EVALUATION OF POSSIBLE GASIFIER-ENGINE APPLICATIONS WITH MUNICIPAL SOLID WASTE (A CASE STUDY OF KAMPALA)

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ABSTRACT
Gasification of biomass for electricity power generation has been a proven technology in a number of countries in the world. MSW consists of biomass, glass, plastics, metallic scrap and street debris. Biomass constitutes the highest proportion of MSW and being an energy resource, implies that it can contribute tremendously to the energy needs of any country since every country is endowed with this resource which is generated in enormous tonnes per day. The challenge would then be the choice of the technology to harness this abundant energy resource subject to financial and environmental constraints.

In Uganda, MSW gasification for power generation has never been implemented in spite of the 500-600 tonnes of MSW collected per day, the biomass component of the MSW comprising 88%. MSW is instead collected in skips, transported by trucks to a landfill were it is deposited and left to decompose releasing methane (CH₄) and carbon dioxide (CO₂) gases which are highly potent greenhouse gases. In this regard, the many tonnes per day of MSW collected in Kampala city (area of the study) portray significant potential of generating producer gas using the technology of gasification to run engines for power generation and this study evaluated possible gasifier-engine system applications for power generation. Experiments were carried out at the Faculty of Technology, Makerere University to determine biomass characteristics (e.g. moisture content, ash content) and gasification parameters (e.g. lower heating value) of MSW required for gasifier-engine applications. After establishing the lower heating value of the producer gas from MSW, a theoretical design of a gasifier-engine system was investigated for possible applications with the biomass component of MSW and an economic analysis was done to assess the feasibility of the project.
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DEDICATION

This report is dedicated to my father, Mr. Paul Ssonko (R.I.P) and my mother, Miss Teddy Nalubega for their parental guidance and financial support that helped me to pursue studies up to University.
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LIST OF ACRONYMS

Atm- Atmosphere
ERL-Environmental Resource Limited
GC- Gas Chromatography
GPR- Gas Production Rate
Ha - Hectare
HHV- Higher Heating Value
IC- Internal Combustion
ICE – Internal Combustion Engine
KCC- Kampala City Council
LHV-Lower Heating Value
MC- Moisture Content
MSW- Municipal Solid Waste
NEMA- National Environment Management Authority
NTP – Normal Temperature and Pressure
RPM – Revolutions per Minute
SFC – Specific Fuel Consumption
LIST OF SYMBOLS

$NH_3$ – Ammonia

$CO$ - Carbon monoxide

$HCl$ – Hydrogen Chloride

$HCN$ – Hydrogen Cyanide

$H_2S$ – Hydrogen Sulphide

$MW_H$ - Molecular weight of hydrogen

$CO_2$ - Carbon dioxide

$C_2H_4$ - Ethane

$H_2$ - Hydrogen

$CH_4$ - Methane

$MW_{air}$ - Molecular weight of air

$MW_C$ - Molecular weight of carbon

$MW_{fuel}$ - Molecular weight of fuel

$MW_O$ - Molecular weight of oxygen

$N_2$ - Nitrogen

$\sigma$ - Standard deviation

$O_2$ - Oxygen
CHAPTER ONE: INTRODUCTION

1.0 Background information

Gasification is a process that converts carbonaceous materials, such as coal, petroleum, or biomass, into a product gas composed primarily of Carbon monoxide and hydrogen with less amounts of methane, higher hydrocarbons, Carbon dioxide, water vapour and nitrogen depending on the oxidant used i.e. air, pure oxygen, steam or a mixture of these oxidants [Hariie.K et al., 2008; Wikimedia, 2009]. Gasification involves thermo-chemical processes at temperatures above 700°C [Wikimedia, 2009]. Thus, thermo-chemical gasification is different from biological processes such as anaerobic digestion which produce biogas at low temperatures of between 32°C - 35°C [www.habmigern2003.info, 2009].

One of the most important applications of producer gas is burning it directly in internal combustion engines for power generation. Petrol and diesel engines can be modified for application with producer gas in either type of engine. Another important use of producer gas is combusting the producer gas in a boiler to produce steam. The steam is then piped to a conventional steam turbine connected to a generator for power generation [AP&T Generation project, 2004]. Other applications include the conversion of the producer gas to methanol and hydrogen or via the Fischer-Tropsch process into synthetic fuel. The producer gas can also be used as a fuel in a gas turbine for power generation.

Power generation equipment that can be integrated with a MSW gasification process includes steam boilers, reciprocating engines, combined cycle turbines and fuel cells. Combined cycle turbines, reciprocating engines and fuel cells offer operational efficiencies of 40%+ [Alexander, 2002]. Small-scale biomass gasification plants have been established in countries like Sweden, Finland, USA, Indonesia, Canada, Belgium, France while large-scale biomass gasification plants have been established in countries like Sweden, Italy, Austria, Netherlands [Hariie, 2005].

In Uganda, small scale gasification plants have been established in Kibaale District, Kampala District (Kyambogo University and Makerere University), Bushenyi District and Masindi District but no large scale gasification has been established since the technology is new in the country. The plant in Kibaale District is estimated at 250kWgross (108kWnet) [Kjellström and Olwa, 2008; Ankur, 2010] and the electricity produced is used for running motors in Muzizi Tea Factory. The gasifier-engine system at Kyambogo University is estimated at 10kW and is used for experimental purposes. The gasifier at Makerere University is an experimental facility which can be run in updraft and downdraft
mode. The plant in Masindi is estimated at 200kW and was installed to supply electricity to Forestry College Nyabyeya. [Ministry of Energy, 2009]

Kampala is the capital city of Uganda. The city is divided into five divisions; Kawempe, Rubaga, Makindye, Nakawa and Kampala Central as shown in Figure 1-2. Figure 1-1 and Figure 1-2 show the location of Kampala city at different scales. The population in Kampala is continuously increasing partly due to rural-urban migration and high fertility rate and so is the amount of waste generated. Domestic waste generation in Kampala city is estimated between 0.5kg – 1.1kg per capita per day [www.anglefire.com, 2009].

The management of MSW in Kampala is done by KCC and the dumping site is found at Mpererwe, a landfill made in 1996. MSW collected in skips is transported by trucks to the landfill where it is deposited and it’s estimated in the range of 500-600tonnes/day [Mudanye, 2009]. The waste is buried with soil, left to decompose and the resulting emissions such as methane (CH₄) and Carbon dioxide (CO₂) which are potent greenhouse gases are released to the environment [US.EPA, 1996].

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**Figure 1-1:** Geographical location of Uganda and Kampala  

**Figure 1-2:** Map of Kampala  
*Source: UN-HABITAT [2007]*
The many tonnes per day of MSW collected in Kampala city portray significant potential for generating producer gas to run engines for power generation. This study evaluated the possibility of gasifier-engine system applications for power generation using MSW.

1.1 Problem statement

Kampala city generates between 500-600 tonnes per day of MSW which is collected, transported and deposited at Mpererwe landfill where it is left to decompose releasing hazardous emissions to the environment. Figure1-3(a) shows a truck carrying MSW arriving at the weighing bridge and Figure 1-3(b) shows the dumping site of MSW at Mpererwe landfill.

There is no alternative use of the fuel such as gasification for electricity power generation being exploited and the following problems were noted.

i. When MSW decomposes, the gases emitted are toxic and irritating due to the stench produced which makes it unhealthy for people to stay in the vicinity of the landfill thus landfills pollute the environment.

ii. The methane from landfills is considered, in the Kyoto treaty to be 21 times more potent as a greenhouse gas than Carbon dioxide [Mark, 2001].
Furthermore, a significant amount of Carbon dioxide is also generated from landfills.

iii. Landfills lead to uneconomical usage of land that would have been utilised for other developments such as roads, buildings and many others.

iv. Although other waste management projects such as “Design of landfill gas recovery and utilization project” have been suggested, no implementation has been done [www.kcc.go.ug ]. Besides, the generation of gas from landfills is time constraining compared to gasification of the MSW to generate producer gas; the waste stabilization and composting time of a conventional landfill is between 30 to 50 years or more [Sean, Hein, Ramin, 2006].

v. No study has been done in Uganda on whether the MSW can be gasified for power generation. Furthermore, little is known on the economic benefits of implementing a gasifier-engine system project with MSW.

Thus, this project seeks to find an environmentally friendly alternative to the waste management of municipal solid waste and its disposal.

1.2 Main objective

To investigate the possibility of gasifier-engine applications with municipal solid waste in Kampala city.

1.3 Specific objectives

i. To quantify the amount of the biomass component of MSW generated in Kampala.

ii. To determine the biomass characteristics and gasification parameters of MSW, for possible power generation using a gasifier-engine integrated system.

iii. To carry out a theoretical design of an internal combustion engine, gasifier and gas cleaning system for use with MSW in Kampala city.

iv. To analyze expected economic benefits for the proposed facility.
1.4 Justification

The project would yield the following benefits:

i. A deeper understanding of biomass characteristics and gasification parameters of MSW in Uganda for use as fuel in a gasifier-engine system. Design requirements for a gasifier-engine system will be addressed as well as the expected economic performance of the system.

ii. The project will provide an estimate of the electrical energy to be obtained from the gasifier-engine system. This electrical energy can supplement the energy demand from hydroelectricity, thermal power and the power from cogeneration in Kampala and Uganda.

iii. The project will provide a greater insight of waste management in Kampala which if implemented would replace the landfill strategy of waste disposal. Consequently it would be a pioneer project from which other urban areas can learn.

1.5 Scope

The study was limited to;

i. Assessment of biomass characteristics and gasification parameters of MSW.

ii. Theoretical design of gasifier-engine system. A downdraft gasifier as well as a spark-ignited gas engine was considered.

iii. Economic analysis of the designed system.
CHAPTER TWO: LITERATURE REVIEW

2.0 Introduction

This chapter describes the processes and terminologies used in gasification namely, gasification sub-processes, gasification parameters, biomass characteristics related to gasification, reactor designs, technical and operational problems with fixed bed gasifiers, gas conditioning, gas utilization, gas quality measurements and requirements for the engine.

2.1 Gasification sub-processes

Gasification (direct oxidation, starved-air or starved oxygen combustion) utilizes less than the stoichiometric amounts of oxygen needed for complete combustion. Solid fuels can be converted to a form that can be used more easily. The producer gas obtained from gasification can be used in furnaces, internal combustion engines and gas turbines [Fakhrai, 2007]. The gasification process can be divided into four steps namely drying, pyrolysis, oxidation/combustion and reduction as illustrated in Figure 2-1 for updraft gasification. The process occurs randomly within the gasifier and the stratification is used for simplicity of presentation.

![Figure 2-1: Gasification sub-processes in an updraft gasifier](Image)

Source: Fakhrai [2007]
2.1.1 Drying and pyrolysis (devolatilisation)

Drying involves removing the water within the fuel by evaporation thus it is endothermic. The devolatilisation step (pyrolysis) is also endothermic and, for temperatures above 500°C, 75 to 90%wt. [Hariie, 2005] of volatile matter is produced in the form of steam plus gaseous and condensable hydrocarbons. The volatile gases, mainly CO\(_2\), CO, and hydrocarbons are released from the dry fuel through thermal degradation. The solid remaining is called char.

2.1.2 Oxidation (combustion)

This involves total and partial combustion of gas and char. Combustion taking place in the oxidation zone is described by the following heterogeneous chemical reactions:

\[
\begin{align*}
C + \frac{1}{2}O_2 &= CO + 123.1 \text{kJ/mol} \quad \text{Equation 2-2} \\
C + O_2 &= CO_2 + 393.8 \text{kJ/mol} \quad \text{Equation 2-1}
\end{align*}
\]

These two reactions are exothermic and provide the heat necessary for the endothermic reactions in the drying, pyrolysis and the reduction zone.

2.1.3 Reduction

According to Fakhrai, 2007 Carbon dioxide (CO\(_2\)) and water(H\(_2\)O) in the presence of heat are reduced by char to form producer gas comprising hydrogen(H\(_2\)), Carbon monoxide (CO), water (H\(_2\)O), CO\(_2\), nitrogen(N\(_2\), if air is used as oxidizing agent) and several hydrocarbons. Depending on the content of N\(_2\) in the fuel and on the gasification process, ammonia (NH\(_3\)) will as well be part of the producer gas. The gas composition and heating value of this product gas varies from 2.0- 6.0 for air blown gasifiers to 13-15MJ/Nm\(^3\) for oxygen/steam-blown gasifiers [Hariie, 2005; Aki, 2003].

