), 2.7 (29 in US EPA) and 162 (264 in US EPA), respectively.

CHAPTER 4

Gasification Experimental Study at UW LEER

In this chapter, the experimental study on the gasification is presented. This chapter briefly introduces the current status and future development of the gasification experimental study at UW LEER.

4 Gasification Experimental Study at UW LEER

4.1 Overview

The University of Waterloo Laboratory for Emerging Energy Research (UW LEER) aims to find potential solutions to challenges in the energy sector. It is focused on characterizing the existing technologies for energy conversion and utilization, as well as researching on the novel solutions by means of new technologies, such as nanotechnology. Combustion and gasification of biomass and natural gas, nano-catalysts and nano-structures are some of the fields that are currently being investigated in this laboratory [46].

Biomass Gasification at UW LEER has started in spring 2011 and is currently expanding in two major categories; experimental and modeling studies. The overall research objectives are as follows:

- Develop the standardized procedure for evaluating energy output (syngas and heat) and characterizing emissions from biomass gasification.
- Develop the applied technologies for improving the energy conversion efficiency and controlling particulate matters and greenhouse gases (GHGs) emitted from gasification.
- Develop predictive models to assist in designing the next-generation of gasifiers.

4.2 Experimental Characterization of Air Gasification of Biomass

4.2.1 Gasifier Experimenter's Kit (GEK) IV System

The experimental characterization of biomass gasification was started by assembling various parts and items in July 2012. An Imbert type, downdraft gasification system was purchased from All Power Labs Inc., a Berkeley-based company that has expertise in the field of gasification. Among various systems designed and developed by this company, the gasifier purchased and shipped to UW LEER is known as the "Gasifier Experimenter's Kit (GEK) level IV".



Figure 18: The GEK IV gasification system purchased by UW LEER [47]

Various parts and components were shipped from California to University of Waterloo and therefore, assembling of the GEK IV gasification system was done entirely at the UW LEER lab space.

GEK IV gasification system has five main sections:

- Hopper, a feedstock storage for long and continuous feeding of biomass into the reactor,
- Gasification reactor or the gasifier, in which all the thermo-chemical reactions take place,
- Cyclone and the jar to remove the tar and the residue from the gaseous producer gas,
- Packed-bed filter to remove the moisture from the gas and trap any dust in the stream and
- Swirl burner, as well as plumbing and tubing parts to burn the syngas produced by the gasifier.

After the assembling step, the *cold test* had to be done to ensure the system is working well before it gets hot. Moreover, a *pressure test* was performed to find the leaks in the system. In this case the system was pressurized and soapy water was used to find the leaks in the system.

In fact, one of the safety features of this gasification unit is the operating pressure, which is below atmospheric level. In other words, the air compressor injects compressed air with the pressure in

the range of 90 to 120 psi and the flow in the range of 6 to 8 cubic feet per minute (cfm) into the ejector venturi and the swirl burner, which results in a pressure drop in the reactor and the packed-bed filter. In fact, if there is a leak somewhere in the system, syngas does not leave the system to pose a danger to the operator; instead, air would go in and dilute the syngas. Figure 19 shows some of the leaks that were identified during the pressure test.



Figure 19: Identifying the leaks using the pressure test and soapy water

After sealing all the leaks that were found in the pressure test, the experimental setup was placed under the fume hood. Figure 20 presents this experimental setup. As shown, the reactor and then the cyclone are connected to the packed-bed filter via a tube. Producer gas (crude syngas), moves from gas outlet of the reactor and goes through the cyclone and the jar. The jar located at the bottom of the cyclone is used to collect any liquid tars, in case they form in the start-up and shut-down parts of the process. The gas then moves upwards in the filter and passes through organic materials (charcoal in this case) to lose its moisture content. At the top of the filter there are two foam disks in place to trap the dust and fine particles in the syngas. Finally, the cleaned syngas will be combusted in the swirl burner, where the excess air is provided.

For measurement and sampling purposes, syngas is collected in the gas sampling bags and does not go to the swirl burner. It is necessary to mention that this system operates under negative pressure difference (to move the syngas from the reactor to the swirl burner), created using an air compressor.

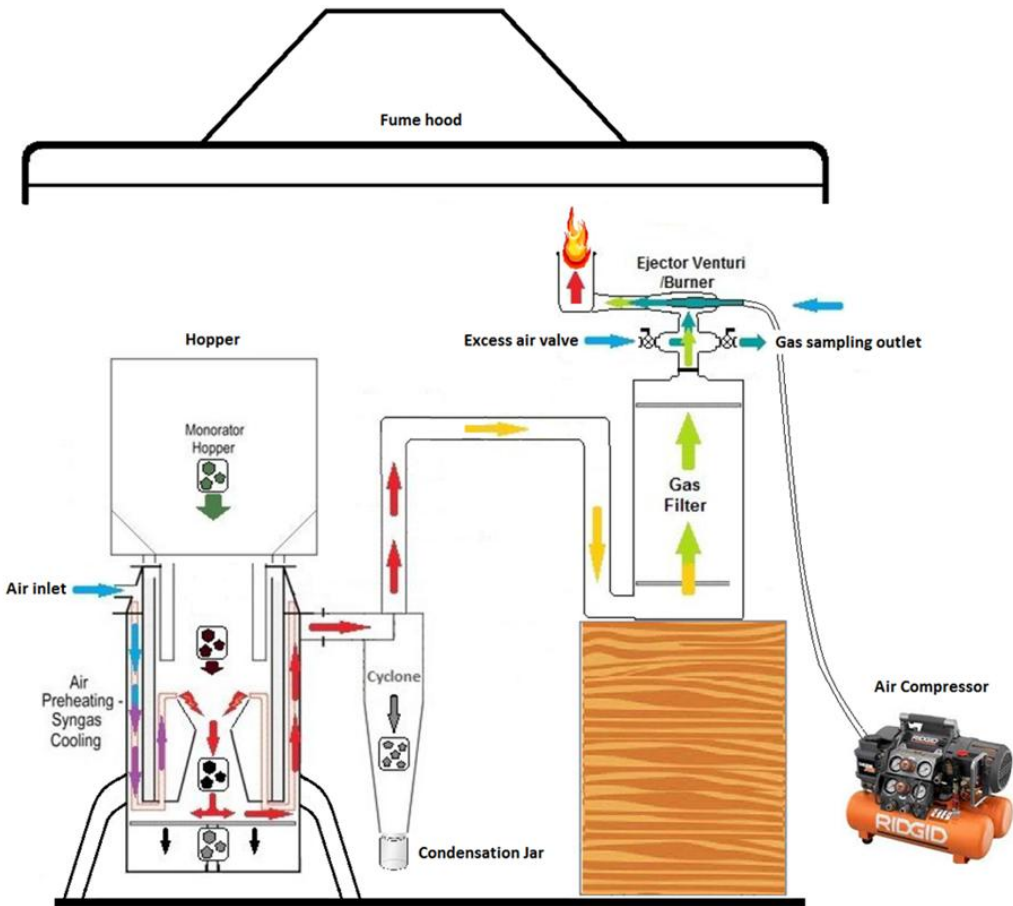


Figure 20: The schematic diagram of the GEK IV gasification system. Partially from [47]

As mentioned earlier, the gasifier in this system is a fixed bed downdraft, Imbert type and a batch unit, which uses air as the gasification medium.

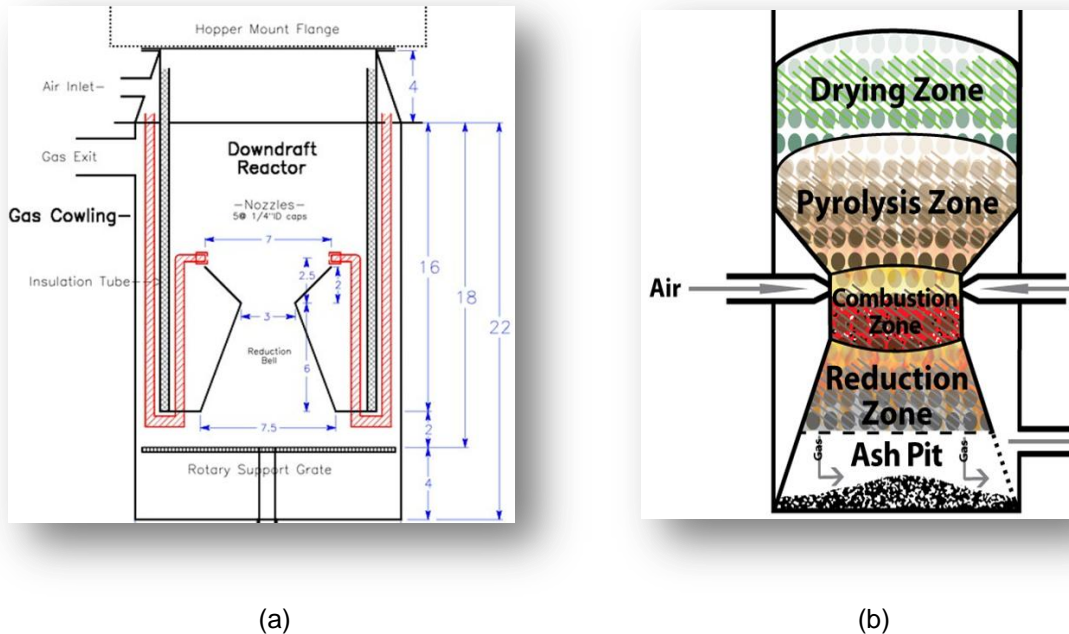


Figure 21: (a) GEK IV gasifier (b) Zones in a downdraft gasifier [47]

As explained in chapter 2, there are four major zones in a gasification process. In a downdraft type, these zones are Drying, Pyrolysis, Combustion and Reduction, respectively. In this type, biomass is fed from the top of the gasifier and goes through the drying zone first, where the moisture content of the biomass is evaporated. In the pyrolysis zone, dried feedstock is heated in a controlled environment ideally with absence of air or oxygen; thus, some chemical bonds between the molecules are broken down and the material is decomposed to some solids and gaseous mixture. In the combustion zone, air is supplied to the system using five radially located air nozzles and travels to the bottom of the reactor in the air tubes and gets pre-heated before reaching the nozzles at the combustion zone. In this zone, exothermic reactions take place and the required heat for the reduction reactions is provided. In this case, carbon monoxide and hydrogen content of the char is extracted to form crude syngas. The remaining material is ash, which is deposited at the bottom of the reactor and removed from the reactor at the end of each run.

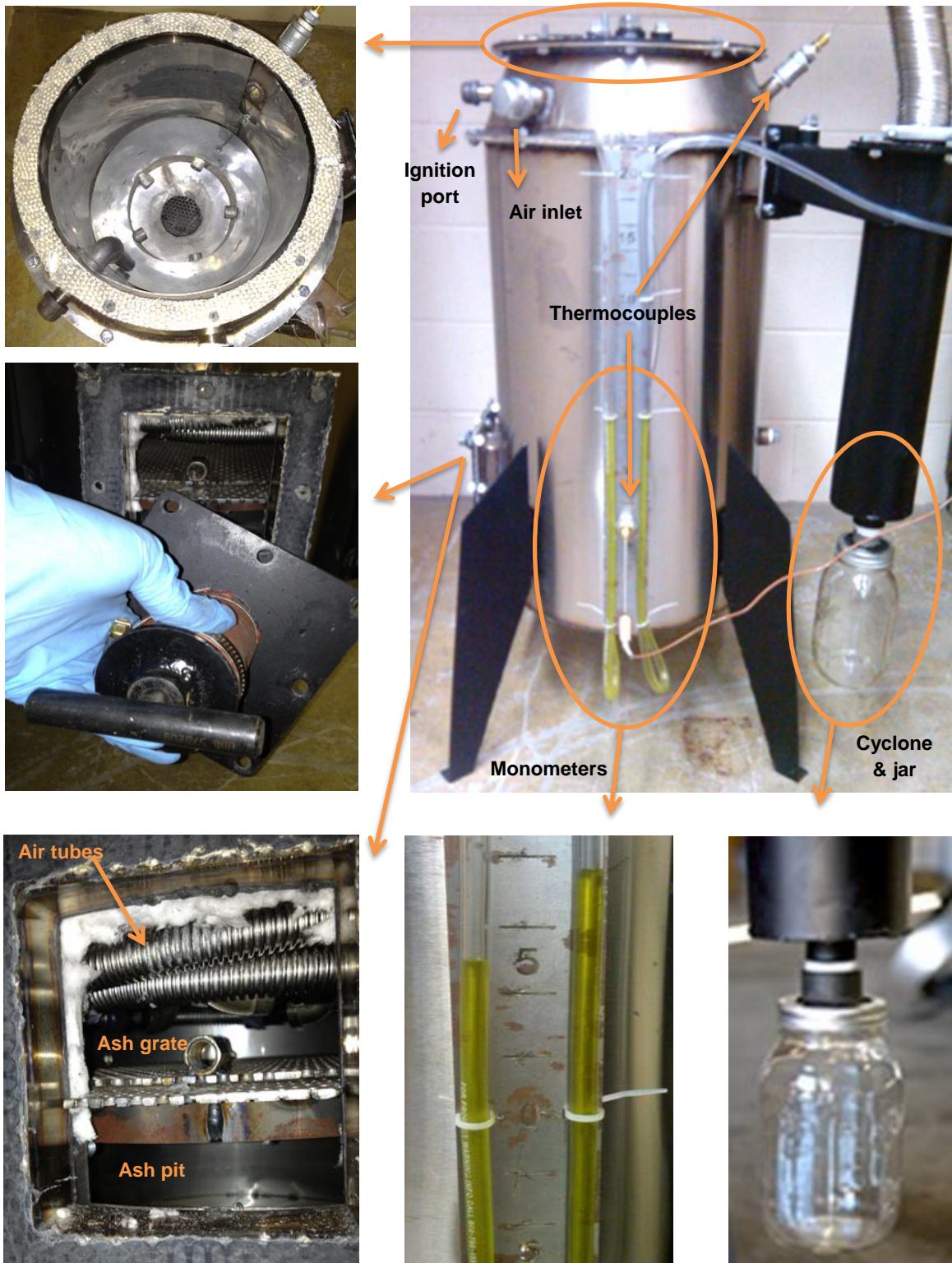


Figure 22: GEK IV gasification reactor and its components

As shown in Figure 22, the gasifier has an air inlet for air delivery and an ignition port designed to feed the combustion zone with fire starting liquid for the start-up of the gasifier. Moreover, ash pit, ash grate and its handle – designed to shake the grate and force the ash to fall into the ash pit – are visible in that figure. It is worth mentioning that the gasifier and the space between the reduction bell and the air nozzles were well insulated using sand. Bridging happens when the movement of the biomass is disrupted and there is no feedstock going into the reduction bell. This issue is mainly due to the inappropriate size of the feedstock inside the reactor. In order to avoid bridging, a coned shaped piece of metal was placed on the top of the reduction bell to guide the biomass into the combustion zone and ensure the flow of biomass is continuous. Figure 23 shows the packed-bed filter part of the system, as well as the valves and the swirl burner on top of it. In fact, there are four valves in this part of the system, as shown. Gas sampling bag is connected to the system via a valve for this purpose, while additional air required for complete combustion of the produced syngas enters the system via the excess air valve. Air compressor valve connects the air compressor line to the system, where compressed air is injected into the ejector venturi and thus, creates the suction in the entire unit to move the syngas from the gasifier to the swirl burner. Gas valve plays a key role in taking samples from the setup, as opening and closing of this valve directly affects the pressure drop in the system.

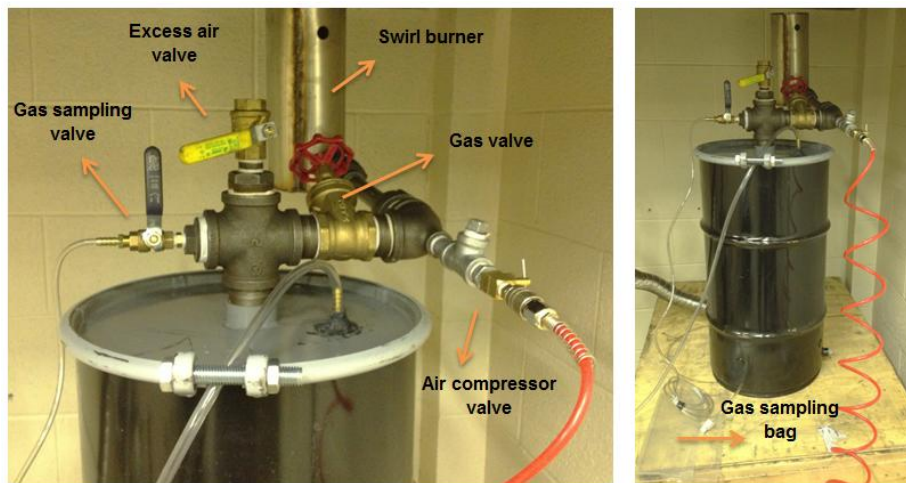


Figure 23: Completed packed-bed filter and the swirl burner on the top

There were few steps involved in preparing the packed-bed filter part of the system. As shown in Figure 24, a metal grate was placed at the bottom and then the filter was filled with some organic material (real wood charcoal in this case). The first 4 inches were filled with charcoal chunks with a size of 1 to 1.5 inches; however, size of the organic material was significantly reduced up to 10 inches to the top of the barrel. The main role of the organic material in the packed-bed filter is to trap the moisture content of the syngas. As briefly mentioned before, two foam filters, one with 65 dots per inch (dpi) and the other one with 45 dpi were then placed on the top of the charcoal. These foams were used to trap the dust and other particles within the syngas. Finally, another metal grate was placed on top of the foams to keep everything in place and only allow the syngas to move upwards during the suction.