The water vapour introduced with the air and production by the drying and pyrolysis of the biomass reacts with the hot char according to the following heterogeneous reversible water gas reaction.

\[
C + H_2O + 118.5 \text{kJ/mol} = CO + H_2 \quad \text{Equation 2-3}
\]

According to Jared & John [2002], the following water gas shift reaction also takes place

\[
CO + H_2O = CO_2 + H_2 \quad \text{Equation 2-4}
\]
The water gas shift equilibrium determines to a large extent the final gas composition and depends on the temperature. The most important reactions are the water gas reaction of Equation 2-3 and the Boudouard reaction of Equation 2-5

\[ C + CO_2 + 159.9 \text{ kJ/mol} = 2CO \quad \text{Equation 2-5} \]

These heterogeneous endothermic reactions increase the gas volume of CO and H\(_2\) at higher temperatures and lower pressures (a high pressure suppresses the gas volume).

According to Hariie, 2005 the final product gas also contains methane as a result of the methanisation reaction of Equation 2-6.

\[ C + 2H_2 = CH_4 + 87.5 \text{ kJ/mol} \quad \text{Equation 2-6} \]

According to Jared & John [2002], the following methanisation reaction also takes place

\[ CO + 3H_2 = CH_4 + H_2O \quad \text{Equation 2-7} \]

Furthermore, part of the Carbon monoxide or hydrogen may be combusted according to Equation 2-8 and Equation 2-9. Although they produce heat which is beneficial to the gasification process, they are not desired because they reduce Carbon monoxide and hydrogen which contribute greatly to the heating value.

\[ CO + \frac{1}{2}O_2 = CO_2 + 283.9 \text{ kJ/mol} \quad \text{Equation 2-8} \]

\[ H_2 + \frac{1}{2}O_2 = H_2O + 285.9 \text{ kJ/mol} \quad \text{Equation 2-9} \]

### 2.2 Gasification parameters

Gasification parameters include equivalence ratio, superficial velocity or specific gas production rate, hearth load, turn-down ratio, gas heating value, gas flow rate, gas production, fuel consumption and efficiency.
2.2.1 Equivalence ratio (ER)

This is the oxygen used relative to the amount required for complete combustion. According to Stephens [2000], for a hydrocarbon fuel given by $C_xH_y$, the stoichiometric relation can be expressed as

$$C_xH_y + a(O_2 + 3.76N_2) \rightarrow xCO_2 + \left(\frac{y}{2}\right)H_2O + 3.76aN_2 \quad \text{Equation 2-10}$$

Where,

$$a = x + \frac{y}{4} \quad \text{Equation 2-11}$$

And the composition of air is assumed to be 21 percent $O_2$ and 79 percent $N_2$ (by volume), i.e. for each mole of air, there are 3.76 moles of $N_2$.

The stoichiometric air-fuel ratio can be found as

$$(A/F)_{stoic} = \left(\frac{m_{air}}{m_{fuel}}\right)_{stoic} = \frac{N_{air}}{N_{fuel}} \cdot \frac{MW_{air}}{MW_{fuel}} \quad \text{Equation 2-12}$$

Where

$N_{air}$ is the number of moles of air, that is, $a + 3.76a = 4.76a$ (Equation 2-10)

$N_{fuel}$ is the number of moles of the fuel, that is, 1 (Equation 2-10)

Equation 2-12 can also be written as,

$$(A/F)_{stoic} = \left(\frac{m_{air}}{m_{fuel}}\right)_{stoic} = \frac{4.76a}{1} \cdot \frac{MW_{air}}{MW_{fuel}} \quad \text{Equation 2-13}$$

According to [Stephens, 2000; Jain, 2006], the equivalence ratio, $\phi$, is defined as

$$\phi = \frac{(A/F)_{stoic}}{(A/F)} \quad \text{Equation 2-14a}$$

$$\phi = \frac{(F/A)}{(F/A)_{stoic}} \quad \text{Equation 2-14b}$$
From Equation 2-14a it is seen that for fuel-rich mixtures, $\phi > 1$ and for fuel-lean mixtures, $\phi < 1$. For a stoichiometric mixture, $\phi$ equals unity.

### 2.2.2 Specific gasification rate (SGR)

Specific gasification rate (SGR) is calculated using the weight of dry fuel gasified for a run, net operating period and the cross-sectional area of the reactor using Equation 2-15.

\[
SGR = \frac{\text{Weight of dry fuel used (kgh}^{-1})}{\text{cross sectional area of the reactor (m}^2)} \quad \text{Equation 2-15}
\]

### 2.2.3 Superficial velocity, $V_s$, specific gas production rate, SGPR and Hearth load, $B_h$

The superficial velocity is defined as the gas flow rate (m$^3$/s) divided by the cross-sectional area (m$^2$) of the reactor taken at the throat (constriction). According to Hariie [2005] as well as Reed, Walt, Ellis, Das and Deutch [1999] superficial velocity is used for choosing gasifier dimensions and it is expressed as;

\[
\frac{\text{Gas Volume}}{\text{Cross sectional area} \times \text{time}} = \frac{\text{m}^3}{\text{m}^2 \text{s}} \quad \text{Equation 2-16}
\]

It is called superficial velocity since the actual velocities are three to six times higher due to the presence of the charcoal and the high temperatures existing at the throat.

According to Jain [2006] specific gas production rate is expressed as;

\[
\text{SGPR} = \frac{\text{Rate of gas production (m}^3/\text{h})}{\text{Cross sectional area of the gasifier (m}^2)} \quad \text{Equation 2-17}
\]

Where, the cross-sectional area of the reactor is taken at the throat (constriction).

Hariie, 2005 suggests an optimum value of $V_s$ of 2.5m/s or SGPR of 9000 m$^3$/h - m$^2$ calculated at NTP from the throat diameter and ignoring the presence of the fuel.

The hearth load $B_h$ is defined as the flow rate of producer gas corrected to normal (pressure, temperature) conditions, divided by the surface area of the
"throat" at the smallest circumference and is usually expressed in m³/cm²/h i.e. the hearth load is the superficial gas velocity at the smallest cross-section

\[ B_h = \frac{\text{Gas Volume}}{A_h} \]  

Equation 2-18

Where,

- \( A_h \) - is the hearth area (cm²)
- Gas volume (m³/h)

A maximum hearth load (\( B_{h_{\text{max}}} \)) value for an imbert-type gasifier is about 0.9Nm³/cm²-h i.e. 0.9m³ of gas is produced for each square centimeter of cross-sectional area at the constriction [Reed & Das, 1988; FAO, 1986].

Thus, \( V_s \), SGPR and \( B_h \) are similar. The superficial velocity is one of the most important parameters determining the performance of a gasifier reactor, controlling gas production rate, gas energy content, fuel consumption rate, power output, and tar/char production rate. For constricted hearth (Imbert-type) gasifiers, the practical range for hearth load is 0.8 – 2.5 m/s [Hariie, 2005].

Limitations of maximum hearth load

i. Mechanical integrity of char bed structure within the gasifier.

ii. Degree of agitation.

iii. Time available for conversion.

The hearth area (\( A_h \)) and air nozzles (tuyeres, \( A_m \)) are related e.g. maximum power is obtained for 130mm hearths that have five 12mm nozzles [Hariie, 2005]. Knowledge of the maximum hearth load permits one to calculate the size of hearth needed for various engine or burner size.

### 2.2.4 Turn down ratio (T.D.R)

This is the ratio of the highest practical gas generation rate to the lowest practical rate.

\[ \text{T.D.R} = \frac{\text{highest practical gas generation rate}}{\text{lowest practical gas generation rate}} \]  

Equation 2-19

For downdraft gasifiers, the turn-down ratio is typically 3-18 [Hariie, 2005; Reed & Das, 1988].
2.2.5 Gas heating Value

The gas heating value is usually expressed in MJ/Nm³. A normal cubic meter (Nm³) is referring to the gas volume at 1 atmosphere and 0°C. The gas heating value can be calculated using the higher heating value (HHV) or lower heating value (LHV). The HHV is defined by the assumption that heat required to evaporate the fuel moisture during combustion is neglected. The LHV is defined with moisture evaporating heat taken into consideration.

2.2.6 Gas flow rate and gas production

The gas flow rate can be calculated from the primary air flow if the nitrogen content in the producer gas is known, or measured by orifice plates, venturis, pitot tubes or rotameters. To calculate the gas flow on a Nm³ basis, also the temperature and pressure need to be measured. From the gas flow rate and fuel input, the gas production can be calculated per unit fuel input (Nm³/kg) or per energy produced (Nm³/kWe).

2.2.7 Efficiency and fuel consumption

The efficiency of a gasifier can be expressed on a hot or cold basis. Cold gas efficiency (CGE) is the chemical energy content of the producer gas divided by the energy content of the biomass. It is called cold gas efficiency as it does not take into account that the product gas exiting the gasifier is hot. The CGE increases with better fuel conversion [Fakhrai, 2007]. The hot gas efficiency is the chemical and heat energy of producer gas divided by the energy content of the biomass. The fuel consumption is needed to determine the gasifier overall efficiency. The fuel consumption can be measured by a balance or automatically by metering bins. The fuel consumption can be expressed on a unit mass per unit time (kg/h), or unit mass per energy produced (kg/kWe) or unit mass per cross-sectional area and time (kg/m²-h). The specific fuel consumption (sfc) is defined as:

\[
sfc = \frac{m_{\text{fuel}}}{PE_{\text{max}}} \]

Equation 2-20

2.3 Biomass characteristics related to gasification

2.3.1 Moisture content

The moisture content of biomass is defined as the quantity of water in the material expressed as a percentage of the material’s weight. This weight can be
referred to on a wet basis (including water in the fuel), on a dry basis (excluding water in the fuel), and on a dry-and-ash-free basis (excluding water and ash in the fuel). The dry biomass feedstock with low moisture content is needed in gasification processes in order to produce a higher quality gas i.e. higher heating value, higher efficiency and lower tar levels. Natural drying (on the field) is cheap but requires long drying times. Artificial drying can utilize waste heat from the engine/turbine to dry feedstock but it is expensive though more effective.

2.3.2 Ash content and ash composition

Ash is the inorganic content of the biomass, which remains after complete combustion. The amount of ash in different feedstock varies widely i.e. 0.1% in wood and up to 15% for some agricultural products [Hariie, 2005] and influences the design of the reactor, particularly the ash removal system. The chemical composition of the ash also affects the melting behavior of the ash and ash melting causes slagging in the reactor.

2.3.3 Elemental composition and heating Value

The generic formula for biomass is CH$_{1.4}$O$_{0.6}$ [Reed & Das, 1988] on dry–and–ash-free basis. The elemental composition of the fuel is important with respect to the heating value and the emission levels in almost all applications. The heating value is determined by the elemental composition, the ash content of the biomass and in particular on the fuel moisture content.

2.3.4 Bulk density and morphology

The bulk density refers to the weight of material per unit volume and it is different for various types of biomass. Together with the heating value, it determines the energy density of the gasifier feedstock i.e. the potential energy available per unit volume of feedstock.

2.3.5 Tar and entrained particles

"Tar" is a collective name for aromatic condensable hydrocarbons. Tar can be defined as "the mixture of chemical compounds which condense on metal surfaces at room temperature" or "all organic contaminants with a molecular weight larger than benzene" as quoted by Erlich, 2006. Tar is always produced during pyrolysis, and the amount is dependent on the fuel, the pyrolysis
conditions as well as the gasification process. Particulates include char, ash and soot entrained in the gas stream.

2.4 Feedstock preparation requirements

Hariie, 2005 suggests that feedstock preparation is required for almost all types of biomass materials because of a large variety in physical, chemical and morphological characteristics for example;

i. Coarse materials like wooden logs need to be sized in two or more steps.

ii. Wet materials like waste from public gardens and newly cut wood, require more drying energy.

iii. Artificial drying of coarse materials requires more time compared to fine materials like saw dust.

iv. Wet materials like waste from public gardens, green waste (vegetable, fruit and garden) usually have small particle size.

v. Screening of wet materials is a less efficient process compared to screening of dry materials.

vi. Hammer mills can only be applied for relatively dry materials. For sizing of wet materials, chippers provided with a knife must be applied.

2.5 Reactor designs

Gasifiers can be classified in different ways, namely, according to the gasification agent, heat for gasification, pressure in the gasifier, design of the reactor. The classification according to the design of the reactor is as follows;

i. Fixed bed

ii. Fluidized bed

iii. Entrained flow

iv. Twin-bed
2.5.1 Fixed bed gasifiers

Heat required for the gasification process can be added directly by partial oxidation of the fuel (autothermal) or by indirect heat transfer (allothermal). The fixed bed gasifiers include updraft and downdraft gasifiers.

**Updraft gasifier**

Here the biomass is fed at the top of the reactor and moves downwards as a result of the conversion of the biomass and the removal of the ash. The air intake is at the bottom and the producer gas leaves at the top. The biomass and gas flow in opposite direction to each other and pass through the drying zone, the pyrolysis zone, the reduction zone and the oxidation zone. Refer to Figure 2-1 for the sketch of the updraft gasifier.

**Advantages of the updraft gasifier**

The advantages of the updraft gasifier include;

i. Simple, low cost process.

ii. High charcoal burn-out.

iii. Improved internal heat exchange.

iv. Due to the internal heat exchange, the fuel is dried in the top of the gasifier and therefore fuels with high moisture content (up to 60%) [Hariie, 2005] can be used e.g. municipal solid waste.

v. It can process relatively small sized fuel particles and accepts some size variation in the fuel stock.

**Disadvantage of the updraft gasifier**

High amounts of tars and pyrolysis products because the pyrolysis gas is not combusted. However, this is of minor importance if the gas is used for direct heating applications in which the tar is simply burnt. Otherwise extensive gas cleaning is required if the gas is to be used in internal combustion engines for power production.
**Downdraft gasifier**

In this type of gasifier, the biomass is fed at the top and the air intake is also at the top or from the sides as shown in Figure 2-2. Most downdraft gasifiers are equipped with a V-shaped “throat” as shown in Figure 2-2. The oxidation zone is located in the narrowest part of this throat. The aim of this throat is to create a concentrated high temperature zone and to force all pyrolysis gases to pass this zone in order to crack the tar. Air is fed directly above this zone by either a central air supply pipe, or “tuyeres” (air inlet nozzles) located at the walls of the throat. The gas leaves at the bottom of the reactor, so the fuel and the gas move in the same direction. The same zones can be distinguished as in the updraft gasifier, although the order is somewhat different [Hariie, 2005].

![Downdraft gasifier](image)

*Figure 2-2: Downdraft gasifier*

Source: Fakhrai [2007]

**Advantages of the downdraft gasifier**

The advantages of the downdraft gasifier include;

i. Production of a gas with a low tar content which is suitable for IC-engine applications.

ii. Proven, simple and low cost process.

**Disadvantages of the downdraft gasifier**

The disadvantages of the downdraft gasifier include;

i. High amounts of ash and dust particles in the gas due to the fact that the gas has to pass the oxidation zone where small ash particles are
entrained. This leads to a relatively high temperature of the leaving gases resulting in lower gasification efficiency.

ii. The high particulate matter carried in the gas stream demands for extensive gas cleaning for small scale applications with power generation.

iii. Downdraft gasifiers demand a relatively strict requirement of the fuel like moisture content less than 25% [Hariie, 2005] on a wet basis and of uniform size in the range of 4-10 cm to realize regular flow, no blocking in the throat, enough “open space” for the pyrolysis gases to flow downwards and to allow heat transfer from the hearth zone upwards. Therefore, pelletization or briquetting of the biomass is often necessary.

iv. This type of gasifier is used in the electricity power production applications in the range from 80 up to 500kW_e [Hariie, 2005; Bio_Energy Research Group, 2009].

v. Producer gas exiting the reactor is at high temperature, requiring a secondary heat recovery system.

2.5.2 Fluidized bed gasifiers

Fluidized bed gasifiers are applied to biomass to overcome the operational problems with fixed bed gasifiers like;

i. Fuels having high ash content.

ii. Bridging and channeling.

iii. Hot spots.

iv. Scale-up limitations.

v. Not suitable to small particles because of plugging and increased pressure drop.

Figure 2-3 shows a sketch of the fluidized bed gasifier. Here the fuel is fluidized in oxygen, steam or air. The ash is removed dry or as heavy agglomerates that defluidize. The temperatures are relatively low in dry ash gasifiers, so the fuel must be highly reactive; low-grade coals are particularly suitable. The agglomerating gasifiers have slightly higher temperatures, and are suitable for higher rank coals. Fuel throughput is higher than for the fixed bed, but not as high as for the entrained flow gasifier.
The conversion efficiency can be rather low due to elutriation of carbonaceous material. Recycle or subsequent combustion of solids can be used to increase conversion. Fluidized bed gasifiers are most useful for fuels that form highly corrosive ash that would damage the walls of slagging gasifiers. Biomass fuels generally contain high levels of corrosive ash [wikimedia, 2009].

Advantages of fluidized bed reactors in comparison with fixed bed reactors

The advantages of the fluidized bed reactors include;

i. Compact construction because of high heat exchange and reaction rates due to the intensive mixing in the bed.

ii. A narrow and uniform temperature profile without hot spots and the like.

iii. Tolerates many feedstock and flexible to changes in fuel characteristics such as moisture content and ash content; ability to deal with fluffy and fine grained materials with high ash contents and/or low bulk density.

iv. Relatively low ash melting points are allowed due to the low reaction temperatures.

v. Easy to scale up.
Disadvantages

The disadvantages of the fluidized bed reactors include;

i. High tar and dust content of the produced gas.

ii. High producer gas temperatures containing alkali metals in the vapor state.

iii. Incomplete carbon burn out.

iv. Complex operation because of the need to control the supply of both air and solid fuel.

v. The need for power consumption for the compression of the gas stream.

The fixed bed gasifier is the available test rig at Makerere University thus it will be considered for this study. Furthermore, the advantages of the fixed bed gasifier outweigh those of the fluidized bed gasifier. The fixed bed gasifier will be run in downdraft mode since the gas quality is better than for the updraft gasifier considering the end use i.e. utilizing the gas for power generation.

2.6 Technical and operational problems with fixed bed gasifiers

2.6.1 Tar production and explosions

Excessive tar production may be caused by inappropriate fuel properties like morphology, size distribution and moisture content and inappropriate flow behavior of the char in the reduction zone. Another cause could be due to periods of unsteady state operation or too low part-load operation. Explosions may occur as a result of leakage of combustible gases through the fuel feeding system, the ash discharge system or any other leakage point. After shut down of the gasifier, combustible gases will remain in the equipment. If the gasifier is ignited again without venting the equipment in advance with fresh air, the combustible gases are still present and may explode during ignition of the gasifier. To minimize the risk of explosions, gasifiers should be provided with spring-loaded top-lid [Reed & Das, 1988] or bursting disks and located in well-vented rooms or in the open air. Operators should be taught the risks of gasification equipment especially during start up and shut down.

2.6.2 Fuel blockages and corrosion

These may occur in the throat of the gasifier. These blockages are caused by inappropriate combination of fuel properties like morphology, size distribution, ash content and ash composition, bulk density and the flow properties of the derived char. Corrosion may be a problem especially on surfaces in the high
temperature areas of the gasifier (the throat). Too high temperatures can cause this corrosion and/or contaminants in the feedstock like chloride. The gasifier design should be adapted to lower the temperature and/or to use other heat resistant materials.

2.7 Gas conditioning

The product gas exiting a biomass gasifier normally contains unwanted components like particles, alkali compounds, tars, and nitrogen containing components. Depending on the design of the gasifier and the type of biomass used as fuel, there can be more or less of the mentioned components. These contaminants are normally incompatible with the end-use systems and therefore gas cleaning is required for those systems. The most frequent impurities are hydrocarbons (tars), dust (particulates), ammonia, sulphur, chloride, alkalis, etc., which need to be removed or converted. When the gas is used for heating applications, the requirement for gas quality is not strict, especially when the gas remains at high temperatures during transportation to the burner (this prevents tars and alkali metals from condensing). Cooling is required for;

i. Combustion in gas engines.

ii. When filters are applied with a maximum allowable temperature.

The various contaminants of producer gas are summarized in Table 2-1. These contaminants should be removed from the producer gas if it is to be used in internal combustion engines for power generation.

Table 2-1: Producer Gas Contaminants

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Example</th>
<th>Potential problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>Ash, char, fluid bed material</td>
<td>Erosion</td>
</tr>
<tr>
<td>Alkali metals</td>
<td>Sodium and potassium compounds</td>
<td>Hot corrosion, catalyst poisoning</td>
</tr>
<tr>
<td>Nitrogen compounds</td>
<td>NH₃ and HCN</td>
<td>Emissions</td>
</tr>
<tr>
<td>Tars</td>
<td>Refractive aromatics</td>
<td>Clogging of filters</td>
</tr>
<tr>
<td>Sulfur, chlorine</td>
<td>H₂S and HCl</td>
<td>Corrosion, emissions, catalyst poisoning</td>
</tr>
</tbody>
</table>

Source: Jared & John [2002]
2.8 Gas utilization

According to Fakhrai [2007], depending on the end application of the product gas and plant size, there are different gasifier designs. Small, packed-bed gasifiers (updraft, downdraft or cross draft) may be suitable for stationary IC-engine operation (with electricity generation) or for gas burner application. Fluidized bed gasifiers (bubbling, circulating or pressurized) can be quite large and are thus applied for larger plants, which for example may involve gas turbines, steam boilers and methanol synthesis. Pressurized entrained flow gasifiers are commercialized for coal as fuel and under development for black-liquor gasification to produce biofuels.

2.9 Gas quality measurements and requirements for the engine

2.9.1 Gas composition and gas energy content

Gas composition is the percentage of Carbon monoxide (CO), Carbon dioxide (CO₂), Hydrogen (H₂), methane (CH₄), higher hydrocarbons and nitrogen (N₂) in the producer gas and it is used to calculate the gas energy content or to analyze gasifier operation. The energy content requirement is greater than 4MJ/Nm³ [Reed & Das, 1988] for most applications.

2.9.2 Quantity of tars, quantity and size of particulates

For engine applications, the amount of particles should be less than 10mg/Nm³ [Reed & Das, 1988]. The tars and oils are troublesome in the gas-processing system and the engine so they must be thoroughly removed by scrubbing. Unless temperatures and pressures are suitable, tars can be in gaseous form. Tars occur as a mist or fog composed of fine droplets that may be less than 1µm in diameter. Tar mists continuously agglomerate into large droplets and tend to saturate and coat solid particles. If not removed, tar mist forms deposits that cause engine intake valves and other moving parts to stick.

2.9.3 Char/ash mixture

Char/ash mixture refers to the black dust and ash that falls naturally through the grate in a downdraft gasifier when gasification is as complete as it will go. The ash composition for MSW and rice hulls is 20% or greater [Reed & Das, 1988]. Char and ash, because of its high mineral content and abrasive potential, is the main cause of engine wear in engine systems and understandably is a main focus in gas cleanup. Very fine char, ash, soot and tar mists which escape the cyclone have to be removed too. Soot and boudouard carbon are inherently ash-free, non abrasive and possibly lubricating thus don’t contribute to engine wear.
CHAPTER THREE: METHODOLOGY

3.0 Introduction

This chapter describes the procedure followed in investigation of the feasibility study. The topics discussed include desk research, data collection and analysis, experimental investigations at Makerere University, design of the gasifier, engine and gas cleaning system and the economic analysis. The project adopted the following elaborated method of study;

3.1 Desk research

The information collected was both qualitative and quantitative and was pertinent to the project, that is, gasification for power generation. Information was obtained from the internet, textbooks, and lecture notes for Sustainable Energy Engineering.

3.2 Data collection and analysis

This involved collection and analysis of data concerning population trend in Kampala, MSW generation in Kampala, MSW composition and the moisture content of MSW generated in Kampala.

3.2.1 Population trend in Kampala

The population trend in Kampala city plays a big role on the amount of MSW generated and collected per day thus a review of the population trend in Kampala was necessary.

3.2.2 MSW generation in Kampala

Information was obtained from KCC (Mpererwe landfill) concerning the amount of waste collected in Kampala city per day, the proportions of the waste i.e. biomass, plastics, street debris and metallic scrap and management of MSW at Mpererwe landfill.
3.2.3 Composition of MSW generated in Kampala

The MSW generated in Kampala was analyzed in order to quantify the biomass component of the waste needed to run the gasifier. This quantity of biomass obtained was on a wet basis and needed to be dried to a certain level of moisture content necessary for gasification.

3.2.4 Moisture content of MSW generated in Kampala

Samples of fresh MSW were obtained and the following procedure was used to determine the moisture content on a wet basis.

i. Six steel containers A, B, C, D, E, and F were weighed using an electronic weighing scale (METTLER PC4400). The mass of each container was recorded.

ii. Samples were put in each of the steel containers. The mass of the sample plus container was recorded.

iii. The samples were placed into a furnace at 105 ± 3°C for a minimum of 24 hours. The samples were removed from the furnace and allowed to cool to room temperature. The containers with the furnace-dried samples were weighed and the mass recorded.