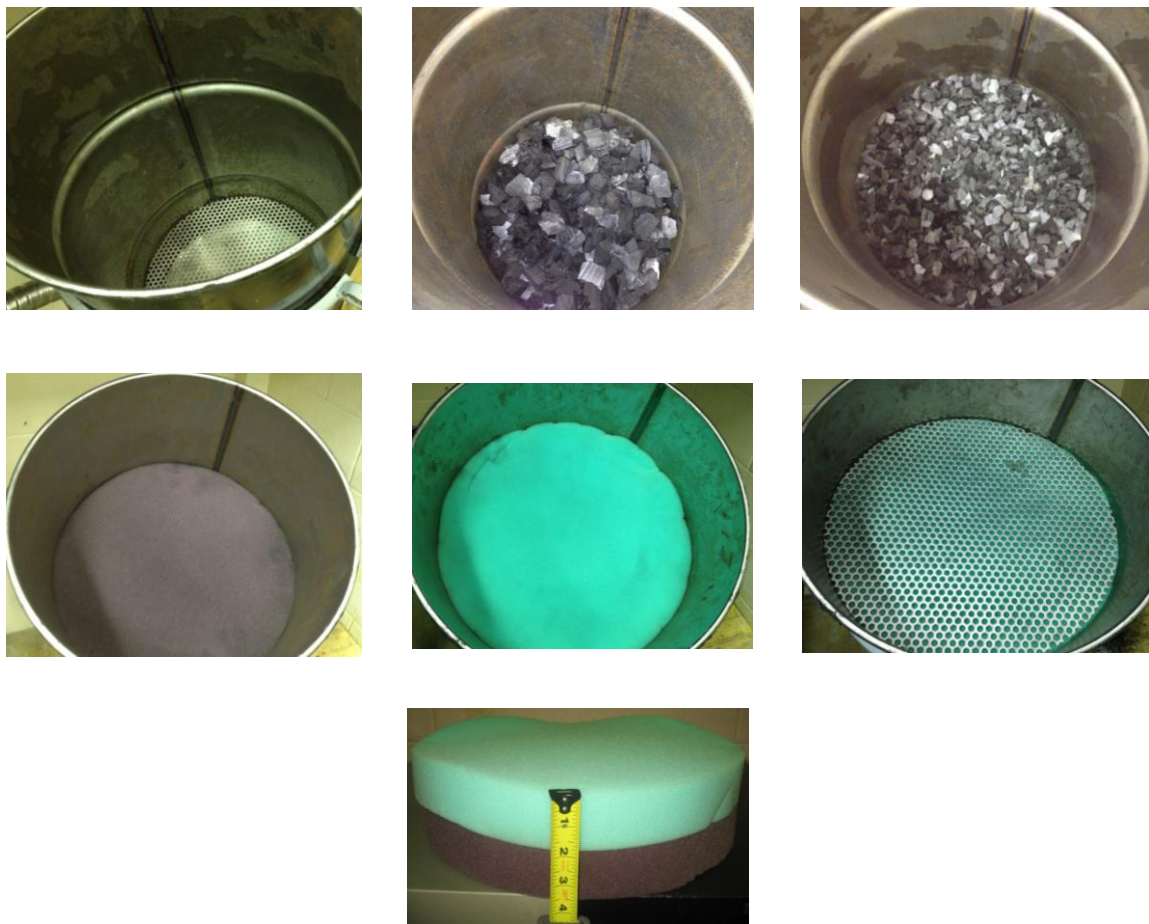


Figure 24: Various steps in preparation of the packed-bed filter

4.2.2 Experimental Procedure

In order to briefly explain the procedure in operating the GEK IV gasification system, it is necessary to start with the feedstock preparation. In this experimental study the following were used as the feedstock:

- sugar maple charcoal
- poplar wood chips
- tamarack wood chips

It was initially decided to use poplar and tamarack barks as well; however, due to high content of volatile matter existing in the barks, gasifier did not react well to the new feedstock and the start-up processes were not successfully executed. Therefore, it was decided to stay at the safe side and leave the bark chips out in this experimental study.

The allowable size of the feedstock for the GEK IV gasification system is between 0.5 to 1.5 inches. As shown below, sifting had to be done to remove very small pieces of wood chips, as they are equally troublesome as the large pieces. Poplar and tamarack wood chips were shredded to the right size and were contained in separate bags with a label by the supplier.



Figure 25: Wood chips used in this experimental study

The GEK IV gasification system requires the moisture content of the feedstock to be below 15% during the start-up and to be below 25% for the rest of the process. On the other hand, any dust and fine particles had to be removed from the biomass. Therefore, the sugar maple charcoal and the wood chips were cleaned and then dried to ensure most of the fine particles are removed.

It is necessary to mention that the charcoal lumps had to be broken down to smaller pieces to fall in the 0.5" to 1.5" range. As shown in Figure 21, this gasifier uses a reduction bell with a 3" diameter *hearth restriction*; therefore, the feedstock consumption rate (dry basis) is reported to be within 2.5 to 14 *kg/hr* [47]. The biomass consumption rate estimated in this study is about 3 *kg/hr*.

Initially, the gasifier had to be fed with real wood charcoal for preliminary runs; thus, the reduction bell was filled with real wood charcoal. Preliminary runs were extremely important to become familiar with the operation of the system. In order to optimize the performance of the system, various practical issues were considered. For example, the ignition port of the gasifier was optimized to provide fire starting liquid more uniformly to the combustion zone and the air nozzle area, as shown in Figure 26 (b).

In order to start the gasification process, it is firstly necessary to create the combustion zone in the reactor. That is why charcoal is used initially for this purpose. The reactor is then filled with the wood chips, which are placed on top of the charcoal that is required to create the combustion zone during the start-up stage. It is important to shake the reactor and the ash grate handle vigorously to push the biomass downwards and make sure that all the space in the reduction bell is filled with charcoal and more importantly, there is no space between wood chips and the charcoal bits in the reactor.



(a)



(b)

Figure 26: (a) Without proper ignition port (b) With proper ignition port



Figure 27: GEK IV reactor being filled with wood chips

Once the reactor is filled to the desired level (usually until it reaches 5 inches below the top), the reactor lid is placed on the top of the reactor. At this point, the gasifier is ready for operation; therefore, initial ignition of the GEK IV gasifier is done using 60 *ml* of fire starter and a propane torch.

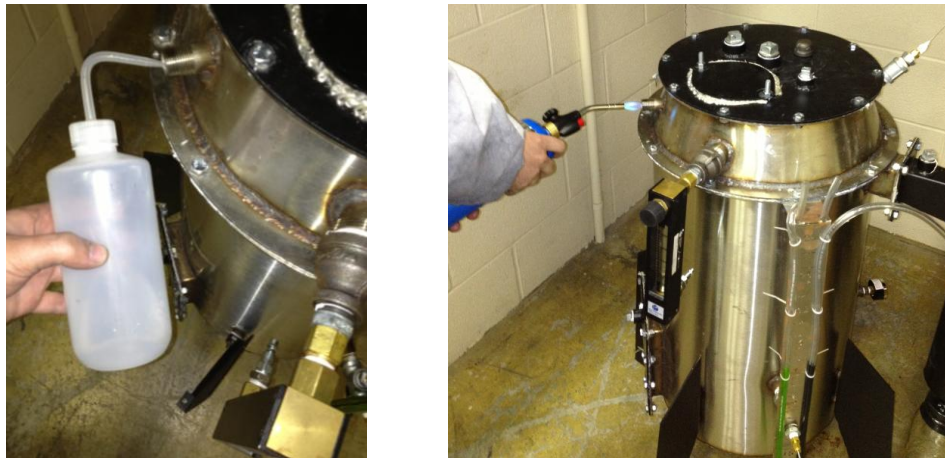


Figure 28: Igniting the GEK IV gasifier

Later on, by optimizing the pressure drop (pull) using the air compressor and also by controlling the amount of air supplied to the system (using the installed flow meter), gasification process starts to occur at the bottom of the reduction bell, in the reduction zone. It is always desirable and also important to know how fast we are consuming the feedstock inside the reactor. Moreover, it is equally important to know how hard we are pushing the gasifier to produce syngas.

In order to have a sense of these two parameters, the monometers and two thermocouples (shown in Figure 22) are used. The monometers can be regarded as the “speedometer” for the GEK IV gasifier, which read the pressure difference between the atmosphere and the pressure inside the reactor and the packed-bed filter in inches of water. As previously shown in Figure 22, the right hand side tube reads the difference between atmospheric pressure and the pressure inside the packed-bed filter, while the one on the left hand side shows the full reactor pressure drop, i.e. pressure drop over nozzles and reduction bell of the reactor (see Figure 29). The optimum level for the latter is between 4 to 6 inches of water, although the full range is from 1 to 12 inches of water. If the pressure drop is too much, syngas will have low energy content (weak syngas) and soot/clinkers are formed. On the contrary, if the pull is too slow (1 to 3“of water), lots of tar will be produced. Thus, during the start-up the full reactor pressure drop is set to be 2” of water and once, the gasifier is fully up and running, the pressure drop is increased to 5 inches of water [47].

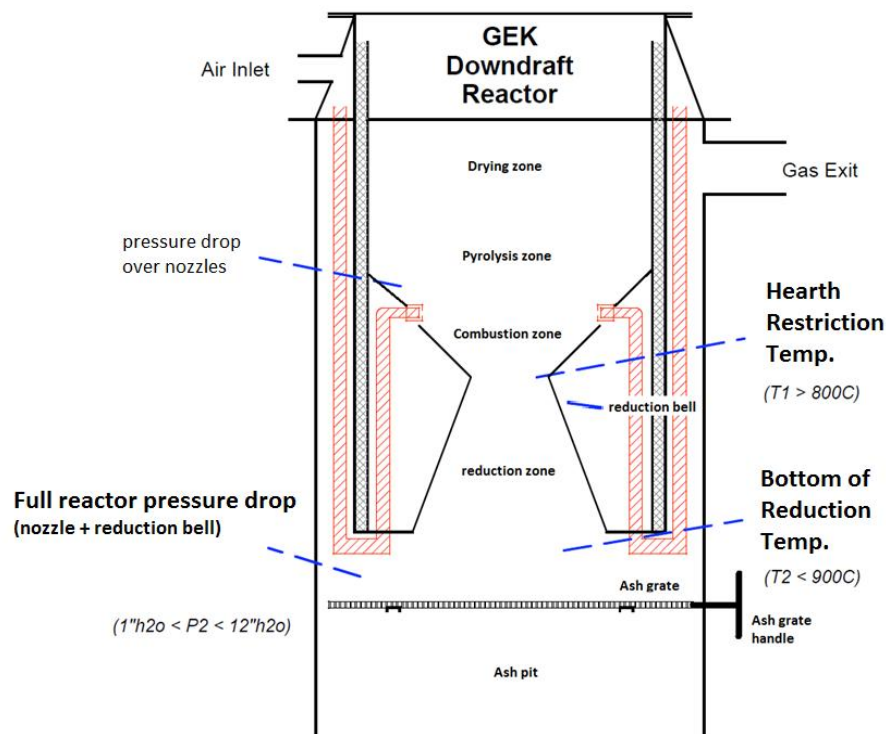


Figure 29: Temperature and pressure readings in the GEK IV gasifier [47]

In the GEK IV reactor there are two K type thermocouples that are used to measure the temperatures for two points: on top of the reduction bell, where combustion occurs (hearth restriction); and at the bottom of the reduction bell, where gasification occurs (reduction zone). The thermocouples can be regarded as the “tachometer” and can show how hard we are pushing the system. In fact, hearth restriction temperature should always be kept above 800°C to ensure a tar-free operation of the gasifier is obtained. In case the temperature at the hearth restriction of the reduction bell falls below that value, tar production rises to the unacceptable levels [47].

The second thermocouple is used to measure the temperature at the bottom of the reduction bell. This is the reduction zone temperature and should be kept below 900°C. If this temperature goes beyond the suggested limit, excessive amount of soot will fill the condensation jar. Furthermore, the bottom of the reduction bell could be clogged by clinkers [47].

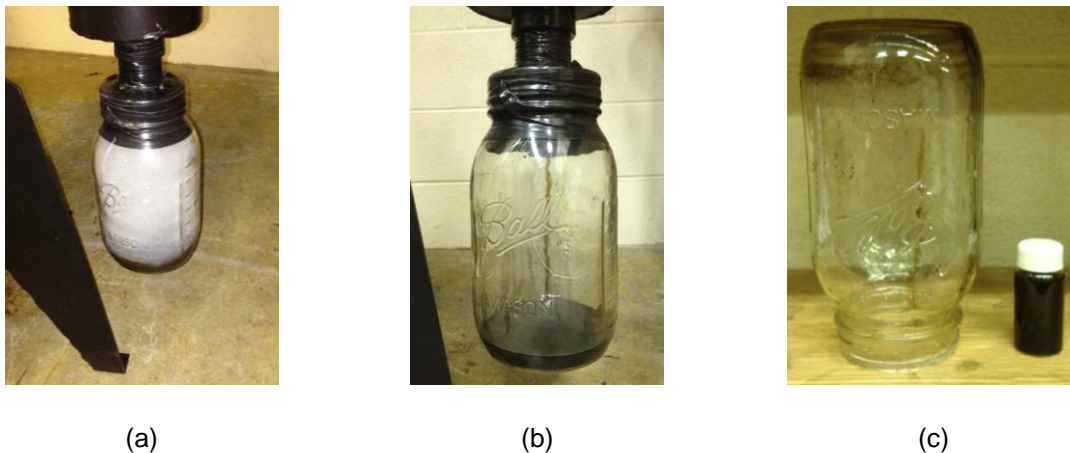


Figure 30: Jar at (a) Start-up process (b) Shut-down process (c) Clean-up

Figure 30, illustrates the condensation jar part of the system. As shown in part (a), when the system is in the start-up mode, due to presence of water vapor and high pressure within the jar, the jar becomes white; however, during the shut-down process, as the temperature and pressure drop decrease, some tars are formed and thus, are collected in the jar. By observing the content of the jar during the operation – when operating within the proper temperature and pressure limits – it can be concluded that once the system is operating within the suggested ranges, the syngas is tar free as expected.

It was observed that within a couple of minutes from the gasifier start-up, gas leaves the swirl burner. As shown below, initially this gas is rich in water vapor and is not combustible; however, within 3 to 4 minutes after the ignition, the system is capable of producing a combustible gas and more importantly maintain the flame.

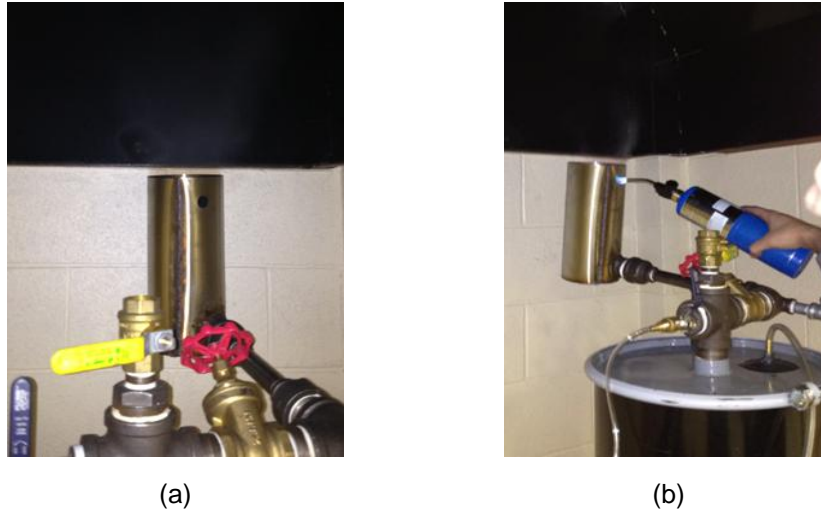


Figure 31: Swirl burner during the star-up process

Figure 32, shows the packed-bed filter and the swirl burner part of the system, when the gasifier is fed with poplar wood chips. The relationship between the hearth restriction temperature of the reduction bell and the flame color from combustion of the produced syngas can be observed as below:

- (a) shows the flame when the hearth temperature was observed to be around 100°C
- (b) shows the flame when the combustion zone was recorded to be around 300°C
- (c) illustrates the flame when the temperature was close to 500°C and finally
- (d) where, the hearth restriction temperature was observed to be above 800°C

By observing the color of the flames in this case, it can be concluded that considerable amount of tar is expectedly present in the gas, when the hearth restriction temperature was well below 800°C. Once the temperature in the combustion zone reaches the desired limit, the color of the flame turns to blue, which is the sign for combustion of considerable amount of carbon monoxide and less tar, as expected.

Combustion of hydrogen occurs extremely fast and is normally colorless; therefore, color of the burning syngas does not provide any information in this regard. It is worth mentioning that the air excess valve on top of the packed-bed filter can also play a key role in this case. In fact, the orange color of the syngas flame could be due to insufficient amount of oxygen and thus, incomplete combustion of the syngas. Once the air excess valve is adjusted, the flame is stable and the complete combustion of the syngas is observed.



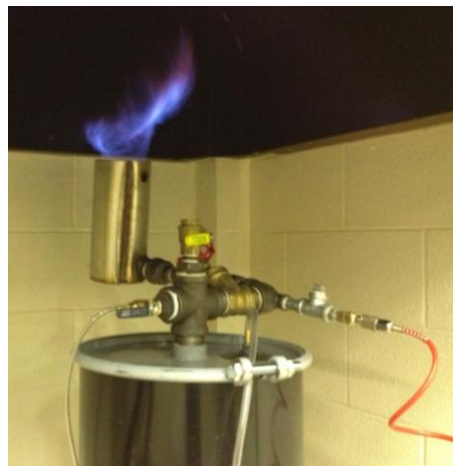
(a)



(b)



(c)



(d)

Figure 32: Swirl burner in the star-up process using poplar wood chips

For safety reasons, a carbon monoxide detector was placed beside the packed-bed filter to beep in case of any carbon monoxide leak from the system. Moreover, the packed-bed filter was elevated to go further up into the fume hood to ensure proper ventilation is in place (see Figure 20). Once the gasifier was within the desired range, the air inlet port and all the valves – including the gas valve (the red valve on the packed-bed filter) – were temporarily shut; hence, the suction in the system was temporarily terminated. Due to the momentum of the syngas within the packed-bed filter, some gas would accumulate on top of the filter and flow into the gas sampling bag, once the gas sampling valve was opened. Figure 33 presents collected syngas that was produced from poplar wood chips.



Figure 33: Gas sampling bag containing the collected syngas

Figure 34 (a) shows the bottom of the reduction bell and the ash pit before the start of the gasification process, while Figure 34 (b) shows the gasified wood chips collected from the bottom of the reduction bell during the reactor cleaning and maintenance.



(a)



(b)

Figure 34: Feedstock (a) Before (b) After the gasification process

4.2.3 Data Analysis and Measurement Procedure

As the analysis of the syngas produced in the GEK gasifier and obtaining the gas composition were the key parts of the experimental study, a **Gas Chromatography (GC)** unit was installed, calibrated and upgraded in the Engineering 3 laboratory space by the UW LEER graduate students, including the author. It is necessary to mention that beside the GC unit, other gas analysis options (e.g. use of the Testo 350 XL, which is a portable gas detection system) were also considered; however, due to the required level of accuracy in the measurements, the GC was chosen to be the gas analysis unit for this project.