The percentage of total solids and moisture content were calculated using Equation 3-1 and Equation 3-2 respectively.

\[
\%\text{Total solids} = \frac{\text{Weight}_{\text{dry container plus dry sample}} - \text{Weight}_{\text{dry container}}}{\text{Weight}_{\text{sample as received}}} \]

\[\text{Equation 3-1}\]

\[
\%\text{Moisture} = 100 - \frac{\text{Weight}_{\text{dry container plus dry sample}} - \text{Weight}_{\text{dry container}}}{\text{Weight}_{\text{sample as received}}} \]

\[\text{Equation 3-2}\]
3.3 Experimental investigations

Experiments were carried out to determine the biomass characteristics of MSW as well as the gasification parameters of MSW required for gasifier-engine applications. The data obtained from the experiments was used to design the gasifier-engine system to consume MSW generated from Kampala. Such data included moisture content of the waste and heating value of producer gas.

3.3.1 Preparation of MSW; collecting, sorting and drying

The MSW at Mpererwe landfill had to be collected and sorted to obtain the biomass component of MSW which is required for gasification. The biomass has a lot of moisture, thus it had to be dried to optimum moisture content suitable for gasification.

3.3.2 Biomass characteristics of MSW related to gasification

The biomass characteristics considered were moisture content, bulk density, particle size and ash content.

Moisture content

Samples of the dried MSW were tested for moisture content using the procedure for testing the moisture content of the fresh waste. Equation 3-1 and Equation 3-2 were used to determine the moisture content on a wet basis as well as the total solids of the dried MSW.

Bulk density and particle size

The bulk density of the dried MSW was estimated using the following procedure.

i. A cylindrical steel container with height, 0.505m, and a radius, 0.2069m, leading to a volume, 0.0679m$^3$, was used for measuring the mass of the waste in kilograms.

ii. The mass of container was measured using a weighing scale and recorded.
iii. MSW was filled to the brim of the container. The mass of the container plus the waste was measured and recorded. The mass of MSW was obtained by subtracting the mass of empty container from the mass of container when filled with MSW.

iv. The bulk density was determined by dividing the mass of MSW with the volume of container.

MSW is heterogeneous due to its composition. Thus, it has a wide variation in its particle size.

**Ash content**

The samples used for determination of the moisture content were also used for determining the ash content. The following procedure was followed.

i. The following ramping procedure was used to ash the samples.
   a. Ramp from room temperature to 105 °C.
   b. Hold at 105°C for 12 minutes.
   c. Ramp to 250 °C at 10°C / minute.
   d. Hold at 250 °C for 30 minutes.
   e. Ramp to 575 °C at 20 °C / minute.
   f. Hold at 575 °C for 180 minutes.
   g. Allow temperature to drop to 105 °C.
   h. Hold at 105 °C until samples are removed.

ii. The steel containers were removed from the furnace and allowed to cool. The steel containers and ash were weighed and the weight recorded.

iii. The samples were placed back into the furnace at 575 ± 250°C and ashed to constant weight. Constant weight is defined as less than ± 0.3 mg change in the weight upon one hour of re-heating the crucible.

The percentage of ash was computed using Equation 3-3.

\[
%\text{Ash} = \frac{\text{Weight}_{\text{container \ plus \ ash}} - \text{Weight}_{\text{container}}}{\text{ODW}_{\text{sample}}} 
\]

...........................................................................................................*Equation 3-3*

Where Oven dry weight (ODW) is the weight of biomass mathematically corrected for the amount of moisture present in the sample at the time of weighing. Since samples from the moisture test were used then ODW was equal to the weight of the dry samples from the furnace.
### 3.3.3 Gasification Parameters of MSW

The gasification parameters of MSW considered were fuel flow, specific gasification rate, air flow rate, temperature, gasifier efficiency, gas composition and lower heating value.

**Fuel flow and specific gasification rate (SGR)**

The mass of dried MSW was measured using a weighing scale before feeding into the gasifier. The fuel consumption was calculated using Equation 2-20. The weighed MSW was used to calculate the fuel flow in kg/s for a particular run. Specific gasification rate (SGR) was calculated using the weight of dry MSW gasified for a run, net operating period and the cross-sectional area of the reactor using Equation 2-15.

**Temperature during operation and gasifier efficiency**

The temperature during gasification was measured using a DATA LOGGER (87623 SRP-6-1.5M) and CHROMEL/ALUMEL (K-type) thermocouples fixed at seven (7) regions, namely, drying/pyrolysis zone, combustion zone, reduction zone, ash zone, after the cyclone, sampling point and tar cracking region. The temperature variations were monitored from the computer using TREND READER software.

The gasifier efficiency was calculated knowing the lower heating value of the producer gas, mass flow rate of producer gas, and lower heating value of the solid fuel and mass flow of solid fuel. The efficiency can be either the cold gas or hot gas efficiency. In this case the cold gas efficiency was computed using Equation 3-4.

\[
\eta_{CG} = \frac{\text{LHV}_{\text{gas}} \times \dot{V}_{\text{gas}}}{\text{LHV}_{\text{fuel}} \times \dot{m}_{\text{fuel}}} \times 100(\%) \quad \text{Equation 3-4}
\]

Where,

\( \eta_{CG} \), Cold gas efficiency (%)

\( \text{LHV}_{\text{gas}} \), lower heating value of producer gas (MJ/Nm\(^3\))

\( \dot{V}_{\text{gas}} \), normal volume flow of gas (Nm\(^3\)/s)

\( \text{LHV}_{\text{fuel}} \), lower heating value of the MSW fuel (MJ/kg)

\( \dot{m}_{\text{fuel}} \), MSW fuel flow (kg/s)
Gas composition and lower heating value (LHV)

The gasifier was run and the gas collected was tested using a Gas Chromatograph (GC) recorder to determine its composition and consequently the gas heating value. Equation 3-5 was used to compute the gas heating value.

\[ \text{LHV}_{\text{gas}} = 11.2[H_2] + 13.1[CO] + 37.1[CH_4] + 83.8[C_nH_m] \quad \text{Equation 3-5} \]

Where, \([X]\), is the percentage concentration of the component in the producer gas. The samples were tested as soon as possible since hydrogen can rapidly diffuse through rubber seals and stopcocks thereby changing the gas composition in a few hours.

3.4 Design of the gasifier, engine and gas cleaning system

A gasifier-engine system was designed to run on the biomass component of MSW generated in Kampala. For the engine, parameters such as the LHV of the gas, GPR and the capacity/power output of the engine were important considerations. For the gasifier, the biomass consumption of the gasifier, sfc and reactor design where important considerations. The producer gas from the gasifier contains impurities such as tars and particulate matter which need to be removed from the gas before feeding the gas to an engine. Thus, a cleaning system comprising a cyclone, venturi scrubber, fine filter and baghouse filter was also designed to clean the gas.

3.5 Economic analysis

A comprehensive economic analysis was carried out on the gasifier-engine system to assess the feasibility of the project. The costs assessed included the investment, feed-in tariffs in Uganda for selling power to the grid, annual electricity production costs, and annual revenues from selling power to the grid and annual benefits. The annual benefits were used to estimate the pay-back period on the investment. The annual benefits were also used to determine the net present value of the project which predicts its economic viability.
CHAPTER FOUR: DATA COLLECTION & ANALYSIS

4.0 Introduction

This chapter explains and analyses in detail population trend in Kampala, MSW generation in Kampala as well as its composition in terms of biomass, plastics, glass, metallic scrap and street debris. It also discusses in detail the preparation of MSW (collecting, sorting and drying) since not all MSW generated in Kampala can be gasified.

4.1 Population trend in Kampala

The population of Kampala City and its suburbs is continuously increasing and so is the amount of MSW generated and collected. The population trend, area and population density in the five divisions of Kampala is shown in Table 4-1. From Table 4-1, Figure 4-1 and Figure 4-2 were obtained.

![Population trend in Kampala City](image)

**Figure 4-1: Population trend in the divisions of Kampala City**

The bar graph in Figure 4-1 shows that the population in all the five divisions (Rubaga, Kawempe, Nakawa, Makindye, and Central) continues to grow and so is the amount of MSW generated and collected from the city. This trend, therefore, represents a significant amount of MSW that can be used for generation of producer gas to run an engine for power generation.
Table 4-1: Population Trend, Area (ha) and Population Density in the Divisions of Kampala

<table>
<thead>
<tr>
<th>Division</th>
<th>Ryanaba</th>
<th>Kawempe</th>
<th>Nakawa</th>
<th>Makindye</th>
<th>Central</th>
<th>Total Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (ha)</td>
<td>4000</td>
<td>3000</td>
<td>5000</td>
<td>4000</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>Population (1991)</td>
<td>179000</td>
<td>158000</td>
<td>137000</td>
<td>187000</td>
<td>113000</td>
<td>774000</td>
</tr>
<tr>
<td>Density (1991)</td>
<td>45</td>
<td>49</td>
<td>89</td>
<td>29</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>Population (1997)</td>
<td>246000</td>
<td>205000</td>
<td>176000</td>
<td>248000</td>
<td>144000</td>
<td>1019000</td>
</tr>
<tr>
<td>Population (2000)</td>
<td>289000</td>
<td>250000</td>
<td>209000</td>
<td>290000</td>
<td>172000</td>
<td>1210000</td>
</tr>
<tr>
<td>Density (2004)</td>
<td>94</td>
<td>100</td>
<td>56</td>
<td>91</td>
<td>140</td>
<td></td>
</tr>
</tbody>
</table>

Source: www.anglefire.com [2009]

Figure 4-2: Total population trend in Kampala over the years

Figure 4-2 shows that the total population of Kampala city continues to grow exponentially thus, an increase in population leads to an increase in the amount
of waste generated and this represents a great potential for its gasifier-engine applications.

4.2 MSW generation in Kampala

The current data obtained from Mpererwe landfill indicates that the average waste collection per day from Kampala city ranges between 500-600 tonnes per day [Mudanye, 2009]. The total amount of MSW collected from Kampala city and deposited in Mpererwe landfill is recorded on a daily basis. The data for the past five years (2004 – 2008) was obtained and tabulated in Table 4-2. From the data of Table 4-2, Figure 4-3 was obtained.

Table 4-2: MSW Mass in Tonnes Recorded at Mpererwe Landfill for 5 Years

<table>
<thead>
<tr>
<th>Month</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>17,000</td>
<td>14,000</td>
<td>12,000</td>
<td>18,000</td>
<td>14,000</td>
</tr>
<tr>
<td>February</td>
<td>17,000</td>
<td>12,000</td>
<td>11,000</td>
<td>17,000</td>
<td>13,000</td>
</tr>
<tr>
<td>March</td>
<td>17,000</td>
<td>14,000</td>
<td>13,000</td>
<td>20,000</td>
<td>19,000</td>
</tr>
<tr>
<td>April</td>
<td>19,000</td>
<td>13,000</td>
<td>13,000</td>
<td>19,000</td>
<td>19,000</td>
</tr>
<tr>
<td>May</td>
<td>19,000</td>
<td>16,000</td>
<td>15,000</td>
<td>21,000</td>
<td>21,000</td>
</tr>
<tr>
<td>June</td>
<td>17,000</td>
<td>15,000</td>
<td>15,000</td>
<td>20,000</td>
<td>15,000</td>
</tr>
<tr>
<td>July</td>
<td>17,000</td>
<td>14,000</td>
<td>16,000</td>
<td>19,000</td>
<td>14,000</td>
</tr>
<tr>
<td>August</td>
<td>14,000</td>
<td>15,000</td>
<td>15,000</td>
<td>20,000</td>
<td>17,000</td>
</tr>
<tr>
<td>September</td>
<td>14,000</td>
<td>15,000</td>
<td>13,000</td>
<td>19,000</td>
<td>17,000</td>
</tr>
<tr>
<td>October</td>
<td>14,000</td>
<td>14,000</td>
<td>15,000</td>
<td>17,000</td>
<td>18,000</td>
</tr>
<tr>
<td>November</td>
<td>14,000</td>
<td>14,000</td>
<td>17,000</td>
<td>15,000</td>
<td>17,000</td>
</tr>
<tr>
<td>December</td>
<td>16,000</td>
<td>13,000</td>
<td>16,000</td>
<td>13,000</td>
<td>17,000</td>
</tr>
<tr>
<td>Total</td>
<td>144,000</td>
<td>169,000</td>
<td>171,000</td>
<td>218,000</td>
<td>201,000</td>
</tr>
</tbody>
</table>

Source: Mudanye [2009]

From Table 4-2, the values considered for the five years were 2004-2008 inclusive.
Figure 4-3 shows that there has been a fluctuation in the amount of MSW generated over the past five years. The amount of waste collected in 2007 was quite high and this is attributed to significant emphasis put towards improving the cleanliness and hygiene in Kampala city.

### 4.3 Composition of MSW generated in Kampala

*Table 4-3: MSW Composition in Kampala According to ERL*

<table>
<thead>
<tr>
<th>Component of MSW</th>
<th>Percentage Composition by Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>vegetable matter</td>
<td>73.8</td>
</tr>
<tr>
<td>paper</td>
<td>5.4</td>
</tr>
<tr>
<td>sawdust</td>
<td>1.7</td>
</tr>
<tr>
<td>plastic</td>
<td>1.6</td>
</tr>
<tr>
<td>metal</td>
<td>3.1</td>
</tr>
<tr>
<td>glass</td>
<td>0.9</td>
</tr>
<tr>
<td>tree cuttings</td>
<td>8</td>
</tr>
<tr>
<td>street debris</td>
<td>5.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Source: www.anglefire.com[2009]

The MSW composition according to Environmental Resource Limited (ERL) [www.anglefire.com, 2009] is summarized in the Table 4-3. From Table 4-3, it is
observed that vegetable matter constitutes the largest fraction of waste while glass contributes the least. It is imperative to note that vegetable matter, paper, sawdust, tree cuttings are classified under biomass and all this can be gasified to generate producer gas.

**Table 4-4: MSW Composition According to KCC-Mpererwe Landfill**

<table>
<thead>
<tr>
<th>Type of solid waste</th>
<th>% (2001)</th>
<th>% (2006)</th>
<th>Mean Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper and board</td>
<td>10.7</td>
<td>5.4</td>
<td>8.05</td>
</tr>
<tr>
<td>Glass</td>
<td>1.8</td>
<td>0.9</td>
<td>1.35</td>
</tr>
<tr>
<td>Metal</td>
<td>0.4</td>
<td>3.1</td>
<td>1.75</td>
</tr>
<tr>
<td>Plastic</td>
<td>11.6</td>
<td>1.6</td>
<td>6.6</td>
</tr>
<tr>
<td>Organics</td>
<td>74</td>
<td>83.5</td>
<td>78.75</td>
</tr>
<tr>
<td>Textiles</td>
<td>0.7</td>
<td>Not captured</td>
<td>0.35</td>
</tr>
<tr>
<td>Construction</td>
<td>Trace(0.4)</td>
<td>Not captured</td>
<td>0.2</td>
</tr>
<tr>
<td>Special care waste</td>
<td>Trace(0.4)</td>
<td>Not captured</td>
<td>0.2</td>
</tr>
<tr>
<td>Street debris</td>
<td>Not captured</td>
<td>5.5</td>
<td>2.25</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100</td>
<td>100</td>
<td>99.5</td>
</tr>
</tbody>
</table>

*Source: Mudanye [2009]*

From Table 4-4, the mean percentage composition is less than 100% due to some components which were not captured.

From Table 4-4, organics, paper and board are categorized under biomass. Plastic, metal and glass remain as distinct materials/waste. Special care waste is always incinerated before disposal to landfills therefore it is trace. Textiles, construction and street debris can all be categorized under one name i.e. street debris. Comparing results of Table 4-3 and Table 4-4, it can be concluded that there is a close similarity in the types as well as the composition of MSW. From Table 4-4, combining the textiles, construction, special care waste and street debris gives a value of 3.0% which is close to the value of 5.5% obtained in Table 4-3 for the street debris. As shown earlier from Table 4-3, the biomass (vegetable matter, sawdust, tree cuttings and paper) when combined gives a value of 88.9% which slightly differs, from Table 4-4 with the biomass (paper and board, organics) value of 86.8%. Therefore combining the data of Table 4-3 and Table 4-4 resulted in the values shown in Table 4-5.

The mean percentage composition value of biomass in Table 4-5 was used to determine the amount that is available for drying and gasification. Glass, metal,
plastics and street debris are not required in the gasifier unit hence they have to be sorted from MSW to separate them from the biomass. Biomass, having the largest percentage composition, represents a big potential for a sustainable energy supply to the gasifier.

Table 4-5: Mean Composition (%) of MSW in Kampala City

<table>
<thead>
<tr>
<th>Type of Waste</th>
<th>Percentage Composition (ERL)</th>
<th>Percentage Composition (KCC-Mpererwe)</th>
<th>Mean Percentage Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>88.9</td>
<td>86.8</td>
<td>87.85</td>
</tr>
<tr>
<td>Glass</td>
<td>0.9</td>
<td>1.35</td>
<td>1.125</td>
</tr>
<tr>
<td>Plastics</td>
<td>1.6</td>
<td>6.6</td>
<td>4.10</td>
</tr>
<tr>
<td>Metal</td>
<td>3.1</td>
<td>1.75</td>
<td>2.425</td>
</tr>
<tr>
<td>Street debris</td>
<td>5.5</td>
<td>3.0</td>
<td>4.25</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>99.5</td>
<td>99.75</td>
</tr>
</tbody>
</table>

From Table 4-2, the total amount of MSW collected for the past five years (2004-2008 inclusive) was 954000 tonnes.

MSW generation per second = \( \frac{954000}{(5 \times 365 \times 24 \times 60 \times 60)} \times 1000 \)

\( \approx 6.050 \text{kg/s} \)

MSW generation per day = \( 6.050 \frac{\text{kg}}{\text{s}} \times \frac{3600 \text{s}}{\text{hr}} \times \frac{24 \text{hr}}{\text{day}} \)

= 523 tonnes/day

This value is within the range of 500-600 tonnes/day quoted by Mudanye[2009].

The population of Kampala in 2004 was 1562000 people. The waste generation per capita per day = \( \frac{523 \text{tonnes}}{\text{day}} \times \frac{1}{1562000 \text{people}} \times 1000 \)

= 0.335 kg per capita per day

This value is close to the range of 0.5 - 1.1 kg per capita per day quoted by [www.anglefire.com, 2009]
The MSW composition was thus calculated using the mean percentage composition values in Table 4-5 and the results in Table 4-6 were obtained. The focus was now on the biomass fuel flow which is needed to run the gasifier. The biomass fuel flow of 5.317kg/s obtained from Table 4-6 has high moisture content thus it had to be dried to an appropriate moisture content required for gasification.

**Table 4-6: Composition (kg/s) of MSW Generated in Kampala**

<table>
<thead>
<tr>
<th>Type of Waste</th>
<th>Mean Percentage Composition,%</th>
<th>Analysis</th>
<th>Amount, kg/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>87.85</td>
<td>0.8785×6.052</td>
<td>5.317</td>
</tr>
<tr>
<td>Glass</td>
<td>1.125</td>
<td>0.01125×6.052</td>
<td>0.068</td>
</tr>
<tr>
<td>Plastics</td>
<td>4.10</td>
<td>0.0410×6.052</td>
<td>0.248</td>
</tr>
<tr>
<td>Metal</td>
<td>2.425</td>
<td>0.02425×6.052</td>
<td>0.147</td>
</tr>
<tr>
<td>Street debris</td>
<td>4.25</td>
<td>0.0425×6.052</td>
<td>0.257</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>99.75</td>
<td></td>
<td><strong>6.037</strong></td>
</tr>
</tbody>
</table>

From Table 4-6, the total amount of waste (6.037kg/s) from the analysis is less than 6.052kg/s due to the fact that the total mean percentage composition was only 99.75%.

### 4.4 Moisture content of fresh MSW generated in Kampala

The values in Table 4-7 were obtained for the moisture content on a wet basis of fresh MSW generated in Kampala. The mean moisture content was 71.09% with a standard deviation of 3.93% while the total solids were 28.91% with a standard deviation of 3.93%. This high moisture content of MSW is not suitable for gasification. Thus, there was need to dry MSW to optimum moisture content suitable for gasification.
Table 4-7: Moisture Content and Total Solids of Fresh MSW

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>% Moisture Content</th>
<th>% Total Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>63.06</td>
<td>36.94</td>
</tr>
<tr>
<td>2</td>
<td>74.31</td>
<td>25.69</td>
</tr>
<tr>
<td>3</td>
<td>73.46</td>
<td>26.54</td>
</tr>
<tr>
<td>4</td>
<td>73.31</td>
<td>26.69</td>
</tr>
<tr>
<td>5</td>
<td>73.11</td>
<td>26.89</td>
</tr>
<tr>
<td>6</td>
<td>69.27</td>
<td>30.73</td>
</tr>
<tr>
<td>Mean</td>
<td>71.09</td>
<td>28.91</td>
</tr>
<tr>
<td>σ</td>
<td>3.93</td>
<td>3.93</td>
</tr>
</tbody>
</table>

Figure 4-4 shows the variation of moisture content and total solids of various samples of fresh MSW.

From Figure 4-4, there is a slight variation in the percentage of moisture content of fresh MSW. This is attributed to heterogeneous nature of MSW implying that different components of the waste vary in the amount of moisture content. The percentage of the total solids is influenced by the amount of moisture content in the samples.
CHAPTER FIVE: EXPERIMENTAL INVESTIGATIONS

5.0 Introduction

This chapter explains in detail the experimental work done at Makerere University. The gasifier was run in downdraft mode and the various parameters investigated were moisture content, ash content, bulk density, temperature profiles, composition and heating value of producer gas from MSW.

5.1 Preparation of MSW; collecting, sorting and drying

The unsorted MSW was collected from Mpererwe landfill which is currently the damping site for MSW in Kampala. In addition, it was a convenient location in terms of distance as well as drying the sorted MSW. The unsorted MSW was then sorted to obtain the biomass material needed for gasification and the remainder i.e. glass, plastics, metal and street debris was taken back to the landfill.

Since the biomass from the landfill has high moisture content (71.09%), it was necessary to dry it under the sun (natural drying) until the moisture content was less than 25% as required for downdraft gasification. Therefore, samples of the dried MSW were tested at intervals to ensure that this demand was met and the values obtained are shown in Table 5-2. The dried MSW was then packed, transported from the preparation area to Makerere University where further gasification experiments were to be carried out. Figure 5-1 shows sacks of MSW sorted, dried and parked.

![Image of sacks of MSW](image)

*Figure 5-1 (a) & (b); MSW sorted, dried and parked for gasification*
5.2 Blower

The type of operation used for the blower is gas pulled (suction operation). The blower was used to pull the hot gas through the system.

5.3 Start up of the gasifier

Char and ash material was removed from the gasifier before each run was conducted. For each run, a small amount of charcoal was weighed and added to the gasifier and the amount of charcoal used was recorded. The purpose of adding charcoal over the grate was to protect the grate from very high temperatures and to have a char bed for the reduction process. The biomass feedstock was batch-fed to the gasifier. Biomass fuels are only partially free flowing from a hopper by gravity alone so a stirrer was used at intervals for pushing down MSW. The fuel to be gasified was also weighed and recorded before feeding it to the gasifier. When the gasifier was full, the top cover was closed and the suction blower switched on. A flame placed at the air intake manifold was used to ignite the fuel, that is, the air and igniting flame were simultaneously sucked into the system prompting combustion to take place. The gasifier was now ready for the experiment. Figure 5-2 shows the start up of the gasifier.

![Figure 5-2: Start up of the gasifier](image)
For each run the temperature at selected regions (drying/pyrolysis, combustion, reduction, ash point, after cyclone, sampling point and heater element), the operating time, gas composition, amount of fuel consumed, and the burning flame (Figure 3a & 3b; Appendix B) of producer gas were monitored. Samples were also obtained for determination of moisture content and ash content. The data obtained was used to design the gasifier-engine system. Figure 5-3 shows the gasifier test rig with some of the selected regions at which temperature measurements were taken.

Figure 5-3: Gasifier test rig showing some of the selected regions at which temperature measurements were taken.

5.4 Biomass characteristics of MSW related to gasification

The biomass characteristics of MSW determined were moisture content, bulk density and ash content.

5.4.1 Bulk density

Figure 5-4 shows the weighing scale and cylindrical container used for measuring the bulk density. The measured values of the bulk density of the samples are shown in Table 5-1.
From Table 5-1, the mean bulk density was 57.67 kg/m$^3$ with a standard deviation of 20.21. From Table 5-1, Figure 5-5 was obtained showing the variation of bulk density of the samples.
Figure 5-5 shows a wide variation in the bulk density of the samples in the range 29.45 kg/m$^3$ - 88.35 kg/m$^3$. This is attributed to heterogeneous nature of MSW. Furthermore, the low bulk density shows that MSW is very light.

5.4.2 Moisture content and total solids

The values in Table 5-2 were obtained for the determination of moisture content as well as total solids of MSW. The mean moisture content was 11.8% with a standard deviation of 2% while the total solids were 88.21% with a standard deviation of 2%. Thus, the material gasified contained this amount of moisture content and total solids.