The GC unit used in this experimental study is a Hewlett Packard (HP) 6890 type and the two GC columns that were purchased from Agilent Technologies to be installed in the GC unit were as follows:

- **Packed Column:** Molesieve column with a diameter of 1/8" and length of 6" and the part number of G3591-80017. This column was used to detect the inorganic elements in the syngas.
- **Capillary Column:** GS-Carbon PLOT with the dimensions of 30 m × 0.32 mm × 3.00 μm and the part number of 113-313. This column was used to detect the organic and hydrocarbons available in the sample.

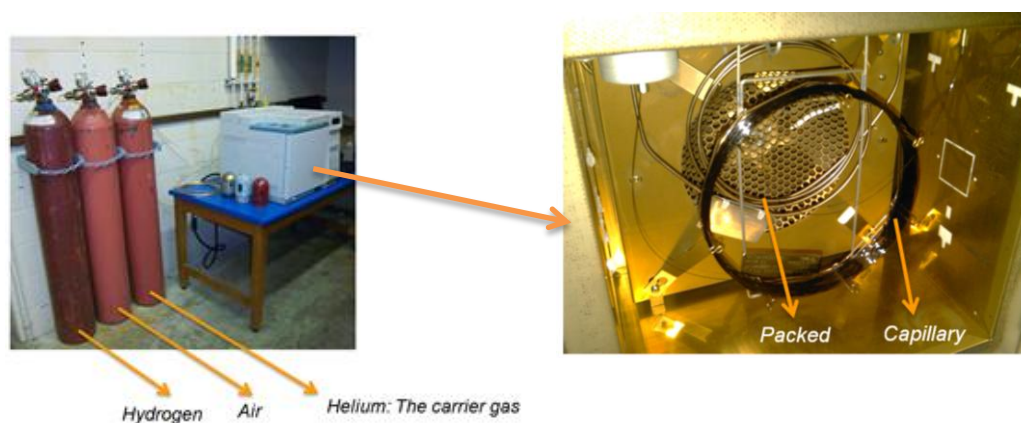


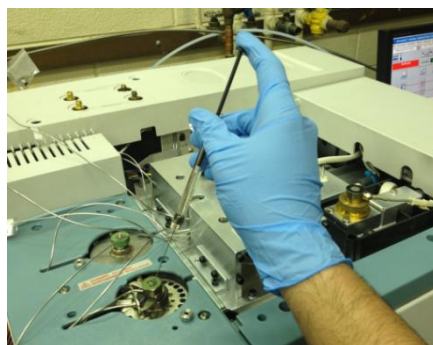
Figure 35: the GC unit with the carrier gas cylinder and the columns

The two detectors in this GC unit were **Thermal Conductivity Detector (TCD)**, which operates based on the thermal conductivity difference between the substances within the sample and is connected to the packed column. This detector is used to identify the inorganic elements, such as hydrogen, oxygen, nitrogen, carbon monoxide and NO_x. The second detector is the **Flame Ionization Detectors (FID)**, which uses the hydrogen and air to burn the sample to detect the composition of the injected syngas. This detector is connected to the capillary column and is best for detecting the hydrocarbons in the syngas. As shown in Figure 35, helium was used as the carrier gas in this GC system, while the hydrogen and the compressed air were necessary for the operation of the FID detector. Moreover, the packed and capillary columns installed in the oven part of the GC unit are shown in the Figure 35. There were several preliminary and crucial steps in preparing the GC unit for operation. Apart from the leak test for the gas cylinders, these tests had to be done for the columns inside the GC oven. Moreover, column conditioning was necessary before operation of the GC unit. In this case, the columns were initially heated at 250°C for 24 hours once installed in the GC, while the carrier gas (helium) was circulating inside the columns.

The next important step before operating the GC unit was the calibration of the system with the calibration mixtures, which were ordered to Praxair Inc. for blending and processing. Due to the nature of the gases and their concentrations, two calibration mixtures were delivered. One contained 5.07% Carbon Monoxide, 4.05% Hydrogen, 0.407% Methane, 9.85% Nitrogen, 1026 ppm Nitric Oxide and 1006 ppm Nitrous Oxide with Helium as the balance gas for the TCD detector and the Packed Column. The second blend contained 0.5% Acetylene, 0.499% Ethylene and 0.5% Ethane with Helium as the balance gas for the FID detector and the Capillary Column. Initially, the idea for calibration and also sample injection into the GC was to use a manual injection GC syringe; however, due to the poor results obtained by this method of injection, it was decided to purchase and install a semi-automatic valve for both inlets (packed and capillary) to improve the injection of the gas into the GC. This work was entirely done by the UW LEER graduate students, who were doing research on combustion and gasification, including the author.



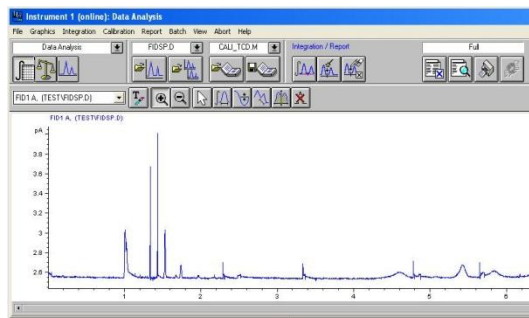
(a)



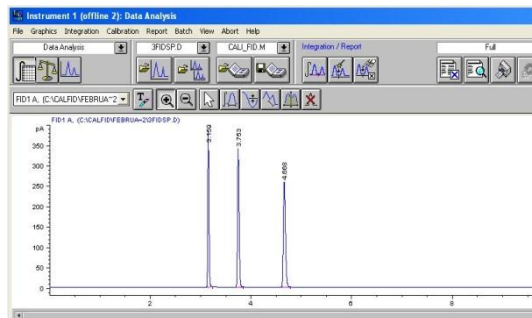
(b)

Figure 36: (a) The manual GC injection syringe (b) The syringe in operation

As shown below, the use of a GC syringe did not create the best signal and due to inaccuracy in the volume of the injected gas and its pressure, the GC syringe was replaced with the injection valve that had to be installed on the GC. Figure 37 compares the calibration of the FID detector when syringe and the valve were used. In the case of the syringe (Figure 37a) the signal was not accurate at all and the target gases could not be identified; however, in the case of using the valve (Figure 37b), peaks for acetylene (C_2H_2) on the left, ethylene (C_2H_4) on the middle and ethane (C_2H_6) on the right hand side were clearly visible.



(a)



(b)

Figure 37: (a) Signal using syringe (b) Signal using the valve

Figure 38 illustrates the valve, the configuration of the system after the valve installation and the mechanism of this part. This valve that was purchased from Valco Instrument Co. Inc. is a high temperature GC injector and has a maximum pressure of 300 psi and a maximum temperature of 330 to 350 °C.

As shown in Figure 38c, carrier gas or the mobile phase constantly flows into the mobile phase inlet and the columns. Providing the columns with a constant flow of mobile phase (helium in this case) is vital, as this approach protects the columns against any thermal damage. When the valve is in “Position 1 or loading” stage, sample coming to the valve fills the sample loop and its excess leaves via the vent or the waste outlet. Once the valve is in “Position 2 or injection” stage, carrier gas coming into the system pushes the sample into the sample loop and to the columns in the GC.

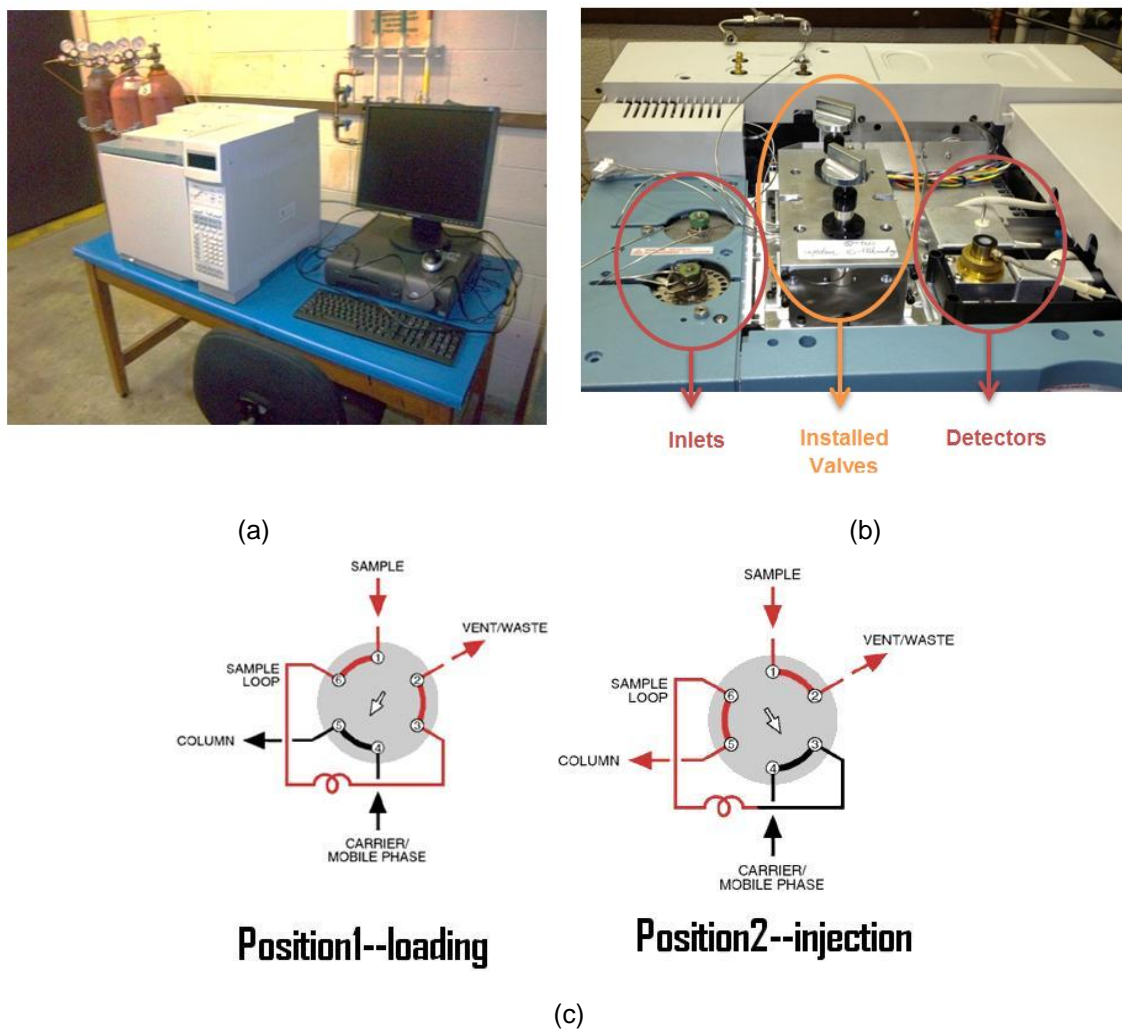
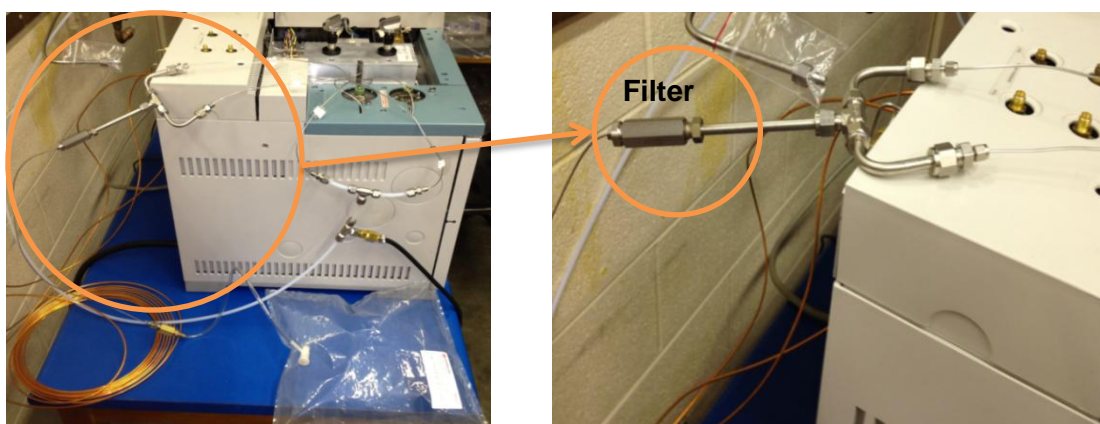


Figure 38: (a) Before upgrading (b) After upgrading (c) Valve mechanism [c from 48]

Once the GC injection system was upgraded, the GC and its two columns and detectors were calibrated again to ensure that the results obtained from this system were accurate.

In this experimental study, gas sampling bags were used to collect samples and inject into the GC. As shown in Figure 39, a T-shaped fitting was used to inject the gas (either the calibration gas or the syngas produced in the gasifier) to both the packed and capillary columns, which were connected to the TCD and FID detectors, respectively. A filter was also installed between the sampling bag and the inlets to ensure there is no solid particle going into the GC. The filter was made by Valco Instrument Co. Inc. and the gas sampling bags, i.e. Supel™ Inert Film with the volume of 5 L and Screw Cap Valve (SCV) were purchased from Sigma-Aldrich Canada.



(a)

(b)

Figure 39: (a) The bag and the injection valve (b) The filter before the valve

Various methods were used in the calibration process using the mixtures delivered by Praxair Inc.; however, the most appropriate method that worked well for both detectors was seen to be the one that is as follows: The oven was programmed to start from 125°C and hold the temperature for 3 minutes and then increase it to 250°C with the rate of 20°C/min; then hold it for another 3 minutes. The calibration gas was injected to both columns and the detectors were working simultaneously. The inlet temperatures for both columns were set to be 250°C and the detector temperatures to be 300°C, while the flow of hydrogen, air and helium (make-up flow) in the FID detector were 40, 400 and 26 *ml/min*. In the TCD detector the reference flow rate and the make-up flow (helium) were set to be 45 and 2 *ml/min*. The inlets for both columns were also set to be operating in the split mode.

Using the calibration cylinders, the final calibration peaks both for the TCD and the FID detectors are presented in Figures 40 and 41. As shown, hydrogen was the first gas to be identified using the TCD detector, followed by nitrogen, nitric oxide, methane and carbon monoxide. The sixth element that was in the inorganic calibration cylinder was nitrous oxide, which was identified well after the rest of the elements. In fact as shown in Figure 40, the response time for the first five elements is approximately 2 minutes; however, it took around 10 minutes for the TCD detector to identify nitrous oxide. That is why the total time for each run was set to be 12 minutes to ensure there is enough time to identify any traces of nitrous oxide in the injected samples. In order to see the peaks more clearly, zoomed views of the calibration results are also shown in the figures below.

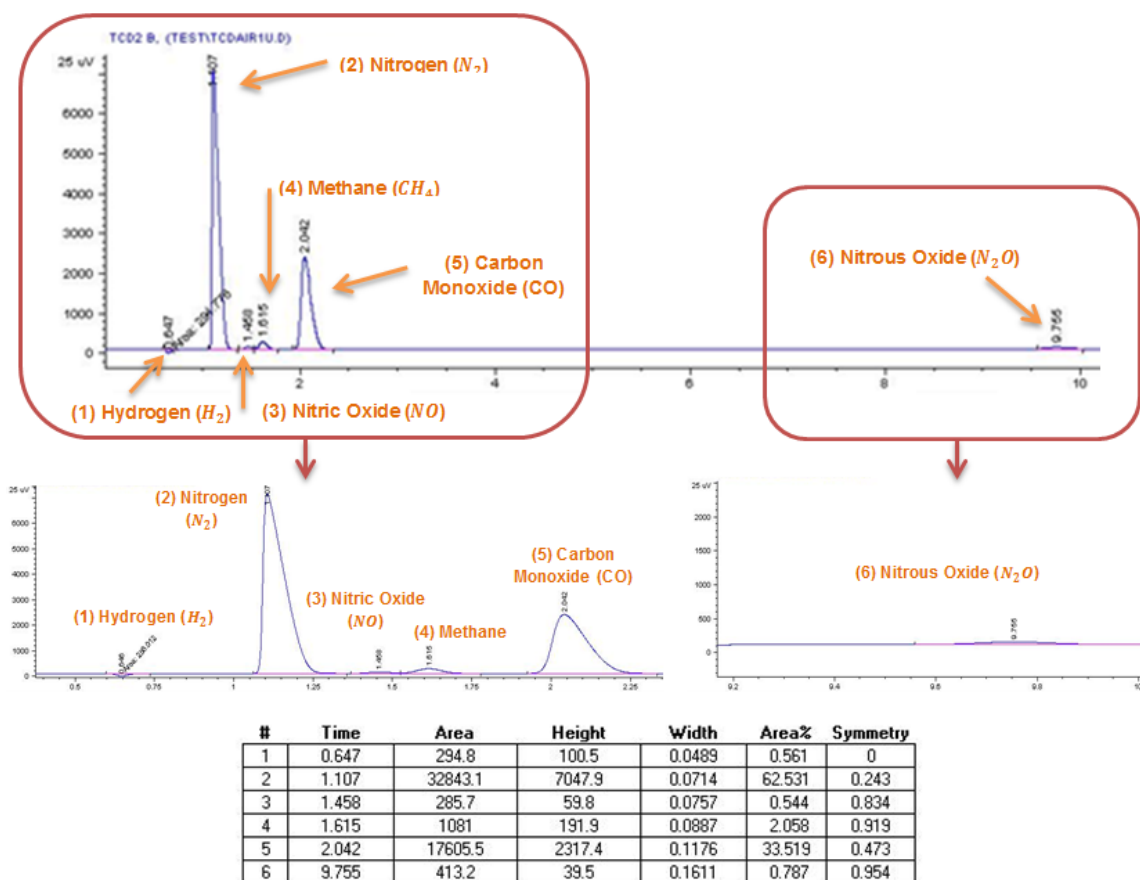


Figure 40: Calibration results for the inorganic elements (TCD detector)

In the FID detector, the response times were all within the first two minutes from the start. Acetylene was the first hydrocarbon that was identified in this case. Ethylene was the next followed by ethane. Although methane was mixed with the inorganic compounds, it could be detected using both the TCD and FID detectors. Therefore, a sample from the inorganic calibration blend was injected to the capillary column and the FID detector and as expected, only methane was identified. The response time in this case was about 1.3 seconds; thus, methane became the first element in the calibration process (before acetylene, ethylene and ethane) using the FID detector. This approach actually worked as a validation criterion in this experimental study, as the peak for methane in TCD detector could be compared with the one obtained in the FID detector. This way, the calculated concentrations found to be approximately identical in both detectors for methane.