Table 5-2: Moisture Content and Total Solids of Dried MSW

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>% Moisture</th>
<th>% Total Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.71</td>
<td>86.29</td>
</tr>
<tr>
<td>2</td>
<td>10.53</td>
<td>89.47</td>
</tr>
<tr>
<td>3</td>
<td>12.84</td>
<td>87.16</td>
</tr>
<tr>
<td>4</td>
<td>10.52</td>
<td>89.48</td>
</tr>
<tr>
<td>5</td>
<td>9.09</td>
<td>90.91</td>
</tr>
<tr>
<td>6</td>
<td>9.97</td>
<td>90.03</td>
</tr>
<tr>
<td>7</td>
<td>14.06</td>
<td>85.94</td>
</tr>
<tr>
<td>8</td>
<td>15.03</td>
<td>84.97</td>
</tr>
<tr>
<td>9</td>
<td>14.04</td>
<td>85.96</td>
</tr>
<tr>
<td>10</td>
<td>11.12</td>
<td>88.88</td>
</tr>
<tr>
<td>11</td>
<td>10.16</td>
<td>89.84</td>
</tr>
<tr>
<td>12</td>
<td>10.47</td>
<td>89.53</td>
</tr>
<tr>
<td>Mean</td>
<td>11.80</td>
<td>88.21</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>2.00</td>
<td>2.00</td>
</tr>
</tbody>
</table>
From Table 5-2, Figure 5-6 was obtained showing the variation of moisture content and total solids of dried MSW for various samples.

Figure 5-6: Variation of moisture content and total solids of dry MSW for various samples.

Figure 5-6 shows that there was a slight variation in the moisture content and total solids of samples. This was due to the fact that MSW, being heterogeneous, had variable moisture content. Thus, after drying, the components could not have the same moisture content. However, the moisture content was below 25% since this was a requirement for proper gasification in the downdraft gasifier [Hariie, 2005]. Furthermore, the moisture content affected the percentage composition of the solids.

5.4.3 Ash content

The values in Table 5-3 were obtained for the determination of ash content of MSW. The mean percentage of ash obtained was 25.94% with a standard deviation of 7.78%. The ash composition for MSW and rice hulls is 20% or greater [Reed & Das, 1988]. Thus, the calculated value is close to the one quoted in literature.
Table 5-3: Ash content of MSW

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>% Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36.25</td>
</tr>
<tr>
<td>2</td>
<td>31.59</td>
</tr>
<tr>
<td>3</td>
<td>27.83</td>
</tr>
<tr>
<td>4</td>
<td>43.01</td>
</tr>
<tr>
<td>5</td>
<td>20.31</td>
</tr>
<tr>
<td>6</td>
<td>23.91</td>
</tr>
<tr>
<td>7</td>
<td>20.25</td>
</tr>
<tr>
<td>8</td>
<td>24.36</td>
</tr>
<tr>
<td>9</td>
<td>21.02</td>
</tr>
<tr>
<td>10</td>
<td>27.13</td>
</tr>
<tr>
<td>11</td>
<td>16.64</td>
</tr>
<tr>
<td>12</td>
<td>18.93</td>
</tr>
<tr>
<td>Mean</td>
<td>25.94</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>7.78</td>
</tr>
</tbody>
</table>

From Table 5-3, Figure 5-7 was obtained showing the variation of ash composition and total solids of dried MSW for various samples.

Figure 5-7: Variation of ash composition of MSW for various samples

Figure 5-7 shows that there was a wide variation in the percentage composition of ash for the MSW samples. This was due to the fact that MSW, being heterogeneous, had variable ash composition. Furthermore, the ash composition of MSW was above 20% as quoted by Reed & Das [1988].
5.5 Gasification parameters of MSW

The gasification parameters of MSW investigated included temperature, gas composition and heating value of producer gas.

5.5.1 Temperature

The temperature values were recorded continuously using a data acquisition system (87623 SRP-6-1.5M DATA LOGGER) and K-type thermocouples. Figure 5-8 shows the Data Logger used for temperature measurement.

Figure 5-8: Data Logger used for temperature measurement

The temperature profiles in the drying/pyrolysis zone, oxidation zone, reduction zone, ash point, sampling point, after the cyclone and heater element were recorded and monitored from the computer. Figure 5-9 is a sketch of the gasifier test rig showing regions at which temperature measurements were taken. The temperature profiles in Figure 5-10 were recorded.

Figure 5-10 shows that the temperature profiles were fluctuating except the ambient temperature. The fluctuation of temperatures inside the gasifier is due to the fact that the zones (drying, pyrolysis, combustion and reduction) are not distinct since fuel/MSW continuously flows down the gasifier thus interfering with the temperature in each zone. Furthermore, the heat generated from the combustion zone is transmitted to other zones. The variation of temperature in the gasifier affected the temperatures after the cyclone and at the sampling point. The high temperature at the ash point was attributed to the red-hot charcoal that drops through the grate.
Figure 5-9: Sketch of the gasifier test rig showing the regions at which temperature was measured.

Figure 5-10: Temperature profiles recorded during gasification of MSW
5.5.2 Gas analysis using gas chromatography

Gas chromatography depends on the ability of certain adsorbent materials to selectively slow the rate of gas passage through a column packed with the adsorbent. H₂ is slowed least, Co, N₂ and O₂ slowed to greater extent, H₂O and CO₂ are slowed to the greatest extent. He (helium) was used as a carrier gas. The GC recorder was set to analyze the gas samples using two modes namely Mass Spectrometry (MS) which detects gas components in the order H₂, O₂, N₂, CO and Parts per Quadrillion (PPQ) which detects gas components in the order N₂, CH₄, CO₂, and C₂H₆. Figure 5-11(a) shows the gas sampling unit which was used to obtain gas samples for laboratory tests. Figure 5-11(b) shows the GC recorder which was used for detecting and plotting the various components in the producer gas from MSW.

The GC recorder automatically plotted a graph showing the quantity of each component on a data sheet. The presence of a particular gas component was indicated by a peak and then compared with that of a calibration gas of known composition. The quantity of each gas component in percent (%) or millimeters was then determined by measuring the height of the peak in the curve. The composition of air was also measured for each test. Table 5-4 shows the percentage composition of producer gas from MSW, calibration gas and air.

![Figure 5-11: (a) Gas sampling unit, (b) The GC recorder](image-url)
Table 5-4: Composition of Producer Gas from MSW, Calibration Gas and Air

<table>
<thead>
<tr>
<th></th>
<th>H₂</th>
<th>O₂</th>
<th>N₂</th>
<th>CO</th>
<th>CH₄</th>
<th>CO₂</th>
<th>C₂H₄</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Producer Gas Samples (%)</td>
<td>3.87</td>
<td>5.04</td>
<td>54.12</td>
<td>9.74</td>
<td>2.17</td>
<td>38.83</td>
<td>0</td>
<td>113.77</td>
</tr>
<tr>
<td>Calibration gas (%)</td>
<td>8.05</td>
<td>0.61</td>
<td>58.97</td>
<td>9.93</td>
<td>5.09</td>
<td>17.96</td>
<td>0</td>
<td>100.61</td>
</tr>
<tr>
<td>Air (%)</td>
<td>20.9</td>
<td>78</td>
<td>98.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From Table 5-4, the graph in Figure 5-12 was generated.

From Figure 5-12, the percentage composition of producer gas from MSW was attributed to the heterogeneous nature of MSW which affected the quality of gas produced. Furthermore, the total percentage of producer gas from MSW was above 100%. This was due to the presence of oxygen (5.04%) and high percentage of Carbon dioxide (38.83%) in the producer gas from MSW. It is likely that the excess oxygen in the producer gas from MSW was not used up in the gasification process or was due to leakages for instance via the ash cover. The high amount of CO₂ in the producer gas from MSW could be as a result of its generation according to Equation 2-1 and Equation 2-4 and not being used up according to the Boudouard reaction of Equation 2-5. The percentage of nitrogen in the producer gas from MSW was 54.12% and this was assumed to be the nitrogen from air. The total percentage composition of air was less than 100% and this is attributed to the rare gases in the air which were not measured.
Thus, considering the percentage of nitrogen in the producer gas from MSW to be 54.12% and setting the percentage of oxygen to zero (oxygen is not expected in the products), the normalized values of the remaining products were obtained using the following calculation.

According to Reed & Das [1988], the overall global reaction of biomass combustion can be represented by,

$$\text{CH}_{1.4}\text{O}_{0.6} + 1.05\text{O}_2 + (3.95\text{N}_2) \rightarrow \text{CO}_2 + 0.7\text{H}_2\text{O} + (3.95\text{N}_2)$$

Equation 5-1

Where,

$\text{CH}_{1.4}\text{O}_{0.6}$ is an average formula for typical biomass. The nitrogen is shown in parentheses because it is an inert portion of the air and does not take part in the reaction.

According to Anders [2008], Equation 5-1 is a stoichiometric reaction since only Carbon dioxide, water and nitrogen appear on the right hand side. The following was considered;

$$\text{MW}_\text{C} = 12.01 \text{kg/Kmol}, \text{MW}_\text{H} = 1.008 \text{kg/Kmol}, \text{MW}_\text{O} = 16 \text{kg/Kmol} \quad \text{[Stephens, 2000]}$$

$$\text{MW}_\text{air} = 28.85 \text{ kg/Kmol} \quad \text{[Stephens, 2000]}$$

$$\text{MW}_\text{fuel} = (12.01 \times 1) + (1.4 \times 1.008) + (0.6 \times 16) = 23.02 \text{ kg/Kmol}$$

From Equation 5-1,

$$N_\text{air} = 1.05 + 3.95 = 5 \text{ moles}$$

$$N_\text{fuel} = 1 \text{ mole}$$

Using Equation 2-12,

$$\frac{\text{A/F}}{\text{stoic}} = \frac{N_\text{air}}{N_\text{fuel}} \times \frac{\text{MW}_\text{air}}{\text{MW}_\text{fuel}} = \frac{5}{1} \times \frac{28.85}{23.02} = 6.27$$

Since gasification is starved air/oxygen combustion, the following reaction takes place [Reed & Das, 1988].

$$\text{CH}_{1.4}\text{O}_{0.6} + 0.4\text{O}_2 \rightarrow 0.7\text{CO} + 0.3\text{CO}_2 + 0.6\text{H}_2 + 0.1\text{H}_2\text{O} \quad \text{...Equation 5-2}$$

Since methane was found in the producer gas from MSW then Equation 5-2 was modified to Equation 5-3 assuming the same moles of water would be obtained.
CH_{1.4}O_{0.6} + a [O_2 + (3.76N_2)] \rightarrow bCO + cCO_2 + dH_2 + eCH_4 + 0.1 H_2O + (3.76aN_2)

\text{Equation 5-3}

From Equation 5-3, the unknowns a, b, c, d, and e were solved as shown below. Considering the balance of atoms:

C balance; \ 1 = b + c + e \ \text{................................. (i)}

H balance; \ 1.4 = 2d + 4e + 0.2 \ \text{........................................... (ii)}

O balance; \ 0.6 + 2a = b + 2c + 0.1 \ \text{........................................... (iii)}

According to Jain [2006] and Kaup[1984], the optimum value of the equivalence ratio for gasification is about 2.5.

From Equation 2-14a,

\[ \phi = 2.5 = \frac{(A/F)_{stoic}}{(A/F)} \]

\[ 2.5 = \frac{6.27}{(A/F)} \]

\( (A/F) = 2.51 \) is the air fuel ratio for the gasification process of Equation 5-3.

Hence, using Equation 2-13,

\[ (A/F) = \frac{4.76a}{1} \times \frac{28.85}{23.02} \]

\[ a = 0.42 \]

The percentage of Nitrogen in the dry producer gas from MSW was 54.12 % (0.5412) from Table 5-4. Then,

\[ \frac{3.76a}{b+c+d+e+3.76a} = 0.5412 \]
\[
\frac{3.76 \times 0.42}{b + c + d + e + 3.76 \times 0.42} = 0.5412
\]

\[b + c + d + e = 1.34 \quad \text{................................................................. (iv)}\]

From Equation (i) and (iv),
\[d + 1 = 1.34 \quad \iff d = 0.34\]

From Equation (ii)
\[e = \frac{1}{4}(1.4 - 2d - 0.2) = 0.13\]

From Equation (i),
\[b + c = 0.87 \quad \text{..................................................................*}\]

From Equation (iii),
\[b + 2c = 1.34 \quad \text{..................................................................*}\]

Solving * and ** simultaneously gave, \[b = 0.4 \quad \text{and} \quad c = 0.47\]

Total number of moles of dry producer gas, \[b + c + d + e + 3.76a = 2.92\]

Thus, the percentage of the normalized values of each component in the dry producer gas from MSW, calibration gas and air were summarized in Table 5-5.

**Table 5-5: Normalized Values of Producer Gas from MSW, Calibration Gas and Air**

<table>
<thead>
<tr>
<th></th>
<th>(H_2)</th>
<th>(O_2)</th>
<th>(N_2)</th>
<th>CO</th>
<th>(CH_4)</th>
<th>(CO_2)</th>
<th>(C_2H_4)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Producer Gas Samples (%)</td>
<td>11.64</td>
<td>0</td>
<td>54.12</td>
<td>13.70</td>
<td>4.45</td>
<td>16.64</td>
<td>0</td>
<td>100.55</td>
</tr>
<tr>
<td>Calibration Gas (%)</td>
<td>8.05</td>
<td>0.61</td>
<td>58.97</td>
<td>9.93</td>
<td>5.09</td>
<td>17.96</td>
<td>0</td>
<td>100.61</td>
</tr>
<tr>
<td>Air (%)</td>
<td>8.05</td>
<td>78</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>98.9</td>
</tr>
</tbody>
</table>

From Table 5-5 the graph in Figure 5-13 was generated.
5.5.3 Heating value of producer gas from MSW

Table 5-6 shows the higher heating value as well as lower heating value of gas components of producer gas. From Table 5-6, Equation 3-5 was used to calculate the lower heating value of producer gas i.e.

$$LHV_{gas} = 11.2[H_2] + 13.1[CO] + 37.1[CH_4] + 83.8[C_nH_m]$$

Where, \([X]\) is the percentage concentration of the component in the producer gas and the units for \(LHV_{gas}\) are MJ/Nm³.

Table 5-6: Higher Heating Value and Lower Heating Value of Gas Components\(^a\)

<table>
<thead>
<tr>
<th>Component</th>
<th>Symbol</th>
<th>HHV(^b) (MJ/Nm³)</th>
<th>HHV(^c) (Btu/scf)</th>
<th>LHV(^b) (MJ/Nm³)</th>
<th>LHV(^c) (Btu/scf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>H₂</td>
<td>13.2</td>
<td>325</td>
<td>11.2</td>
<td>275</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>CO</td>
<td>13.1</td>
<td>322</td>
<td>13.1</td>
<td>322</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>41.2</td>
<td>1013</td>
<td>37.1</td>
<td>913</td>
</tr>
</tbody>
</table>

\(^a\) Btu/scf = 8.26kCal/Nm³ = 40.672kJ/Nm³  
\(^b\) Standard conditions, 0°C and 760 mm Hg Dry  
\(^c\) Standard conditions, 60°F and 30 in. Hg Dry

**Source:** Reed & Das [1988]
Table 5-7 shows the LHV of producer gas obtained from gasification of MSW.

**Table 5-7: Lower Heating Values (LHV) of Producer Gas for MSW Obtained from Experiments**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Run 1 LHV, MJ/Nm³</th>
<th>Run 2 LHV, MJ/Nm³</th>
<th>Run 3 LHV, MJ/Nm³</th>
<th>Run 4 LHV, MJ/Nm³</th>
<th>Run 5 LHV, MJ/Nm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.40</td>
<td>2.52</td>
<td>2.06</td>
<td>3.55</td>
<td>1.49</td>
</tr>
<tr>
<td>2</td>
<td>2.36</td>
<td>2.33</td>
<td>2.87</td>
<td>4.74</td>
<td>2.12</td>
</tr>
<tr>
<td>3</td>
<td>2.63</td>
<td>3.30</td>
<td>3.14</td>
<td>3.86</td>
<td>1.49</td>
</tr>
<tr>
<td>4</td>
<td>4.34</td>
<td>3.71</td>
<td>2.44</td>
<td>2.95</td>
<td>1.68</td>
</tr>
<tr>
<td>5</td>
<td>3.06</td>
<td>4.46</td>
<td>3.45</td>
<td>3.62</td>
<td>1.85</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>2.70</td>
<td></td>
<td></td>
<td>1.80</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.76</td>
</tr>
<tr>
<td>Sum</td>
<td>15.78</td>
<td>16.32</td>
<td>16.67</td>
<td>18.71</td>
<td>12.20</td>
</tr>
<tr>
<td>Mean</td>
<td>3.16</td>
<td>3.26</td>
<td>2.78</td>
<td>3.74</td>
<td>1.74</td>
</tr>
<tr>
<td>σ</td>
<td>0.77</td>
<td>0.87</td>
<td>0.49</td>
<td>0.65</td>
<td>0.22</td>
</tr>
</tbody>
</table>

The values obtained from the gas analysis using the GC recorder were transferred to a Gas Analysis Excel Sheet (Appendix A-1) were the lower heating values of the gas samples for each run were calculated and these values are shown in Table 5-7. The maximum and minimum values were 4.74MJ/Nm³ and 1.49MJ/Nm³ respectively. From Table 5-7, the values in run 5 were discarded since they were too low compared to those in the other runs. Hence the mean lower heating value was obtained by adding up all the values (sums) in runs 1, 2, 3 and 4 and then divided by the total number of samples and a value of 3.21MJ/Nm³ was obtained. The heating value of the producer gas is within the range of 2-5MJ/Nm³ quoted by Aki, 2003. The low value is attributed to the lower percentages of the gas components (H₂, CO, and CH₄) that contribute to the lower heating value as depicted by Equation 3-5.

Using Equation 3-5 and the values in Table 5-5 the normalized heating value of producer gas from MSW was obtained as:

\[ \text{LHV}_{\text{gas}} = 11.2[0.1164] + 13.1[0.137] + 37.1[0.445] + 83.8[0] = 4.75 \text{ MJ/Nm}^3 \]

The normalized lower heating value is close to the maximum value of 4.74MJ/Nm³ obtained from experimental results (Table 5-7). The normalized lower heating value was thus used in the design of the gasifier-engine system.

### 5.5.4 Fuel flow of MSW

The amount of charcoal and MSW gasified were weighed using an analogue weighing scale (Figure 5-8) before feeding to the gasifier. After running the
EVALUATION OF POSSIBLE GASIFIER-ENGINE APPLICATIONS WITH MUNICIPAL SOLID WASTE (A CASE STUDY OF KAMPALA)

gasifier for some time, the level of fuel was checked and more MSW added when necessary. No more charcoal was added for a particular run. At the end of the run, the total amount of MSW and charcoal gasified were recorded. The consumption time was automatically recorded by the data logger. The results are shown in Table 5-8.

Table 5-8: Fuel Flow of MSW during Experimental Investigations

<table>
<thead>
<tr>
<th>Run</th>
<th>Amount of Charcoal Used, kg</th>
<th>Amount of MSW Used, kg</th>
<th>Consumption Time, hrs</th>
<th>Fuel Flow, kg/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>18</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>7.5</td>
<td>9</td>
<td>0.53</td>
<td>16.98</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>18</td>
<td>0.7</td>
<td>25.71</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>16</td>
<td>0.57</td>
<td>28.07</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>17</td>
<td>0.57</td>
<td>29.82</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>37.5</td>
<td>1.62</td>
<td>23.15</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>20</td>
<td>1.017</td>
<td>19.67</td>
</tr>
<tr>
<td>Mean</td>
<td>7.64</td>
<td>19.36</td>
<td>0.86</td>
<td>22.56</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>1.49</td>
<td>8.73</td>
<td>0.39</td>
<td>22.24</td>
</tr>
</tbody>
</table>

From Table 5-8, the mean fuel flow was 22.56kg/h with a standard deviation of 22.24kg/h. The high standard deviation could be attributed to the improper timing of when the MSW was completely gasified for a particular run.
CHAPTER SIX: DESIGN OF THE ENGINE, GASIFIER AND GAS CLEANING SYSTEM

6.0 Introduction

This chapter covers in detail the design of the gasifier-engine system to consume MSW generated in Kampala. The design includes engine design, gasifier design and design of the gas cleaning system (cyclone, venturi scrubber, fine filter and baghouse filter). The complete lay-out of the system was also drawn using SOLID EDGE software. The environmental aspects of electricity generation from gasifier-engine systems are also briefly discussed.

6.1 Engine design

6.1.1 Selecting an engine to run on the generated producer gas

For large scale applications (e.g. between 25-50MWe) the preferred and most reliable system is the circulating fluidized bed gasifier while for the small scale applications (e.g. up to 0.5MWe), the downdraft gasifiers are the most extensively studied [Bio_Energy Research Group, 2009; Harie, 2005].

Since the gasifier selected is a downdraft gasifier then the maximum possible power for an engine connected to the gasifier would be at most 0.5MWe. CumminsPower.com [2009] gives the following general information for Natural gas generator sets QSV91 series engines in the range 1250kW-2000kW shown in Appendix A-4.

6.1.2 Calculation of the power output of the producer gas engine

From Appendix A-4,

Displacement, D = 91.6 litres

Maximum Air/gas intake = \(\frac{1/2 \times (\text{rpm}) \times D}{60 \times 1000}\) = \(\frac{1/2 \times (1500) \times 91.6}{60 \times 1000}\) = 1.145m³/s

Air/gas ratio (stoichiometric); 1.1: 1.0

Maximum gas intake = \(\frac{1.0}{2.1} \times 1.145 = 0.545\text{m}^3/\text{s}\)
The real gas intake is 0.545 x f, in which

\[ f = \text{volumetric efficiency (\%)} \text{ of the engine and is dependent on:} \]

- Rpm of the engine.
- Design of the air inlet manifold of the engine.
- Fouling of the air inlet manifold of the engine.

At 1500 rpm, for a well designed and clean air inlet manifold f can be taken at 0.8 [www.fao.org, 1986]. Therefore, the real gas intake is:

\[ 0.545 \times 0.8 = 0.436 \text{m}^3/\text{s}. \]

Inlet conditions to the engine; 25°C (298K) and 1 atm pressure [Kaupp, 1984]. Converting the real gas intake to normal conditions [0°C (273K)] and a pressure of 1 atmosphere), Equation 6-1 was used.

\[ \frac{\dot{V}_1}{T_1} = \frac{\dot{V}_2}{T_2} \]

Equation 6-1

\[ \dot{V}_1 = 0.436 \text{m}^3/\text{s}; \ T_1 = 298K; \ T_2 = 273K \]

\[ \dot{V}_2 = \frac{0.436 \times 273}{298} = 0.4 \text{Nm}^3/\text{s} \]

The calculated lower heating value of the gas was 4750 kJ/Nm³ (normalized value from experiments at Makerere University). Therefore, the thermal power in the gas was:

\[ P_g = 0.40 \times 4750 = 1898.09 \text{ kJ/s (1898.09 kW)} \]

The engine efficiency depends partly on the engine's compression ratio. For a compression ratio of 9.5:1, the efficiency can be estimated at 28% [www.fao.org, 2009]. Therefore, the maximum mechanical output of this engine was:

\[ P_{\text{mm}ax} = 1898.09 \times 0.28 = 531.46 \text{ kW} \]

The maximum electrical output (generator electrical efficiency = 0.8) was,

\[ P_{\text{emax}} = 531.46 \times 0.8 = 425.17 \text{ kVA} \]

The low power output from this engine is attributed to the lower heating value of the gas. Since the mechanical power output was only 531.46 kW then the 1250kW QSV91 series engine was selected.
6.2 Gasifier design

www.fao.org [1986], asserts that designing an "Imbert" type gasifier boils down to estimating the maximum amount of gas needed. This is easily done by taking into account the cylinder volume and number of revolutions as well as the volumetric efficiency of an internal combustion engine coupled to the system. From this gas amount as well as from the $B_r$ maximum value (0.9) the area of the smallest constriction and the diameter of the throat can be calculated. The gasifier was designed for operation in conjunction with the 1250kW QSV91 series engine selected.

6.2.1 Biomass consumption of gasifier

The thermal efficiency of the gasifier was taken at 70 % [www.fao.org, 1986]

Thermal power consumption (full load): \( \frac{P_g}{0.7} = \frac{1898.09 \text{ kW}}{0.7} = 2711.55 \text{ kW} \)

Heating value of MSW (11.8% moisture content): 12000 kJ/kg [Fakhrai, 2007]

Biomass consumption of gasifier: \( \frac{2711.55 \text{ kW}}{12000 \text{kJ/kg}} = 0.226 \text{ kg/s (813.47kg/h)} \)

From Equation 2-20, Specific fuel consumption:

\[
\text{Specific fuel consumption} = \frac{m_{\text{fuel}}}{P_{E_{\text{max}}}}
\]

Specific fuel consumption = \( \frac{813.47 \text{kg/h}}{425.17 \text{kW}} = 1.913 \text{ kg/kWh} \)

Thus 1.913 kg of MSW is consumed to produce 1kWh of electricity.