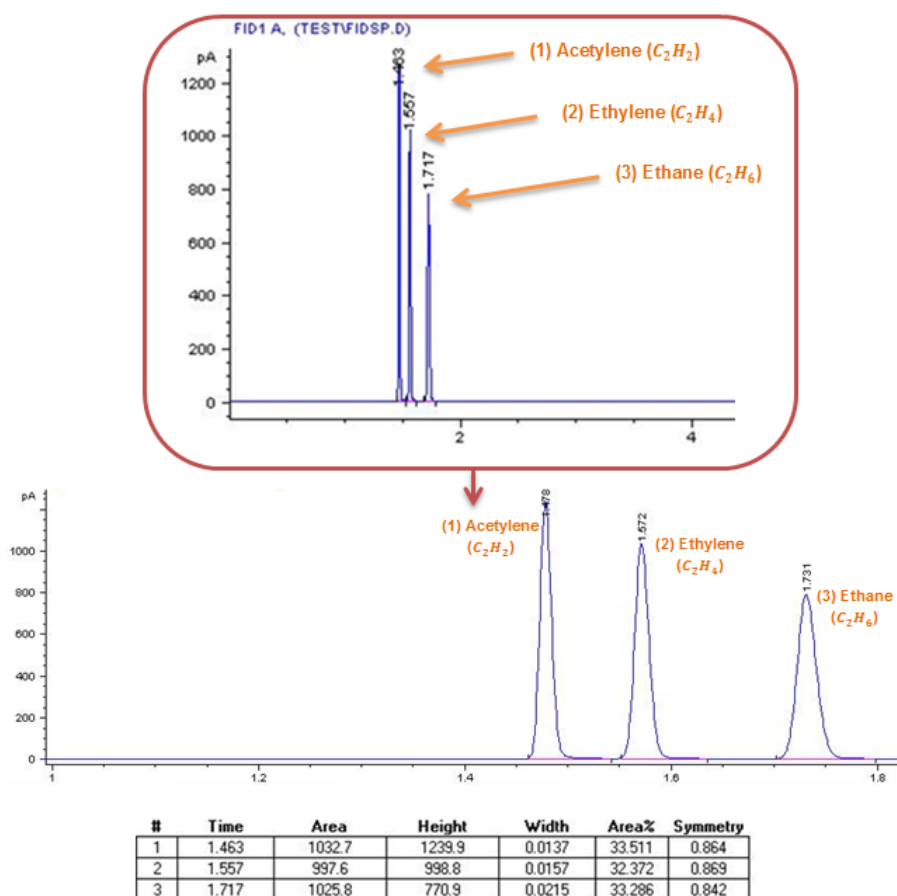


Figure 41: Calibration results for the hydrocarbons (FID detector)

It is necessary to remind that as the concentrations of the calibration blends were known to us, its correlation with the peak area of the detected elements calculated by the GC system could be used to calculate the concentration of the syngas, while a comparative analysis on response times could assist us in the identification of the elements within the syngas. This information is summarized in Figure 42. In fact, in the calibration stage, several runs were executed and the “Measured Peak Area” presented is the average value of the five best results in both TCD and FID detectors; hence, by injecting the syngas produced in the gasifier, syngas components could be identified based on the response time (location on the x axis of the chromatogram) and the concentrations could be calculated based on the area under each peak.

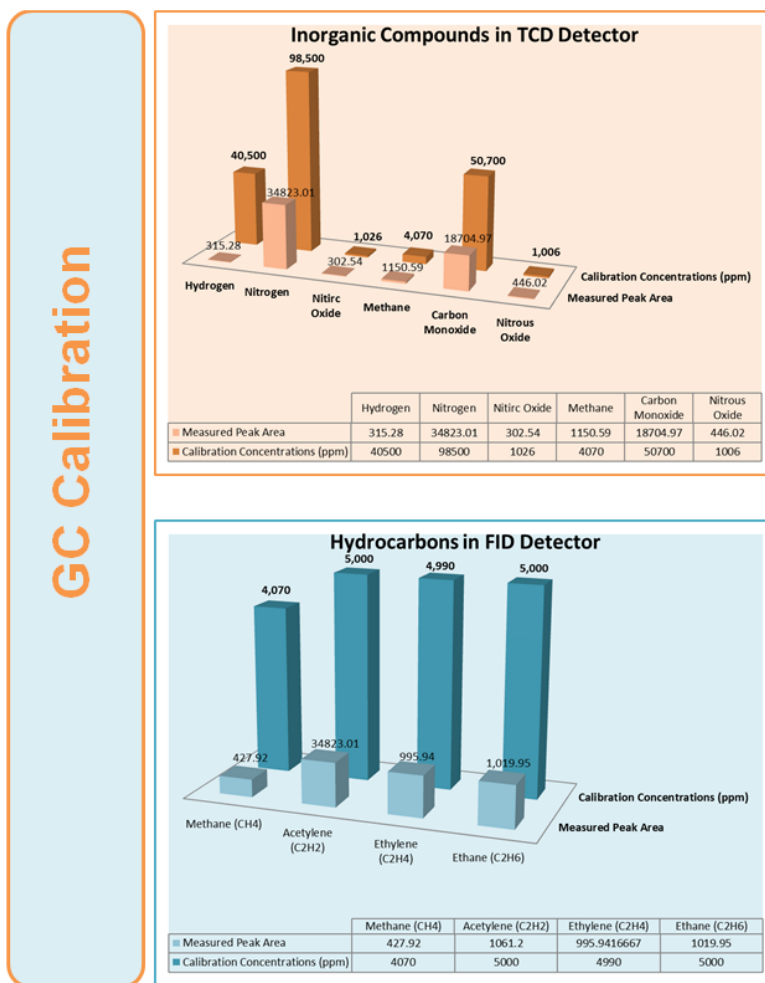


Figure 42: Average peak areas and calibration concentrations

4.3 Experimental Results and Discussions

In this section, key findings from the experimental study are presented. Moreover, the results are shown and briefly discussed.

4.3.1 Proximate and Ultimate Analysis of the Feedstock

The table below presents the proximate analysis of the biomass used in this study. As proximate and ultimate analyses are time consuming and expensive, data reported by literature is used in this case.

Table 9: Proximate analysis of the biomass used in this study. Data from [49]

biomass	Proximate Analysis (Wet basis)				Proximate Analysis (Dry basis)		
	VM *	FC **	M ***	ASH ****	VM	FC	ASH
Maple	70.1	17.8	8.4	3.7	76.6	19.4	4.0
Poplar	79.7	11.5	6.8	2.0	85.6	12.3	2.1
Tamarack	63.7	24.1	8.4	3.8	69.5	26.3	4.2

* VM: Volatile Matter *** M: Moisture
 ** FC: Fixed Carbon **** ASH: Ash

It is of significance to know the heating value of the feedstock. In fact, *higher heating value (HHV)* or the gross calorific value of the feedstock is the amount of thermal energy released by the unit mass or volume in the case of combustion of the feedstock, once the products are cooled down to 25°C. HHV actually considers the water content in the products to be in liquid form, which means it includes the latent thermal energy of water vaporization [50].

In order to estimate the HHV of the biomass, experimental studies can be very beneficial. In fact, some researchers in their scientific work [51] have developed an empirical correlation for variety of fuels that also works for biomass. In this case, ultimate analysis of the biomass is required. Using the empirical formula shown below, one can obtain the HHV of the feedstock.

$$HHV = 349.1 C + 1178.3 H + 100.5 S - 103.4 O - 15.1 N - 21.1 ASH [kJ/kg] \quad (5.1) [51]$$

On the other hand, *lower heating value (LHV)* or the net calorific value is the thermal energy produced by the fuel combustion without the latent heat of vaporization of the water. Therefore, LHVs are always either equal or smaller than HHVs for any type of fuel. The units for HHV and LHV of a fuel could be kJ/Nm^3 , MJ/Nm^3 if expressed based on volume and kJ/kg or MJ/kg if expressed based on mass.

The relationship between LHV and HHV can be written as follows [50]:

$$LHV = HHV - h_g \left(\frac{9H}{100} + \frac{M}{100} \right) \quad (5.2)$$

Where H is the hydrogen percentage, M is the moisture percentage of the fuel and h_g is the latent heat of water vapor in the same unit as HHV, i.e. 2260 kJ/kg .

The table below shows the ultimate analysis of the biomass feedstock that was used in this study, as well as the calculated HHV and LHV values.

Table 10: Ultimate analysis of the biomass used in this study. Data partially from [49, 50]

biomass	Ultimate Analysis (Dry and Ash free basis)					Calculated HHV (MJ/kg)	Calculated LHV (MJ/kg)
	C	O	H	N	S		
Maple	51.0	40.3	6.2	0.4	0.11	21.193	19.742
Poplar	50.6	40.7	6.1	0.6	0.02	20.882	19.487
Tamarack	56.0	31.0	10.2	0.7	0.11	28.609	26.344

4.3.2 Gasification Medium (agent)

As explained in chapter 2, there are a number of candidates for the gasification medium or the gasification agent. Air, oxygen, steam and carbon dioxide are the most well-known gasification agents. The simplest and the most economically feasible one is clearly air. Therefore, in this study air is the gasification medium for the GEK IV gasification system.

In order to compare the calorific values of the syngas resulted from biomass gasification when air, steam and oxygen were used as the gasification agents, it is reported that oxygen and steam produce the richest syngas, while air, expectedly resulted in the production of the lowest quality syngas [52].

If the gasification medium (air) flow rate increases, biomass consumption increases as well. As a result, rate of combustion in the combustion zone rises. This actually leads to enhancement of the drying and pyrolysis zones, although there is always a limit for every parameter to make sure complete gasification takes place. While air flow rate into the system is an important factor, biomass consumption rate is equally important in this case. In order to tangle these two parameters together and consider both of them simultaneously in air gasification of biomass, a parameter called “Air to Fuel Equivalence Ratio” (ER) is defined as follows [52]:

$$\text{Pyrolysis } ER(= 0) \leftarrow \text{gasification } ER (< 1) = \frac{\text{Actual air}}{\text{Stoichiometric air}} = EA (> 1) \text{ Combustion} \quad (5.3)$$

where EA is the excess air coefficient and is used for combustion. In other words, ER can be written as follows [53]:

$$ER_{\text{Air to Fuel}} = \frac{(\text{Flow rate of air/rate of biomass consumption})_{\text{actual}}}{(\text{Flow rate of air/rate of biomass consumption})_{\text{stoichiometric}}} \quad (5.4)$$

In a combustion process, the amount of air supplied should be at least equal or in most cases greater than the stoichiometric amount of air; however, in the gasification process, due to the nature of this process, the air supplied to the system is actually a small ratio of the stoichiometric amount. The stoichiometric amount of air for complete combustion can be determined based on the ultimate analysis of the feedstock and is written as below [50]:

$$M_{\text{air,stoichiometric}} = [0.1153 C + 0.3434 \left(H - \frac{O}{8} \right) + 0.0434 S] \quad [\text{kg/kg dry fuel}] \quad (5.5)$$

It is worth mentioning that dry air has 76.8 wt. % nitrogen, 23.16 wt. % oxygen and 0.04 wt. % of other gases; therefore, by using equation (5.5), we can calculate the stoichiometric amount of air for our biomass samples. Once this value is obtained, the ER value can be calculated. As mentioned previously, ER value is a significant parameter in air gasification of biomass. If ER is zero the process is 100% pyrolysis; if it is more than 1, the process is actually combustion. Literature suggests that air gasification of biomass should have the ER between 0.2 to 0.3. Moreover, research on downdraft gasifiers shows that the optimum value of ER in these systems is determined to be 0.25 [54].

It is necessary to mention that the flow rate of the air going into the system was measured to be 59.8 to 60 L/min ($3.58 \text{ m}^3/\text{h} \cong 3.6 \text{ m}^3/\text{h}$) once the system was in steady state condition and the reactor was up to the required temperature. The biomass consumption rate was also estimated to be around 3 kg/h, as 0.5 kg of feedstock was fed into the gasifier every 10 minutes. The calculated values for ER then, can be found in the table below.

Table 11: ER values and related parameters

biomass	$M_{air,stoich.}$ (kg/kg fuel)	$V_{air,stoich.}$ (m ³ /kg fuel)	Air flow rate (m ³ /h)	Biomass feed rate (kg/h)	Calculated ER
Maple	6.35	5.27	3.6	3	0.227
Poplar	6.25	5.19	3.6	3	0.231
Tamarack	8.7	7.22	3.6	3	0.166
* Density of air = 1.205 kg/m ³ at 20 °C					

As literature suggests [52], if ER value goes well below 0.2 (e.g. < 0.09), an incomplete gasification takes place; therefore, the process is favored for char production. In this case, the calorific value of the gas is low. On the contrary, if the ER value goes well above 0.3 (e.g. > 0.45), the process is favored towards complete combustion of biomass [52].

4.3.3 Syngas Composition

In this part, result obtained from the GC unit, which identified the composition of the collected samples and calculated the concentrations are presented. Figures 43 and 44 summarize the syngas composition obtained in the gasification process of maple sugar, poplar and tamarack samples. It is necessary to mention that few preliminary runs were done before collecting the produced samples for analysis.

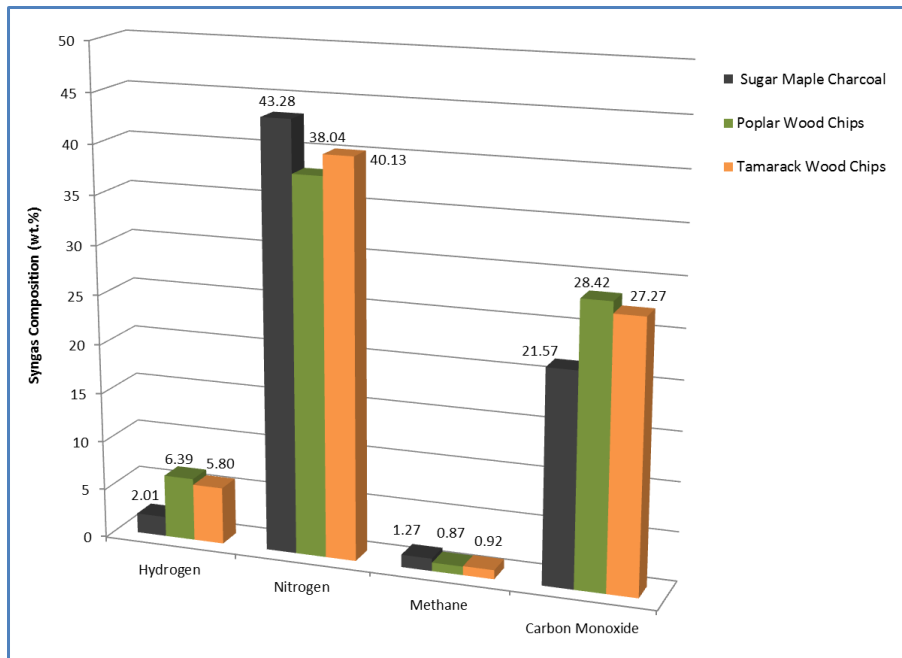


Figure 43: Syngas composition in wt. % for the biomass samples

As shown above, the producer gas obtained from sugar maple charcoal has the lowest amount of hydrogen (2.01 wt. %), as opposed to poplar and tamarack wood chips which produce a gas with higher concentration of hydrogen. Due to utilization of air as the gasification medium, nitrogen dominated the composition of the produced syngas with the maximum of 43.28 wt. % in sugar maple charcoal. The gas from poplar had the lowest amount of nitrogen (38 wt. %). The amount of methane obtained from sugar maple syngas was 1.27 wt. %, which was the highest amount among the studied samples and explains why the concentration of hydrogen was the lowest. The concentration of carbon monoxide was in the range of 21 wt. % to 28 wt. %.

Figure 44 shows the concentration of the hydrocarbons detected using the FID detector in the GC unit. As mentioned earlier, methane was the only element that could be detected using both the TCD and FID detectors; therefore, values obtained in one were compared to the other for each measurement. No considerable difference was observed in this case.

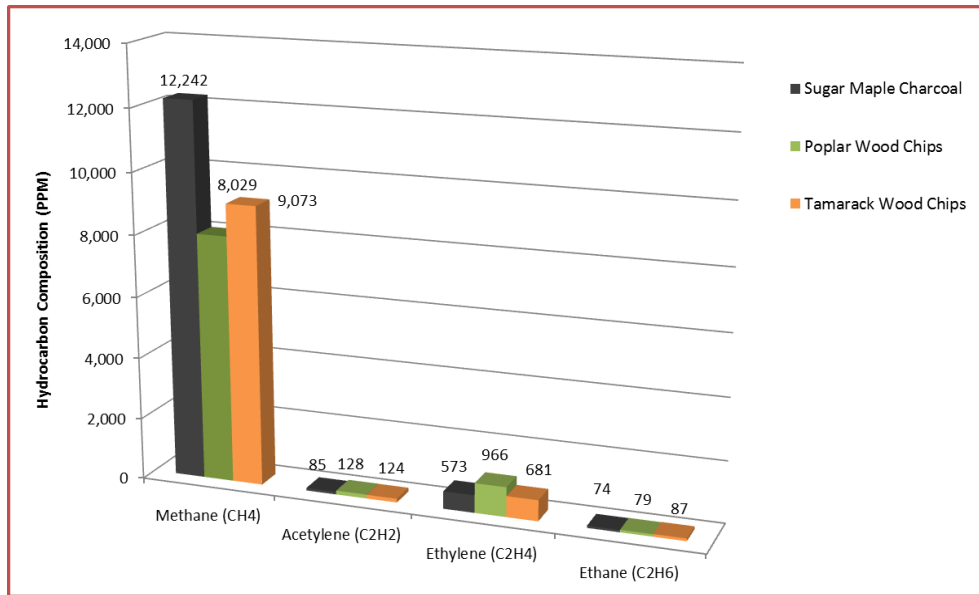


Figure 44: Composition of hydrocarbons in PPM for the biomass samples

As previously explained, the syngas produced from sugar maple charcoal contains the highest concentration of methane, in comparison with poplar and tamarack wood chips. Traces of acetylene and ethane were also detected, as the GC was calibrated for these gases. Considerable amount of ethylene was also detected. The syngas from poplar had 966 ppm of ethylene, while the one produced from tamarack and sugar maple charcoal had 681 and 573 ppm, respectively.

In order to assess the accuracy of the obtained experimental data from GEK IV gasifier, it is necessary to compare it with experimental results reported in the literature [55, 56]; however, there are plenty of data for different gasifiers with various biomass types. Therefore, it is more beneficial to define a range (minimum and maximum) using the data obtained from experimental studies using biomass (wood chips) with air as the gasification agent. Figure 45 presents this comparison.

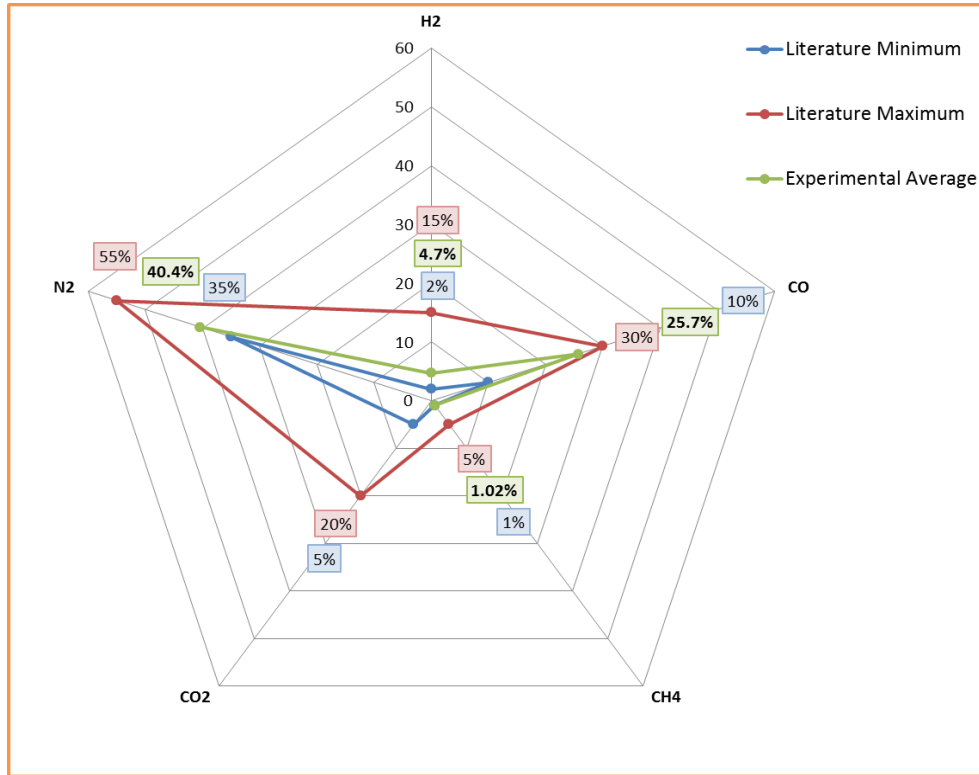


Figure 45: Literature and experimental results for syngas composition

Hydrogen, carbon monoxide, methane, carbon dioxide and nitrogen are shown on the axes and the literature maximum value, GEK IV experimental average and the literature minimum values are shown in red, green and blue colors, respectively. By considering this comparison, we can conclude that the results from our experimental study lean towards the literature minimum values, as expected. This issue might be due to the size and the efficiency of the GEK IV gasification system.

Apart from the gas composition, stability of the gas was also monitored. In fact, two measurements from the same sampling bag were performed in different time frames; one right after production; and the other one after 48 hours of production. The aim here was to observe whether concentration of the syngas changes with respect to time. Although no significant change was observed, it was found that the concentrations slightly increase after 48 hours. This minimal increase could be related to the change in the temperature of the syngas samples. This issue was the case for all of samples. Here, the results for sugar maple charcoal are shown in Figure 46 and 47.

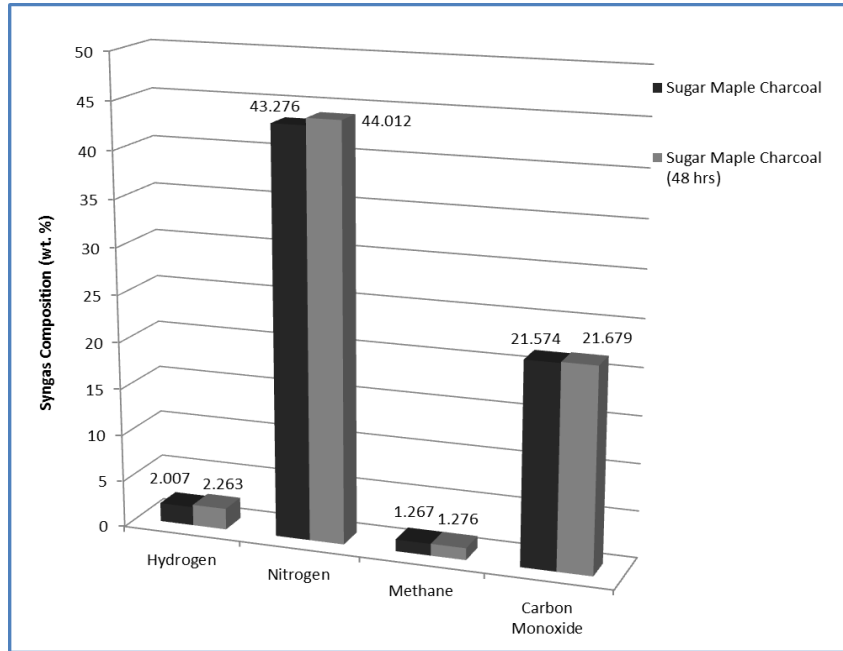


Figure 46: Stability of the syngas from sugar maple (TCD detector)

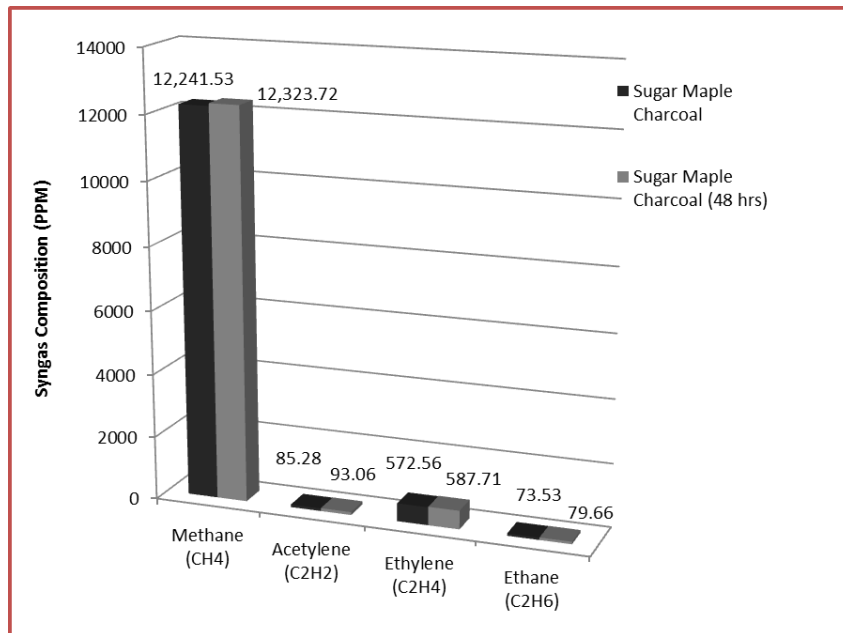
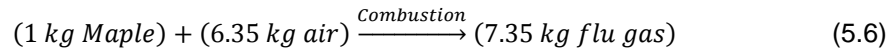


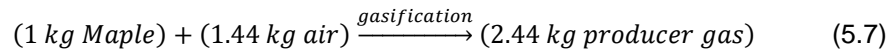
Figure 47: Stability of the syngas from sugar maple (FID detector)

4.3.4 Syngas Flow Rate

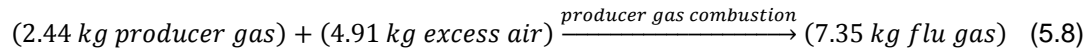
As shown previously in Table 11, for complete combustion of maple, poplar and tamarack wood chips, respectively, 6.35 kg, 6.25 and 8.7 kg of dry air is required. As mentioned earlier, this value is known as stoichiometric ratio. Moreover, it was thoroughly explained that in the gasification process in general, the ER ratio should be well below the stoichiometric ratio. In a combustion process, 1 kg of maple wood chips with 6.35 kg of air results in 7.35 kg of flu gas. In other words,



The calculated ER value for maple was 0.227; therefore 1.44 kg ($0.227 \times 6.35 \text{ kg}$) of air was consumed with 1 kg of maple chips. Therefore, the following could be stated:



and to burn the produced gas, we take the additional air using the excess air valve; thus,



The above actually means that for 2.44 kg of producer gas we need 4.91 kg air, which makes the stoichiometric ratio of producer gas equal to 2.012:1 (kg air per kg producer gas); although this does not occur in one step due to the nature of the gasification process. By considering the densities for air ($\rho_{air} = 1.205 \text{ kg/m}^3$) and also for the producer gas ($\rho_{producer \text{ gas}} = 0.950 \text{ kg/m}^3$) with the composition of 20% CO, 20% H₂ and 60% N₂, we can obtain the following relationship between the volumes:

$$\text{air input (m}^3\text{)} : \text{producer gas output(m}^3\text{)} = 0.46:1$$

This means that the producer gas output volume is approximately 2.15 times the air input volume at constant temperature; thus, it could be roughly estimated that the gas output rate for the GEK IV system was around $7.74 \text{ m}^3/\text{h}$ ($3.6 \text{ m}^3/\text{h} \times 2.15$).

4.3.5 Cold-gas Efficiency

One of the most important factors in a gasification process is the “cold-gas efficiency”, which is defined as follows [57]:

$$\text{Cold gas efficiency} = \frac{(\text{calorific value of the gas}) \times (\text{kg gas})}{(\text{Calorific value of the biomass}) \times (\text{kg biomass})} \quad (5.9)$$

$$\eta_{\text{cold gas}} = \frac{HHV_{\text{gas}} \times M_{\text{gas}}}{HHV_{\text{biomass}} \times M_{\text{biomass}}} \quad (5.10)$$

Cold gas efficiency is the efficiency resulted by combusting the cold producer gas obtained in the air gasification of biomass. In other words, the producer gas is in high temperatures upon production and this high temperature could be utilized along with the heat release by the syngas combustion. In fact, cold gas efficiency only considers the heat release without this temperature benefit and primarily relates to the composition of the gas. Therefore, by calculating the calorific value for the producer gas based on the concentrations of hydrogen, carbon monoxide and methane, the cold gas efficiency for the samples can be calculated.

Table 12: Calculated gas HHV and cold gas efficiencies

biomass	Calculated HHV (producer gas) (MJ/Nm ³)	Cold gas efficiency (%)
Maple	~ 3.9	53.8
Poplar	~ 4.3	57.7
Tamarack	~ 4.1	48.2

As expected, the HHV of the syngas produced from maple, poplar and tamarack chips were almost within the range specified in the literature (4 to 7 MJ/Nm³) closer to the minimum limit. It was observed that the gasifier had the maximum cold gas efficiency of 55.7% for poplar wood chips. These results clearly show that the GEK IV gasifier is not capable of producing high quality syngas, due to use of air as the gasification agent. Moreover, the HHV of the gas is low, which could be related to the design features of the gasifier in this system. It is worth mentioning that, the accuracy of the GC unit and the inability in measuring the carbon dioxide might have affected the results.

CHAPTER 5

Gasification Computer Modeling at UW LEER

In this chapter, the computer modeling and the simulation efforts on the gasification are briefly explained. This chapter focuses on the computer model that was created in the Aspen Plus® environment and aims to shed more light on the gasification studies at UW LEER by comparing the results obtained in the experimental and simulation parts with each other.

5 Gasification Computer Modeling Studies at UW LEER

5.1 Overview: Computer Modeling and Simulation

A *model* could be defined as “*the schematic description of a system that accounts for its known properties that could be used for further study of its characteristics*” [58]. Generally, we attempt to determine the unknown quantities from the known ones, in any problem; however, in many cases this direct solution is not possible due to the complexity of the system. Therefore, we seek to solve the problem with recourse to a simplified simulation of the real problem, which is called a model. Nowadays, with considerable advancement in the technology, computer modeling and simulation has become an inseparable part of scientific research and development.

In this part, a thermo-chemical computer model of the Gasifier Experimenter’s Kit (GEK) level IV is briefly explained. This model has been created using a well-known thermo-chemical software package, called ASPEN PLUS® V.7.3.

5.2 Thermo-chemical Computer Modeling in ASPEN PLUS®

Due to ever-increasing importance of characterization of the chemical mixtures in the gasification process, thermo-chemical computer modeling has become extremely popular. For this gasification project, a number of process simulation software packages were considered and ASPEN PLUS®, which is arguably the most popular one in thermo-chemical and energy industries, was chosen for this task.

The main objective of this modeling work is to characterize and understand the air gasification of biomass in more depth. Moreover, a computer model that has the ability to simulate the existing experimental setup (GEK IV in this case) could be greatly beneficial in optimizing and predicting the performance of such a system. Therefore, the gasification reactor or the gasifier part of the GEK IV system, in which all the major chemical reactions occur is modeled in the ASPEN PLUS® environment.

5.2.1 ASPEN PLUS® Flow Diagram Design

As previously mentioned, drying, pyrolysis, combustion and reduction zones were four zones in a downdraft gasifier that were created and connected to each other to form the gasification process in this thermo-chemical model. In addition to the operating conditions, such as temperature and pressure values in various points of the reactor, relative reactions for combustion and reduction zones were implemented in the model to define the theoretical interactions between these elements in various zones. Figure 48 illustrates the model in the Aspen Plus environment.

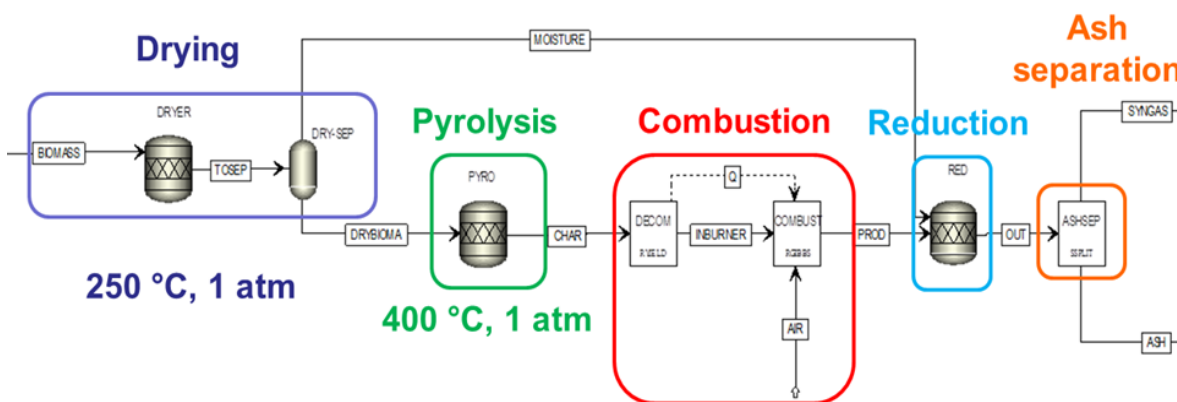


Figure 48: GEK IV gasification reactor model in ASPEN PLUS® environment

As Figure 48 shows, the final version of the model was created after few modifications and enhancements of the initial model. For instance, the moisture content of the biomass is also considered. More importantly the model was re-designed, in such a way to become very sensitive to the change in ultimate analysis of the feedstock. Some of the key features of this kinetic-free model are as follows:

- There are several types of *Property Methods* in Aspen Plus. Moreover, it is possible to modify any of these methods and customize it based on the nature of the project. In fact, the equation of state provides the relationship between pressure, temperature and volume of species. In the case of this project, an *ideal property method* is used in this model.

- All the physical properties of the species involved are taken from the Aspen Plus data bank.
- The pyrolysis zone has been modeled using an *RStoic reactor*, which works based on the stoichiometry of the reactions. The *pyrolysis* block uses mass balance, atomic balance and conversion rate to operate; therefore, relevant reactions were specified here in this block.
- *Decom* block, which comes right after the pyrolysis block, decomposes the char created in the system before sending it to the combustion zone. This step is in place to change the unconventional solid (char) to the conventional. An *RYield reactor* has been used in the *Decom* block. This type of reactor operates based on the mass balance and % yield of reactants and products.
- The material in *inburner* block is now conventionally known by Aspen Plus and is ready to go to the *combustion* block.
- *RGibbs reactor* has been used in the combustion block, which works based on Gibbs free energy minimization principle. This block is used to model the combustion zone and calculates the amount of each component in the product stream.
- Reduction zone of GEK IV gasifier has been modeled using the *reduction* block, which utilizes an *RStoic reactor*; the Boudouard, water gas-shift and methanation reactions are considered here (see section 2.3.4 Thermodynamics of Gasification).
- The output of the reduction block gives us the energy required (heat duty) calculated by Aspen Plus, as well as concentrations of various gases in the syngas stream. The *Ashsep* block actually separates the ash content of the stream from the gaseous part.
- It is necessary to mention that GEK IV model is kinetic-free and considers the system in the steady-state and equilibrium condition.

5.2.2 Modeling Input Parameters

Every modeling work extensively relies on the input parameters. In fact, computer models should be performed such that one can follow all the details step by step and obtain similar results. Therefore, reporting of the input parameters and any assumption used in the modeling work is strongly recommended. Thus, in this modeling work a number of input parameters and assumptions/approximations were used. These points are briefly explained here.

5.2.2.1 Proximate and ultimate analyses

As discussed in the experimental part of this work, proximate and ultimate analyses were not performed for the feedstock; however, based on the type of the wood chips, scientific data were used from the literature. It is necessary to mention that technical problems (Aspen Plus errors) were observed in the model, once the exact experimental parameters were used. Therefore, in order to solve this problem, the proximate and ultimate analyses of the feedstock were slightly modified. Table 13 compares the original ultimate analysis with the modified version used in the modeling part of this study.

Table 13: Ultimate analysis for the biomass used in the modeling work

biomass	Ultimate Analysis (Dry and Ash free basis)				
	C	O	H	N	S
Maple	51.0	40.3	6.2	0.4	0.11
Modified – Maple (Total 100%)	51.5	40.5	7.4	0.45	0.15
Poplar	50.6	40.7	6.1	0.6	0.02
Modified – Poplar (Total 100%)	50.25	40.8	8.2	0.7	0.05
Tamarack	56.0	31.0	10.2	0.7	0.11
Modified – Tamarack (Total 100%)	56.15	35.5	7.6	0.6	0.15

It is necessary to mention that the moisture content of the feedstock was approximated to be 35%.

5.2.2.2 Air flow rate and biomass feed rate

Another modeling technical challenge happened when the actual experimental air flow and biomass rates were implemented into the model. It was observed that the simulation could not converge in this case. Therefore, an approximation was used to overcome this issue. As shown before, the ER values for sugar maple charcoal, poplar and tamarack wood chips were determined to be 0.227, 0.231 and 0.166, respectively. The stoichiometric amount of air per unit of feedstock was previously calculated using equation (5.5) and is shown in Table 11. In fact, this equation is based on the ultimate analysis of the feedstock; thus, if the ultimate analysis data changes (which slightly did because of the problem in the model), the stoichiometric amount of air per unit of feedstock also changes. Table 14 summarizes the experimental and adjusted values (for modeling purposes) for $M_{air,stoich.}$, $V_{air,stoich.}$, air flow rate, biomass feed rate and the ER.

Table 14: Adjusted air flow and biomass feed rates in the modeling work

biomass	Model Stoichiometric Air (Experimental Stoichiometric Air)		Experiment			Modeling		
	$M_{air,stoich.}$ (kg/kg fuel)	$V_{air,stoich.}$ (m ³ /kg fuel)	Air Flow (m ³ /h)	Biomass Feed (kg/h)	ER	Air Flow (m ³ /h)	Biomass Feed (kg/h)	ER
Maple	6.75 (6.35)	5.60 (5.27)	3.6	3	0.227	12.712	10	0.227
Poplar	6.86 (6.25)	5.69 (5.19)	3.6	3	0.231	13.144	10	0.231
Tamarack	7.56 (8.7)	6.28 (7.22)	3.6	3	0.166	10.425	10	0.166

It was observed that with constant ER but different air flow and biomass feed rates, the model generates very identical results. Although one might argue about the validity of this approximation, it was decided to keep the air flow equivalence ratio (ER) equal to the ones calculated from the experimental study but increase the air flow rate and biomass feed rate to avoid the technical problem seen in the model. It was found that once biomass feed rate is in the range of 10 kg per hour, the model works well and the problem disappears. Therefore, the biomass feed was set to 10 kg per hour and by having the ER values in the experimental study, adjusted air flow rates (for modeling purposes) were calculated. These values are shown in Table 14.

5.3 Computer Modeling Results and Discussions

In this part, the results from the computer modeling of air gasification for sugar maple charcoal, poplar and tamarack wood chips are shown. A brief discussion will follow the modeling results in this section.

5.3.1 Concentration Comparison for Sugar Maple

The figure below shows the comparison between the experimental and modeling results for sugar maple charcoal. As previously mentioned, the proximate and ultimate analyses of the feedstock were not performed in the experimental part; instead, data from literature was used; therefore, the same data was used for the computer model as well. As shown here, most of the wt. % concentrations fall within about +/- 5% of the ones obtained in the experiments. The exception however, is the CO content, which is determined to be 30.5% for sugar maple charcoal, while this value was measured to be around 21.6 % in the experiments. Although the concentration of carbon dioxide could not be experimentally measured, the model determined this value to be about 17 wt. %, which is in agreement with the typical values.

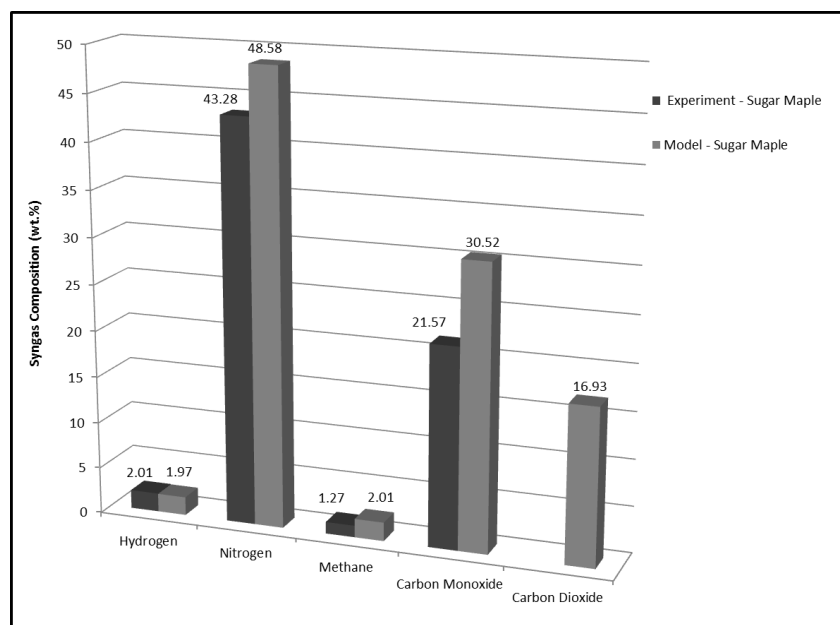


Figure 49: Experimental and modeling results for sugar maple charcoal

5.3.2 Concentration Comparison for Poplar

In the case of poplar wood chips, the concentration of hydrogen went up, as expected. The measured concentration in the experiment was about 6.4 wt. %, while the model predicted this value to be 5.43 wt. %. The results from the model show that the concentration of nitrogen and methane decreased, while CO content of the producer gas increased to 33.74 wt. %. The concentration of carbon dioxide is predicted to be around 15.4%.

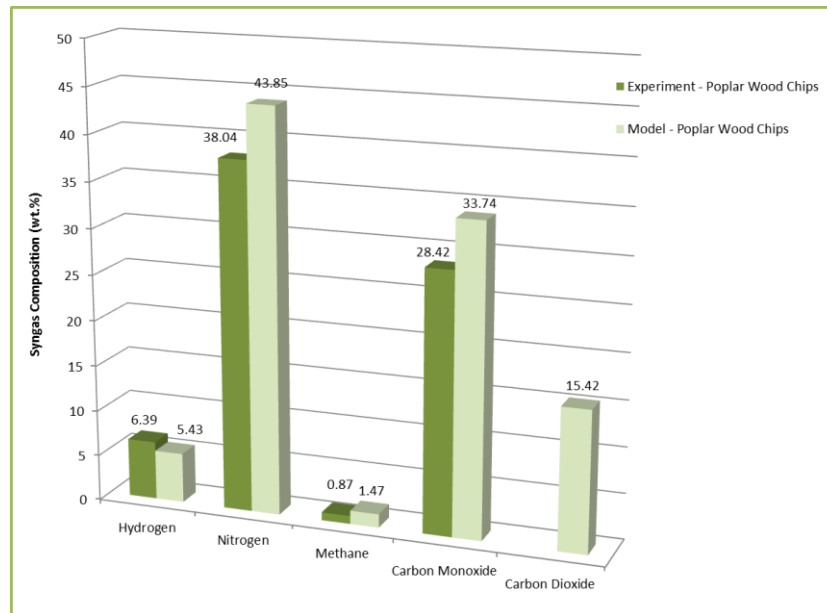


Figure 50: Experimental and modeling results for poplar

As shown here, the model also somewhat correctly predicted that the concentration of the hydrogen and carbon monoxide would increase, when poplar wood chips were used. Although the concentrations of these two gases increased, the model on the other hand predicted a decrease in the concentration of nitrogen, methane and carbon dioxide; the point that was also experimentally observed at least for nitrogen and methane. Although it seems the model can predict the trend quite well, there is still a considerable difference between the concentrations obtained in the experimental study and the ones predicted by the model. The author believes that lack of experimental proximate and ultimate analyses of the feedstock and relying on the data from the literature have considerable effect on the modeling results.

5.3.3 Concentration Comparison for Tamarack

Figure 51 illustrates the modeling results for tamarack wood chips. In this case, the concentration of carbon dioxide is calculated to be 15.2 wt. %. The modeling results seem to be in reasonable range in comparison with the experimental results, as the difference is within +/- 5% range.

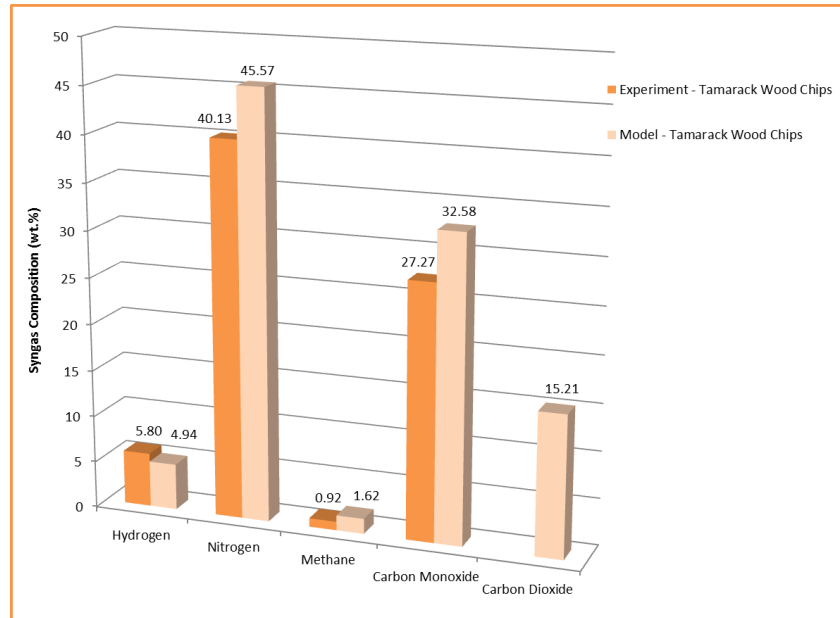


Figure 51: Experimental and modeling results for tamarack

The results obtained here are quite similar to the ones obtained for poplar wood chips. By considering the results obtained in the experimental and modeling parts, some issues might arise, which are explained below:

- Although the most of the concentrations are within a +/- 5 wt. % range, this tolerance might not be accurate enough for a particular application.
- The model is able to predict the concentration of hydrogen and methane quite accurately; however, for nitrogen and carbon monoxide, some difference between the experimental and modeling results could be noted.
- The model predicts the concentration of carbon dioxide to be around 15-16 wt. %, which is in agreement with the typical values for this gas in the air gasification of biomass.

Some of these issues will be addressed in chapter 6 where the future developments are discussed. Finally in chapter 8, conclusions for chapter 4, 5, 6 and 7 are presented.

5.3.4 Sensitivity Analyses

Generally, a computer model is capable of predicting the performance of the system based on various parameters, once its validation is examined. As explained earlier, the ER value relates various parameters to each other and therefore, makes simultaneous analysis of those parameters easier. In order to do so, the following sensitivity analyses have been used to predict the composition of main elements in the syngas. In these analyses, composition of the specified gas is plotted against the ER value, which changes from 0.06 to nearly 0.46. Moreover, the heat generated in the combustion zone of the gasifier (kW) using exothermic reactions is plotted against ER values. It is worth mentioning that the following results are based on the proximate and ultimate analyses of sugar maple charcoal, poplar and tamarack wood chips. It was observed that all three of them behaved almost in the same way against the variation of ER value.

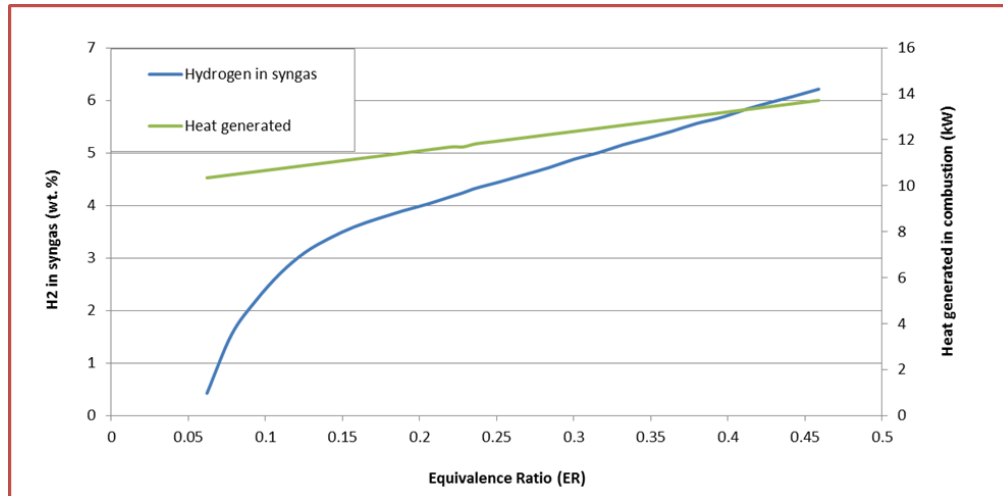


Figure 52: Change in wt. % of hydrogen against ER

As shown in Figure 52, hydrogen concentration dramatically increases with increase in the ER value. The rate of this increase, as predicted by the model, is much higher from 0.06 to ER value of 0.15; however, this rate of increase declines after this point.

The heat generated also linearly increases, as expected. In fact, the more the ER value, the more air is provided to the combustion zone; hence, the temperature in that zone increases. The heat release is in complete accordance with the data provided by the manufacturer of the gasifier. In fact, they have reported a heat duty range of 10 to 20 kW for this type of system [47].

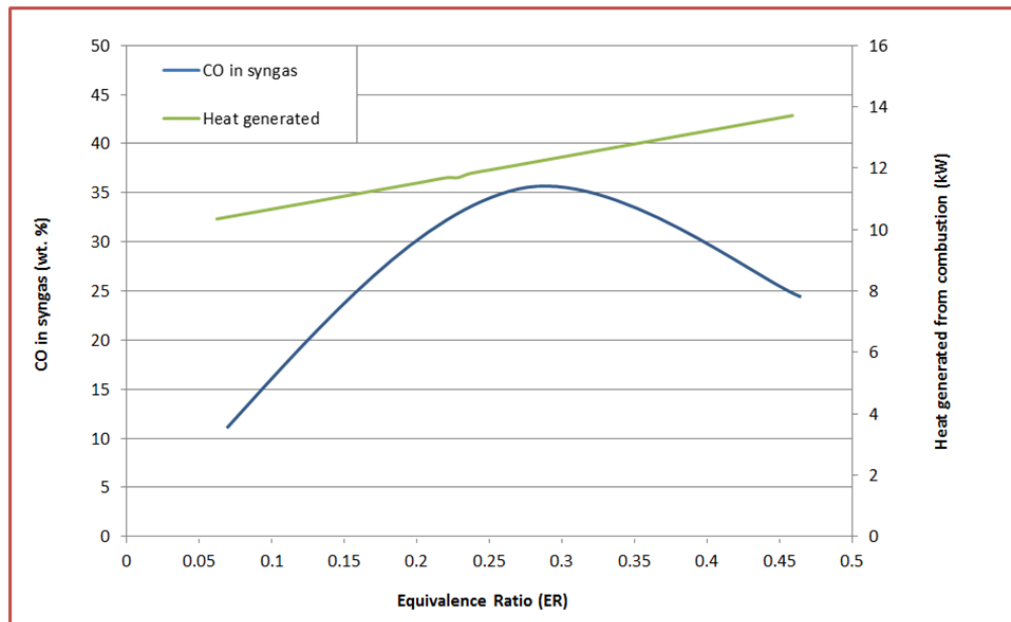


Figure 53: Change in wt. % of CO against ER

The figure above shows the trend of the carbon monoxide concentration in wt. % against change in ER value. As shown, carbon monoxide concentration increases initially and peaks when ER value is about 0.3. At this point the model predicts that the wt. % concentration should be around 36%, which is quite reasonable. By further increase in the ER value, which translates to increase in the air flow rate into the system, CO concentration drops, as expected.

In fact, increase in ER value translates to going towards combustion process. As explained earlier in this paper, the air to fuel ER values for combustion (shown by EA), are equal or greater than one. Therefore, by increasing the ER value from 0.3 (the optimum point for CO production in gasification) onwards, the CO concentration steadily declines, as CO content of the gas is combusted and forms carbon dioxide. Shortly after this figure, result for carbon dioxide actually confirms this issue.

In the case of methane, the concentration peaks at the ER of 0.281 where the predicted wt. % is about 2.5%. Similar to the trend of CO, the concentration of methane decreases after this point. It is worth mentioning that since hydrogen, carbon monoxide and methane are the gases that significantly contribute to the overall calorific value of the syngas, their concentrations (wt. % or vol. %) are of high importance; therefore, it is vital to operate the gasification system in a way to ensure their levels are maximized.

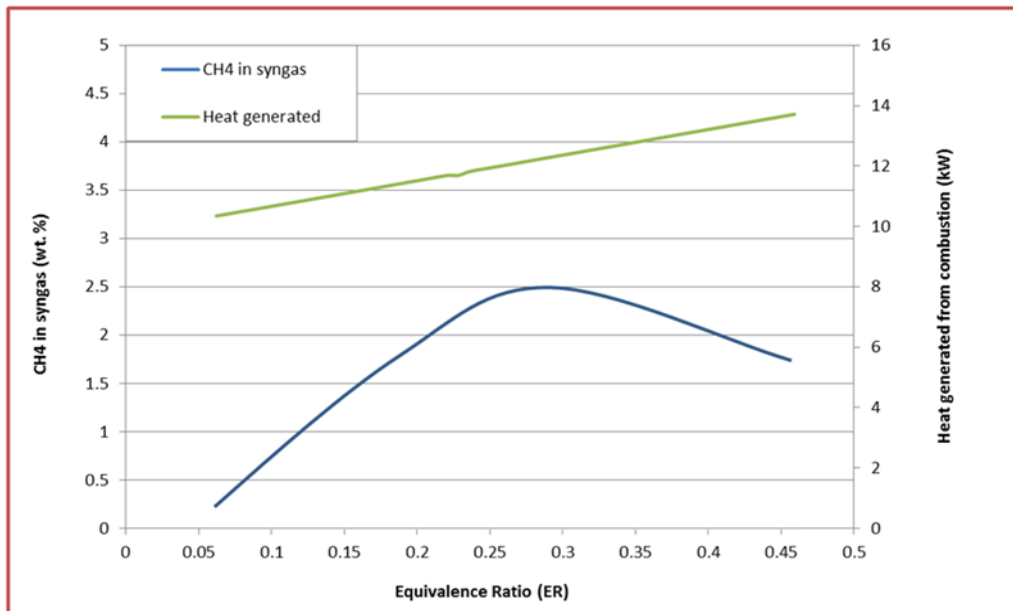


Figure 54: Change in wt. % of methane against ER

In fact, ER value plays an important role here. By means of this model therefore, we can conclude that at the ER around 0.28, the highest concentrations of these gases are achieved. This is an important finding. In fact, from this sensitivity analyses one can optimize the performance of the gasifier and operate it with the ER value close to 0.28 to 0.3 to ensure the highest quality syngas is obtained.

It is necessary to mention that, although this model seems to be somewhat inaccurate in terms of predicting the exact concentrations of the gases within the syngas, it is observed that proper predictions of concentration trends with respect to change in the ER value is achieved.

Figure 55, similarly shows the sensitivity analysis for carbon dioxide. The importance of this analysis is due to the inability of the experimental study to provide information about the concentration of this gas in the produced syngas. As explained earlier, this limitation arises due to the type of the columns in the GC unit. As shown below, the carbon dioxide level increases from the selected optimum value of ER (0.28) onwards.

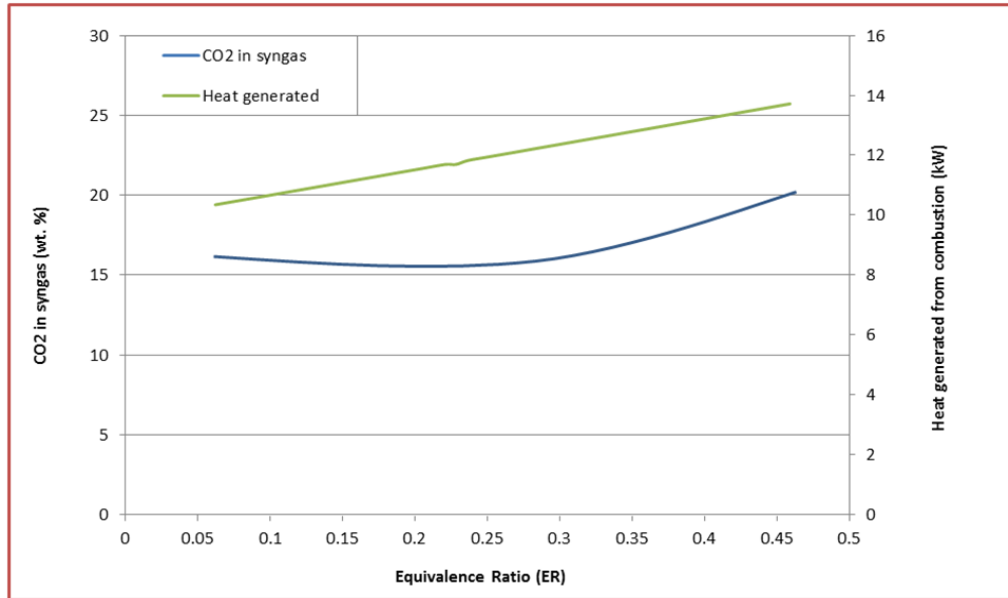


Figure 55: Change in wt. % of carbon dioxide against ER

The concentration of carbon dioxide reaches to about 20 wt. % at the ER of 0.45. This trend is typical, as by increasing the air flow rate in the system and increasing the equivalence ratio, the process tends to move towards combustion; hence, chemical reactions move away from partial oxidation, which results in less carbon monoxide in the syngas. On the other hand, more carbon dioxide will appear in the syngas. By closely analyzing the results from Figure 55, we can conclude that carbon dioxide concentration does not change significantly when the ER value is below 0.3. In other words, variation in ER does not heavily influence the concentration of this gas, when the gasifier is operating with an ER lower than 0.3. Thus, another parameter, such as temperatures in the combustion and reduction zones might be influential. In addition, monitoring the temperature of the air injected to the combustion zone might provide more information in this regard.

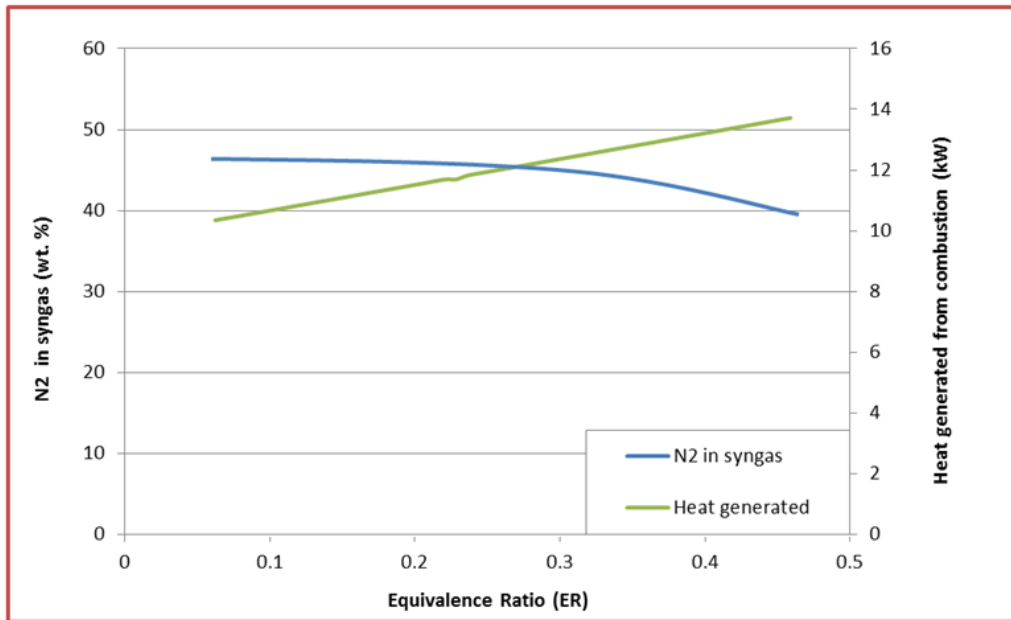


Figure 56: Change in wt. % of nitrogen against ER

Furthermore, Figure 56 illustrates the sensitivity analysis for nitrogen. The concentration of this gas does not seem to be changing significantly, once ER value changes. Initially, the nitrogen wt. % is about 48%. Once the ER reaches to the 0.3 limit, nitrogen concentration starts to decline steadily. This issue could be the result of a shift from gasification towards combustion. Once ER value increases, temperature in the combustion zone will also increase; therefore reactions between oxygen and nitrogen molecules to form NO_x could occur.

Similar to the previous case (the trend in carbon dioxide), it can be concluded that change in ER does not result in drastic change in the concentration of nitrogen. Therefore, it is recommended to expand these sensitivity analyses and study the effect of other parameters, such as air inlet temperature and combustion/reduction zone temperatures. This way, it will be possible to find which concentration is sensitive to what parameter. In the next chapter, the future development of the experimental and modeling studies are explained.

CHAPTER 6

Future Developments of the Experimental and Modeling Studies on the Gasification

This chapter aims to recommend some of the possible future developments of the experimental and modeling parts of the gasification project. Moreover, some thoughts regarding the expansion of the gasification research at UW LEER are briefly explained here.

6 Future Developments of the Experimental and Modeling Studies on the Gasification

Generally, there are various parameters that contribute to the expansion and development of a particular project. One of the most important elements is the research funding available to the research group. The future development of the biomass gasification project can be divided into two parts; future work on the experimental part; and on the computer modeling part.

6.1 Future Development of the Experimental Study

The expansion of the gasification experimental study could be divided into various parts. In this section, some future work on the following topics is briefly presented:

- GC unit and the calibration process
- GEK gasifier and making the existing system smarter
- Upgrading the GEK IV gasifier and installing plasma torch(es), if one finds it possible
- use of a “Fourier transform infrared spectroscopy (FTIR)” unit
- use of a Power Pellet[®] gasification system

6.1.1 GC Unit and the Calibration Process

As discussed previously in chapter 5, the GC unit was calibrated to detect various gases; however, some important compounds in the syngas, such as oxygen and carbon dioxide were left behind. As mentioned earlier, the GC unit in UW LEER is currently used in variety of research projects beside biomass gasification, such as catalytic combustion of natural gas. In order to optimize the cost and increase the efficiency of the research, it was decided to equip the GC unit with such columns that were useful in both projects. Moreover, calibration blends were chosen such that both of the projects could simultaneously use the GC unit. As a result, the columns are not capable of detecting the carbon dioxide. On the other hand, oxygen could not be included in either of the calibration blends. Therefore, it is recommended to install columns that are fully capable of handling and detecting all important compounds in the syngas and also, calibrate the GC for oxygen using a third calibration blend.

6.1.2 GEK Gasifier and Making the System Smarter

Although GEK gasification system designed and manufactured by All Power Labs Inc. comes in various models and features, UW LEER purchased the basic version of this unit. Therefore, experimental capabilities were clearly limited in some ways. For instance, the temperature reading could be done in two locations only; one on the top of the heath (combustion zone) and the second one at the bottom of the reduction bell (reduction zone). In fact, some devices and equipment can be added to the GEK IV gasifier that makes the setup much smarter and eventually, will result in significant expansion of the experimental study.

The recommended equipment is as follows [47, 59]:

- **Process Control Unit (PCU):** This control unit has been designed for integrated instrumentation and data logging purposes. PCU enables the operator to simultaneously collect information from various locations of the system. Although a Universal Serial Bus (USB) port connects the unit to a computer, a processor which enables the stand-alone operation of the unit is in place for operation without a computer [59].

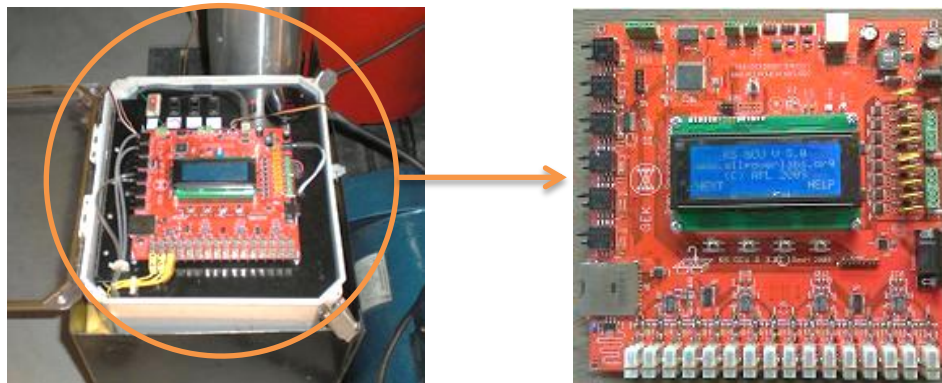


Figure 57: Proposed process control unit (PCU) for the GEK IV system [59]

- **Temperature measurement**
 - 6 type K thermocouple (soft probes) for measurement purposes in drying, pyrolysis and combustion zones.
 - 10 type K thermocouple (hard probes)
 - ceramic thermocouple protector for combustion zone
- **Pressure measurement**
 - tubing
 - Various items for connection to the PCU ports
- **Syngas Flow Rate**
 - two flow meters for reading the air inlet and syngas outlet
 - a servo valve for the air ejector, in order to control the flow rate in the gasifier
 - tubing and other items for connecting the flow meters to the system
- **Tar Testing**
 - gas sampling pump and a gas filter
 - filter discs and the filter holder
 - a colorimeter for performing measurements on the concentration of tar
- **Utilization of Plasma Torch in the GEK IV Gasifier**
 - As a future work, it could be technically possible to install and use one or more low power plasma torches to experimentally study plasma-assisted gasification

6.1.3 Use of a Fourier Transform Infrared Spectroscopy (FT- IR) Unit

In recent months, UW LEER has successfully installed an FT- IR unit in the laboratory. It is necessary to mention that this systems has not been calibrated yet; however, once it is calibrated and is basically up and running, the GEK IV system could be connected to this unit and therefore, online monitoring of the syngas composition would become possible. In this case, the hopper

(feedstock storage) should be filled with feedstock and should be installed on the top of the GEK reactor, as this approach requires continues feeding of the biomass into the system.



Figure 58: FT-IR system located at the UW LEER lab space

6.1.4 Use of a Power Pellet[®] Gasification System

The newest product designed and manufactured by All Power Labs Inc. is the Power Pellet[®] gasification system, which converts biomass into electricity by means of an engine. This system comes in two versions; 10 kW and 20 kW. The engine installed on the 10 kW model is a Kubota DG 972, while the one installed on the 20-kW version is a GM Vortec 3.0 L I-4. The Power Pellet[®] gasification system in general, is capable of producing 0.75 kWh electrical energy from 1 kg of biomass [60].

Power Pellet[®] is in fact excellent in handling variety of feedstock such as, hardwood and softwood chips with the size of 0.5" to 1.5", nut shells and coconut shell broken into chunks. In addition, this system works fairly well with coffee grounds and sawdust in pelletized form and manure that has the moisture content equal or less than 30%. Based on the reports from All Power Labs Inc., this company is working on this waste-to-energy (WTE) gasification system to make it compatible with rice husks, sugar cane bagasse and poultry litter. It is disappointing news that this system will not be capable of handling municipal solid waste (MSW), medical waste and coal anytime soon [60].

Table 15 summarizes the Power Pellet[®] specifications, reported by All Power Labs Inc. [60].

Table 15: Power Pellet[®] Specifications reported by All Power Labs Inc. [60]

Emissions	10 kW	20 kW
Power Output	3 to 10 kW	5 to 20 kW
Feedstock Feed Rate	12 kg per hour	22 kg per hour
Fuel Moisture Tolerance	Up to 30%	Up to 30%
System's Size	1.2 m x 1.2 m x 1.8 m	1.2 m x 1.3 m x 1.8 m
Weight	499 kg	658 kg
Price	US\$ 18,995	US\$ 26,995

6.2 Future Development of the Computer Modeling Study

Future development of the computer modeling part can be divided into two sections; development of the thermo-chemical computer simulation in the Aspen Plus[®] environment; and a new computational fluid dynamic (CFD) model in Ansys FLUENT[®].

6.2.1 Development of the Thermo-chemical Model in Aspen Plus[®]

As discussed previously in chapter 5, the thermo-chemical computer model, which did not use reaction kinetics was created in the Aspen Plus[®] environment had some limitations in modeling the real case gasification of biomass in GEK IV system, although most of these issues were resulted from lack of information from the experimental study. The most important issue is that this model is an equilibrium model, which considers the ideal situation where the GEK IV is in the steady-state and equilibrium conditions. In addition, for the sake of simplicity, this model was created in a kinetic-free condition. It is recommended to add the kinetics of the biomass gasification reactions to the existing model to see if there is a better match between the experimental results and the ones obtained in the modeling part. There are also a number of unsolved technical problems in the model. It is very important to resolve these technical issues. Moreover, this model could be used in optimizing the syngas quality and quantity once it is fully validated using the experimental results and any unsolved technical problem is overcome.

6.2.2 Computational Fluid Dynamics (CFD) Modeling in Ansys FLUENT®

In order to overcome the limitations existed in the thermo-chemical model, a Computational Fluid Dynamics (CFD) modeling work has been recently started in UW LEER, which aims to accurately model the reactor part of the GEK IV gasification system. As we have four main stages in the GEK IV reactor, i.e. drying, pyrolysis, combustion and reduction, this model focuses on these zones only. This model has been created in the Ansys FLUENT® environment and based on the preliminary results is expected to deliver promising outcome [61]. In general, CFD modeling is a type of computer simulation that uses numerical methods and various algorithms to solve fluid mechanics and fluid flow problems. Necessary calculations are all computerized and interaction between solids, liquids and gaseous mixtures existing under specific physical and chemical conditions could be simulated. Figure 59 (b), schematically demonstrates the mechanisms involved in the GEK IV gasifier and parts (a) and (c), represent some preliminary results obtained from the constructed CFD model [61].

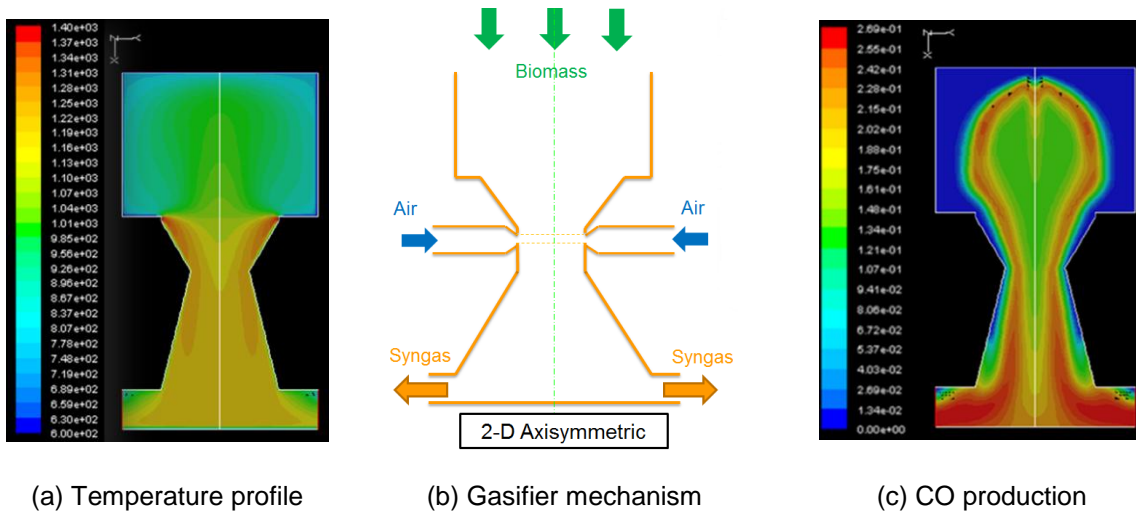


Figure 59: GEK IV gasification reactor model in FLUENT for CFD analysis [61]

It is recommended to continue the work that has been initiated for construction of the CFD model. This model can overcome the limitations that have been identified in the thermo-chemical model and once validated by the experimental results, has the potential to act as a reliable tool in modeling and prediction of the GEK IV gasification reactor.

CHAPTER 7

Policy Issues of WTE

In this chapter policy issues are discussed. In the beginning, we start by introducing the possible drivers of the WTE technology and then barriers and challenges are discussed.

Policy recommendations have been given by the author, in order to minimize the barriers and challenges that Waste to Energy (WTE) thermal technologies are currently facing.

7 Policy Issues of WTE

In this chapter policy issues of the WTE processes are analyzed, but before going to these issues, it is crucial to briefly name the drivers, challenges and also barriers that exist on the way of commercialization and growth of the WTE technologies, such as plasma gasification.

7.1 Drivers of WTE Sector

This part could be divided into two parts:

- Technology drivers
- Strategic drivers

7.1.1 Technology Drivers

7.1.1.1 Improvement in emissions controls in combustion processes

One of the major barriers that negatively affects waste incineration, even if used to generate electricity, is the release of particulate matter (PM) and pollutants, such as NO_x to the environment.

In fact, enhanced processes for handling gaseous wastes are currently utilized for reducing these elements and should be able to continue to do so [44].

7.1.1.2 Enhanced non-combustion technologies

Updated thermal gasification technologies, such as plasma gasification could resolve problems with generating electricity from waste and minimize environmental concerns significantly. Once fully commercialized, it has the potential to provide better economic prosperity for the WTE industry as well [44].

7.1.2 Strategic Drivers

7.1.2.1 Significant reduction in landfilling

It is clear that landfills demand considerable amount of land that could be used for many other purposes. In fact, if municipalities do not have space for landfilling disposal of their MSW, should alternatively, pay a third party to move their MSW and dispose it in another location. For instance, the city of Toronto annually pays \$22 per ton to ship approximately 800,000 tons of MSW to Michigan, which costs the city more than \$17.5 million per year. Another example is New York City, which should pay up to \$120 per ton to send its MSW into landfills. In fact, energy recovery has the potential to reduce landfilling up to 90% and at the same time produce useful products [44].

7.1.2.2 Reducing the reliance on the fossil fuels

By utilization of advanced thermal waste-to-energy (WTE) technologies, waste can be converted to generate fuel. In fact, this produced fuel did not come from a mine or is not the result of drilling in a deep offshore oil well to make it a non-renewable fossil-fuel resource.

7.1.2.3 Reducing greenhouse-gas emissions (GHGs)

As discussed previously, energy recovery of waste results in reduction in the emissions of hazardous elements to the atmosphere. While mass burning still pollutes the environment, advanced technologies, such as plasma gasification are capable of providing much more benefits compared to incineration. As methane is an important greenhouse gas and contributes to the climate change issue, these advanced WTE thermal technologies can significantly decrease methane emissions by the landfills.

7.1.2.4 Carbon tax credits and other incentives

As these technologies do not use fossil fuels, most of them are eligible for carbon or GHG tax credits. These incentives can be a good solution for the industries to cancel out their emissions, or alternatively, can be traded in carbon cap-and-trade programs.

7.2 Barriers to the Deployment of Waste-to-Energy

The barriers and challenges facing WTE technology could be divided into five parts:

- Technical barriers
- Financial barriers
- Social barriers
- Industry-related barriers
- Political barriers

7.2.1 Technical Barriers

This section is devoted to challenges and barriers related to the technology and the technical aspects of the thermal processes [44].

7.2.1.1 Improvement in diversity in the feedstock

Still many WTE technologies are not flexible enough to treat a wide variety of waste material; however, it is sometime impossible or extremely expensive to sort the MSW. Moreover, it is not easy to find the exact composition of highly mixed waste materials. A feasible way of resolving this issue is to enable the industry to either sort and separate the material, or use more advanced technologies.

7.2.1.2 Improvement in gas cleaning

Cleaning the syngas produced in pyrolysis and conventional gasification is an important part of the process. These filtration and cleaning processes should become optimized.

7.2.1.3 Improvement in conversion efficiency

If plasma gasification plants are not integrated to form an Integrated Gasification Combine Cycle (IGCC), they could be highly energy-intensive. Their feasibility might vanish if they do not have enough waste to process (e.g. Utashinai plant in Japan). For instance in India, termination of the subsidies and grants offered by the Indian government resulted in closure of many plants, as they were not financially stable and profitable [44].

7.2.2 Financial Barriers

If we consider WTE sector a renewable energy industry (in fact it is partly renewable), the financial challenges play key roles in the success or failure of such projects. Thus, we consider the barriers related to the financial part of the technology as below [45]:

7.2.2.1 Issues in financing and high capital costs

As it has been discussed before, one of the major problems WTE projects are facing is the high up-front costs, mainly capital investment. This seems to be a bigger challenge for more advanced processes, such as plasma gasification. It could be seen that there is a lack of customized financial mechanisms, which are specifically designed for these advanced processes.

7.2.2.2 Lack of overall experience

As these technologies are relatively new in operation (e.g. plasma gasification), lack of testing information is one of the challenges for advisors, investors and experts in this field. In fact, there are just quite a few of these facilities operating around the world and in comparison with other technologies and sources, they are considered to be fairly new. This issue creates uncertainty, when it comes to the long term planning and forecasting.

7.2.2.3 Unstable and uncertain financial policies

In fact when the financial regulation framework is not clear, public and more importantly investors may lose interest in proceeding with their initial plan. It is a key point that a clear and optimized regulatory environment attracts renewable energy investors, especially in the bioenergy and WTE by guaranteeing a reasonable return on their investments.

7.2.3 Social Barriers

In this section, there are some social barriers that WTE industry faces. The following section aims to identify those issues and point out the challenges posed by the society [44, 45].

7.2.3.1 Opposition to renewable energy and WTE

As these new technologies are emerging, a gap between industry and society seems to be growing. As the industry moves forward by benefiting from the research and experiments, society is not aware of these advancements and usually refers to all these technologies by only mass burn or incineration. It is necessary to increase awareness in the society by speaking more and also interviewing on media regarding the new emerging technologies to provide people with new and correct information.

7.2.4 Industry-related Barriers

7.2.4.1 Lack of experience with advanced WTE technologies and modern handling of MSW

This issue highlights the problem within the industries that are involved in the energy production or in the renewable energy sector. If we consider the industries and people working in the related fields, they form a community. The author has the impression that this community is not fully aware of the advancements and developments of these new technologies. It is necessary that waste management companies and even utility companies look for any updates regarding these technologies and try to convey the message to their staff. This way the industry is promoted and WTE could gain a better position in the electricity generation sector.

7.2.4.2 Limited training opportunities

Training opportunities are limited for these technologies. Although new generation of experts are now currently working on the pilot plants, it is expected to see a next generation of experts coming to this field in the next 5 to 10 years.

7.2.5 Political Barriers

In this section, political issues related to the WTE thermal processing technologies are discussed and some recommendations are presented in order to address these barriers.

7.2.5.1 WTE Industry should prove itself to the policy makers in the energy sector

Author believes that when it comes to planning and forecasting supply mix for the next 20 years or so, WTE sector cannot have a significant contribution to the future supply mix. In fact, politicians have gradually realized that it is possible to generate electricity from MSW and that can actually solve multiple problems with just one action. It is recommended that WTE industry frequently updates the policy makers in the energy sector to eventually play an important role in the future of the electricity supply mix, especially in the distributed power generation sector.

7.2.5.2 Outdated municipal by-laws in terms of MSW

At the moment, municipalities have not completely considered WTE technologies and that partially comes from the fact that the tendency is to continue with the mechanism they have already in place and it is not an easy task to change the path. It is recommended that WTE community especially plasma gasification industry approaches various municipalities and basically shows the capabilities of this technology to address the MSW problem. One important step is to convince the municipalities to allow them and support them to construct their pilot plants in a particular landfill to demonstrate their systems and assess the potentials in that particular region.

7.2.5.3 Complex and expensive permitting requirements for WTE projects

To continue on the previous issue, once there is an agreement between the municipality, a utility company and a WTE firm, there are several permits that are mandatory for the WTE plant to obtain. It is recommended to reduce the complexity of these permitting procedures and make it easier for companies to run their tests and build their pilot plants.

7.2.5.4 Environmental assessment requirements

More specifically about the environmental assessment requirements, it is recommended that a close relationship builds up between the community, the municipality or the provincial and/or federal governments when they all have clear and correct information about the effect of the WTE facility on the region's environment.

7.2.5.5 Development of the smart grid network

One of the key promoters of the WTE technology is the compatibility of these systems with the smart grid and new energy systems. As these technologies are emerging, tremendous amount of work is also being done on the development of the smart grid networks. Therefore, it is crucial to align these two paths and make sure WTE technologies that are emerging will be easily utilized in the future smart grid networks.

7.2.5.6 Setting targets for the renewable and WTE industry

It is recommended to set higher targets for WTE electricity sector. If the policy makers demand the WTE industry to meet the defined targets, thermal processing technologies and their associated industries, all will grow better and faster, as they feel the pressure to reach their goals. On the other hand, if there is not a clear target for these industries and the electricity sector does not show interest in these technologies, the progress and development will be slow and limited.

7.2.5.7 Prioritizing the WTE technologies and projects

It could be seen that when we speak of renewable energy, solar and wind energy systems are more well-known in comparison with bio-energy and WTE sector. It is recommended to promote this field in a way that WTE technologies get similar attention as other renewable technologies normally do. In fact, WTE sector benefits from the fact that it could be utilized almost everywhere. WTE facilities are indeed good options of remote and off grid communities (e.g. First Nation communities in Canada) and eliminates the high cost of fuel transportation to those areas.

7.2.5.8 Promoting the local manufacturing industries for WTE technologies

Governments or governing bodies in a particular region can promote WTE technologies by supporting them when it comes to local manufacturing and technical and engineering requirements. These technical and logistical supports contribute significantly to the success rate of WTE industries in the region, as they have access to other industries in the region. For instance when a particular jurisdiction has a complete plan and has implemented tools for its long term strategies in this regard, a WTE company will be attracted to that region and will establish its head-quarter or facility in that region, which eventually will contribute to the wealth and growth of that area.

7.2.5.9 New educational and training initiatives based on the local capacity

Now that the region is promoting the WTE industry and companies are attracted to this area, educational institutions, such as universities and colleges should have an updated set of courses and programs to ensure compatibility with the plan developed by the policy makers. This way, local graduates who already have the knowledge of the industry can easily find employment in WTE facilities in the region. These programs and courses should cover a wide range of fields, from electrical, mechanical, chemical or civil engineering to environmental studies.

CHAPTER 8

Conclusions

This chapter aims to summarize and conclude some of the key points presented chapters 4, 5, 6 and 7 where research contributions were made. In this part, final recommendations and remarks are highlighted.

8 Conclusions

In this chapter, the conclusions are separately presented for the experimental study, modeling study and the policy-related issues. These highlights are as follows:

8.1 Conclusions of the Experimental Study

An experimental investigation of air gasification of biomass in an Imbert type, downdraft gasification system, called GEK IV was carried out.

The feedstock in this study was

- sugar maple charcoal chips,
- poplar wood chips and
- tamarack wood chips

GEK IV gasification system benefits from a relatively robust design and some key safety features such as operation under negative pressure difference; however, it is necessary to mention that due to this safety feature, the author found the system not flexible enough in terms of gas sampling collection.

The wt. % concentration of hydrogen, carbon monoxide, methane, nitrogen and some hydrocarbons were measured, while the ER value for sugar maple, poplar and tamarack was found to be 0.227, 0.231 and 0.166, respectively. The syngas produced by poplar wood chips showed the highest concentration of hydrogen, carbon monoxide and methane. This could mean that the syngas produced from poplar has the highest quality and calorific value.

The mean calorific value of the syngas obtained is about $4 \text{ MJ}/\text{Nm}^3$, which is leaned towards the minimum limit in air gasification of biomass. The maximum cold gas efficiency of the gasifier is found to be about 55%. It can be predicted that the overall efficiency of the system (from biomass to electricity generation) is in the range of 10 to 12%.

8.2 Conclusions of the Computer Modeling Study

In the modeling part, it can be concluded that the concentration of hydrogen steadily increases with the increase of ER, while carbon monoxide and methane peak with the ER equal to 0.28. In order to have a better sense of this model, it is necessary to report the advantages and also limitations of this thermo-chemical mode:

- Advantages:
 - This is a simple model and seems to be correctly simulates the GEK IV to some extent. Furthermore, it is easy to use, as Aspen Plus is generally user-friendly.
 - This model is easy to modify; in fact, it is quite easy to make this model more complicated. One of the areas in which the model could be upgraded is the kinetics part of the system. Once the gasification kinetics is incorporated into the model, the accuracy would improve dramatically.
- Limitations:
 - Detailed information could not be incorporated in this model, as the experimental setup was not able to provide very detailed information regarding the gasification process.
 - This model does not take the gasification reaction kinetics into account.
 - This model is a steady-state model, which looks at the system during equilibrium conditions, while in reality, the GEK IV gasification system is a batch system. Although Aspen Plus is capable of modeling batch systems, for the sake of simplicity, this work has not used the batch modeling features.
 - Aspen Plus might not be the best simulation software package for the purpose of this study, as it is not the best for solid systems modeling. Moreover, some technical problems and errors were found in the model that may have affected the results significantly.

8.3 Conclusions of the Policy-related Issues

In chapter 4, the focus was on the drivers of the WTE technology, identifying the barriers and possibly recommending solutions to address the existing challenges. The author does hope that one finds the recommendations for WTE issues effective. The author also believes that this piece of work at least will start a discussion that eventually can lead to creation of some effective solutions for policy-related issues in the WTE industry. In fact, a more inclusive study of the specific strategies and actions seems to be essential, in order to see a successful WTE industry in a particular region. At the end, the issues discussed above could be summarized in the following three points:

- Supportive policy infrastructure
- Human Resources and Capacity Development and
- Premiums for new companies and Entrepreneurs.

The most important opportunities, challenges and the author's recommendations regarding the plasma gasification technology are as follows:

➤ **Opportunities**

- + Minimizes the need for landfilling, if becomes commercially spread around the world
- + Processes variety of materials; e.g. Municipal Solid Waste (MSW) and medical waste
- + Has potentials in syngas commercialization, which could reduce the need for crude oil
- + Produces various products and by-products, including vitrified slag
- + Minimizes the pre-treatment processes due to very high operating temperatures
- + Presents environmental benefits; achieving significant reduction in air pollution

➤ **Challenges**

- Suffers from high levels of capital cost and investments (economic Issues)
- Suffers from environmental skepticism and lack of public awareness (social related)
- Lacks clear and specific standards (policy/regulation issues)

➤ **Recommendations**

- Reduce complexities and promote the construction of new plasma gasification plants
- Promote the products and by-products in the market, i.e. syngas, liquid fuels and slag
- Increase the government involvement for creating the necessary legislations
- Raise awareness about dangers of landfilling and promote the technology at the social and industrial levels by advertising *“one plasma gasification plant for every landfill”*

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Appendix

Executive Summary

❖ Conventional Gasification

Conventional Gasification or simply *Gasification* is a thermochemical process that results in production of a gaseous fuel. Drying, pyrolysis, combustion and reduction are the main processes that are involved in this case. In drying, moisture is removed from the feedstock. Pyrolysis removes the volatiles and thus, fixed carbon goes to the combustion process. In combustion, char reacts with the provided oxygen and supplies heat for reduction reactions to take place. In the reduction zone, the carbon that has not been vaporized forms *Syngas*, which has various applications, mainly in the energy industry.

❖ Plasma- assisted Gasification

Plasma-assisted Gasification technology is known to be the advanced and environmentally improved version of the conventional gasification. This thermal process is not combustion and uses plasma torch to create extremely high temperatures in a controlled and oxygen-starved environment. This process completely breaks down the bonds in the feedstock and extracts the syngas from organic part of the waste, while the inorganic portion is solidified to form a sealed, safe and vitrified *slag*.

❖ Experimental and Modeling Studies

The Gasfier Experimenter's Kit (GEK) IV gasification system was used to experimentally study the syngas composition obtained using sugar maple charcoal, poplar and tamarack wood chips as the feedstock. Moreover, a computer simulation work was performed to model the GEK IV gasification reactor. The summary of the experimental and modeling findings are as follows:

- GEK IV gasification system benefits from a relatively robust design and some key safety features, such as operation under negative pressure difference.

- The wt. % concentration of hydrogen, carbon monoxide, methane, nitrogen and some hydrocarbons were measured, while the ER value for sugar maple, poplar and tamarack was found to be 0.227, 0.231 and 0.166, respectively.
- The syngas produced by poplar wood chips showed the highest concentration of hydrogen, carbon monoxide and methane. This could mean that the syngas produced from poplar has the highest quality and calorific value.
- The mean calorific value of the syngas obtained is about $4 \text{ MJ}/\text{Nm}^3$, which is leaned towards the minimum limit in air gasification of biomass.
- The maximum cold-gas-efficiency of the gasifier is found to be about 55%.
- It can be predicted that the overall efficiency of the system (from biomass to electricity generation) is in the range of 10 to 12%.
- In the modeling part, it can be concluded that the concentration of hydrogen steadily increases with the increase of ER, while carbon monoxide and methane peak with the ER equal to 0.28. Thus, the optimum operational ER value for GEK IV is between 0.28 to 0.3.
- This Aspen Plus model is simple and simulates the GEK IV reasonably well to some extent. It is also easy to use and modify.
- Detailed information could not be incorporated in this model, as the experimental setup was not able to provide very detailed information regarding the gasification process.
- For the sake of simplicity, reactions kinetics were not incorporated into this model.
- This model is a steady-state model, which looks at the system during equilibrium conditions, while in reality, the GEK IV gasification system is a batch system. Although Aspen Plus is capable of modeling batch systems, for the sake of simplicity, this work has not used the batch modeling features.
- Aspen Plus was initially developed for liquid-vapor systems and solid systems were added to it later on; therefore, it might not be the best simulation software package for the purpose of this study.

❖ Policy-related highlights

➤ Opportunities

- + Minimizes the need for landfilling, if becomes commercially spread around the world
- + Processes variety of materials; e.g. Municipal Solid Waste (MSW) and medical waste
- + Has potential in syngas commercialization, which could reduce the need for crude oil
- + Produces various products and by-products, including vitrified slag
- + Presents environmental benefits; achieving significant reduction in air pollution

➤ Challenges

- Suffers from high levels of capital cost and investments (economic Issues)
- Suffers from environmental skepticism and lack of public awareness (social related)
- Lacks clear and specific standards (policy/regulation issues)

➤ Recommendations

- Reduce complexities and promote the construction of new plasma plants
- Promote the products and by-products in the market, i.e. syngas and slag
- Increase the government involvement for creating the necessary legislation
- Raise awareness about dangers of landfilling and promote the technology at the social and industrial levels by advertising *“one plasma gasification plant for every landfill”*