From Table 4-6, the amount of MSW (biomass waste) generated in Kampala amounts to 5.317 kg/s on a wet basis and its approximate moisture content, from Table 4-7, was 71.09%. From the laboratory tests, the mean moisture content of dry MSW gasified was estimated at 11.8%. Hence, the fuel flow at 11.8% moisture content was calculated from;
Fuel flow at 71.09% M.C (28.91% total solids) = Fuel flow at 11.8% M.C (88.2% total solids) i.e.
\[ \frac{1 - \left( \frac{71.09}{100} \right)}{1 - \left( \frac{11.8}{100} \right)} \times 5.317 = \frac{1 - \left( \frac{11.8}{100} \right)}{1 - \left( \frac{11.8}{100} \right)} \times \text{Fuel flow at 11.8% M.C} \]

Thus, Fuel flow at 11.8% M.C (88.2% total solids);
\[ \frac{1 - \left( \frac{71.09}{100} \right)}{1 - \left( \frac{11.8}{100} \right)} \times 5.317 = 1.743 \text{ kg/s} \]

Biomass consumption of gasifier was obtained as 0.226 kg/s. Then, the total number of gasifiers needed to consume this waste is;
\[ \frac{1.743}{0.226} = 7.7 \text{ gasifiers} \approx 8 \text{ gasifiers} \]

For each gasifier-engine system, the net electrical power is estimated at 425.17 kW. Hence the total power output from the 8 gasifier–engine systems would be, \( 8 \times 425.17 = 3401.37 \text{ kW (3.4MW)} \).

### 6.2.2 Reactor design

Due to the morphology of the MSW a throatless gasifier will be considered for ease of movement of the MSW in the reactor. A maximum hearth load (\( B_{\text{hmax}} \)) value for an imbert-type gasifier is about 0.9 Nm\(^3\)/cm\(^2\)-h i.e. 0.9 m\(^3\) of gas is produced for each square centimeter of cross-sectional area at the constriction [Reed and Das, 1988; FAO,1986].

\[ B_h = 0.9 \text{Nm}^3/\text{cm}^2\cdot\text{h} (9000 \text{Nm}^3/\text{m}^2\cdot\text{h}) \]

Real gas flow rate to the engine = 0.436 m\(^3\)/s.

The inlet conditions to the engine are 25° C (298K) and 1 atm pressure. The gas leaves the gasifier at a temperature of 700°C (973K) [Kaupp, 1984]. The gas production from the gasifier was obtained using Equation 6-1 i.e.

\[ \frac{\dot{V}_1}{T_1} = \frac{\dot{V}_2}{T_2} \quad ; \quad \dot{V}_1 = 0.436 \text{ m}^3/\text{s} \; ; \; T_1 = 298 \text{K} ; \; T_2 = 973 \text{K} \]

Gas production from the gasifier \( \dot{V}_2 = \frac{0.436 \times 973}{298} = 1.424 \text{ m}^3/\text{s} (5127.14 \text{ m}^3/\text{h}) \)

Converting this GPR to normal conditions [0°C (273K), 1 atm pressure];
\[ \dot{V}_1 = 1.424 \text{m}^3/\text{s}; \ T_1 = 973K; \ T_2 = 273K \]

\[ \dot{V}_2 = \frac{(1.424 \times 273)}{973} = 0.4 \text{ Nm}^3/\text{s} (1438.55 \text{ Nm}^3/\text{h}) \]

From Equation 2-18,

\[ B_h = \frac{\text{Gas Volume}}{A_h \times h} \]

\[ 9000 = \frac{1438.55 \text{ Nm}^3/\text{h}}{A_h} \]

Thus, cross-sectional area of the throat (air inlet in this case since it is a throatless gasifier), \( A_h = 0.16 \text{ m}^2 \)

\[ 0.16 = \frac{\pi d_t^2}{4} \]

Where, \( d_t \) is the diameter of the throat (air inlet)

Diameter of the air inlet, \( d_t = 0.451 \text{m} (451\text{mm}) \). Once the throat (air inlet diameter) was fixed, further important gasifier dimensions were derived as follows;

a) Height, \( h \) of the nozzle plane above the smallest cross-section of the throat

*Figure 6-1:* Height of the nozzle plane above the hearth constriction for various generator sizes

Source: [www.fao.org](http://www.fao.org) [1986]
From Figure 6-1,
\[ d_t = \text{diameter of throat} \]
\[ h = \text{height of the nozzle plane above the constriction} \]
For \( d_t = 451\text{mm} (0.451\text{m}) \)
\[ \frac{h}{d_t} = 0.48 \]
\[ h = 0.48 \times 0.451 = 0.217\text{m} (21.7\text{cm}) \]

b) Diameter, \( d_f \) of the fire box

![Diagram](image)

*Figure 6-2: Diameter of nozzle ring and nozzle opening in relation to hearth constriction, as a function of hearth diameter, for various generator makes*

Source: [www.fao.org](http://www.fao.org) [1986]

Where,
\[ d_r \text{ - Diameter of nozzle ring} \]
\[ d_{r_1} \text{ - Diameter of nozzle opening} \]

From Figure 6-2,
For \( d_t = 451 \text{mm} (0.451 \text{m}) \)

\[
\frac{d_r}{d_t} = 2.1
\]

\[
d_r = 2.1 \times 0.451 = 0.948 \text{m} (948 \text{mm})
\]

c) Nozzle diameter, \( d_n \)

Referring to Figure 6-3,

Assumption: gasifier to be equipped with 5 nozzles [Reed & Das, 1988]

Total nozzle area, \( A_n: 5 \times \frac{1}{4} \pi \times d_n^2 \) \hspace{1cm} \text{Equation 6-2}

Throat (air inlet area, \( A_t): \frac{1}{4} \pi \times d_t^2 \) \hspace{1cm} \text{Equation 6-3}

\[\begin{array}{c}
100 \frac{A_n}{A_t} \\
V_m (\text{m/s})
\end{array}\]

\[\begin{array}{c}
100 \frac{A_n}{A_t} \\
d_t (\text{mm})
\end{array}\]

\( 100 \frac{A_n}{A_t} \)

\( V_m \)

\( d_t \)

\( 4 \)

\( 5 \)

\( 6 \)

\( 7 \)

\( 160 \)

\( 180 \)

\( 200 \)

\( 220 \)

\( 250 \)

\( 300 \)

\( 35 \)

\( 30 \)

\( 25 \)

\( 21 \)

\( 100 \frac{A_n}{A_t} \)

\( V_m \)

\( d_t \)

\( \text{Figure 6-3: Graph of suitable nozzles for operating four-cycle engines with several cylinders} \)

Source: [www.fao.org](http://www.fao.org) [1986]

From Equation 6-2 and Equation 6-3,
For  $d_t = 451$ mm (0.451 m)

\[
\frac{100 \times A_n}{A_t} = 4.7
\]

\[
\frac{100 \times 5 \times \frac{1}{4} \times \pi \times d_n^2}{\frac{1}{4} \times \pi \times d_t^2} = 4.7
\]

But,  $d_t = 0.451$ m

Thus,  $d_n = 0.0437$ m (43.7 mm)

**Specific gasification rate (SGR)**

Cross-sectional area of the reactor (throat) = 0.16 $m^2$

Fuel flow of MSW in the gasifier = 813.47 kg/hr

From Equation 2-15,

\[
SGR = \frac{813.47}{0.16} = 5089.29 \text{ kgh}^{-1}m^{-2}
\]

Jain [2006] reported an optimum specific gasification rate of 200 kgh$^{-1}$m$^{-2}$ for large systems up to 100 kgh$^{-1}$ capacity. This high value of SGR is attributed to the high biomass consumption of the gasifier obtained i.e. 813.47{kgh}^{-1}.

**Superficial velocity, $V_s$ (Nm/s) or specific gas production rate, SGPR (Nm$^3$/h-m$^2$)**

Gas production rate (GPR) = 0.4 Nm$^3$/s (1438.55 Nm$^3$/h)

From Equation 2-16,

\[
V_s = \frac{\text{Gas Volume}}{\text{Cross sectional area} \times \text{time}} = \frac{0.4}{0.16} = 2.5 \text{ Nm} / \text{s}
\]

From Equation 2-17,

\[
SGPR = \frac{\text{Rate of gas production (m}^3/\text{h)}}{\text{Cross sectional area of the gasifier}} = \frac{1438.55}{0.16} = 9000 \text{ Nm}^3/\text{h} \cdot \text{m}^2
\]
Hariie, 2005 suggests an optimum value of $V_s$ of 2.5 m/s or SGPR of 9000 m$^3$/h.m$^2$ calculated at NTP from the throat diameter and ignoring the presence of the fuel. Calculated values are thus similar to the ones quoted.

**Specific energy demand, GJ/m$^2$-h**

Specific energy demand = $\frac{\text{GPR} \times \text{LHV}_{\text{gas}}}{\text{cross sectional area of air inlet}}$ .......Equation 6-4

The GPR was 1438.55 Nm$^3$/h

The LHV$_{\text{gas}}$ was 4.75 MJ/Nm$^3$ (normalized value)  

Thus, specific energy demand = $\frac{1438.55 \times 4.75}{0.16}$

= 42750 MJ/m$^2$-h (42.75GJ/m$^2$-h)

According to Hariie [2005] if the gas has a (typical) energy content of 6.1 MJ/Nm$^3$, this results in a specific energy rate of 54.8 GJ/m$^2$-h. Thus, the low specific energy demand obtained is partially attributed to the low value of LHV of the gas from MSW.

Figure 6-4 shows a sketch of the downdraft gasifier with selected dimensions.

![Figure 6-4: Sketch of the gasifier design](image)
6.2.3 Overall efficiency of the gasifier-engine system

From Equation 3-5,

$$\eta = \frac{\text{Electrical power output}}{\text{LHV}_{\text{fuel}} \times (m_{\text{fuel}})}$$

Where,

- $m_{\text{fuel}}$ - The fuel flow for the gasifier.
- Electrical power output, $P_{\text{emax}} = 425.17$ kW.

$LHV_{\text{fuel}} = 12$ MJ/kg = 12000 KJ/kg

$m_{\text{fuel}} = 0.226$ kg/s = 813.47 kg/h

Thus,

$$\eta = \frac{425.17}{12000 \times (0.226)} = 15.68\%$$

6.3 Gasifier fabrication and manufacture

Fabrication is easy using basic sheet metal and welding assembly techniques. Fabrication refers to the construction of a single gasifier for use or for an experiment. Manufacture is when one undertakes the construction of a number of identical units.

Materials Construction

The commercially available materials such as steel pipes, sheet, and plate can be used for the construction. Smaller atmospheric-pressure gasifiers require a minimum metal thickness of 20-gauge (0.9144mm) [Reed & Das, 1988], with double thickness reinforcements extending a few centimeters around all fittings and fastenings. Stainless steel is recommended to give the extra temperature resistance for critical areas such as the grate, hearth or nozzles.
6.4 Design of the gas cleaning system

The gas is very dirty during startup and should be burned at the gasifier unit until the system is fully operational. The basic clean up system strategy was based on the required cleanliness goals (determined by the application), the order of removal, and temperature and intended deposit site for the collected materials. Furthermore, size, weight, cost, reliability, the need for exotic materials, water consumption, effluents disposal, the time between cleaning cycles and the ease of equipment servicing were also considered.

6.4.1 Cyclone design

These are simple and inexpensive dust and droplet separators. This device separates the contaminants into one stream and the gas into another stream. Hot gas cyclone separators are well suited to remove solid particles larger than 10µm as a prefilter for the gas cooler and fine particle removal.

Cyclone operating principle

A cyclone separator imparts a rotary motion to the gas and thereby enhances the settling rate to many times that induced by gravity alone. Cyclone performance is rated in terms of particle cut diameter (dpc or dp50) or cut size. The cut size, dp50 is the particle size/diameter at which 50% of the particles are captured e.g.

\[
dp_{80} = 2 \times \text{dp50} \\
dp_{90} = 3 \times \text{dp50}
\]

E.g. a cyclone rated at dp50=10µm can be expected to capture 50% of particles having 10µm aerodynamic diameter, 80% of particles with dp= 20µm and 90% of particles with dp=30µm [Reed & Das, 1988].

The gas contaminants consist of solids and liquids. The solids include char, ash and soot. The liquids include fine mist or fog composed of droplets smaller than 1µm but the droplets agglomerate to increase in size as the gas cools. The solids can be quite abrasive and the tar mist can cause the inlet valves, rings, throttle shafts and other moving parts to stick. Thus, both contaminants should be removed for reliable engine operation. Solids and liquids are classified as follows;

- Solids (>1µm; dust, < 1µm; fume)
- Liquids (>10µm, spray, <10µm; mist)
Aerosols are solids or liquids suspended in a gas.

The other factors in cyclone performance include:

i. Optimum velocity intake. Low velocity and oversized cyclone should be avoided.

ii. Entrainment of solid particles caused by improper cone design or faulty design of the discharge receiver.

iii. Air leaking into the char/ash hopper at the bottom of a cyclone separator deteriorates performance substantially.

iv. Removing the gas through the bottom improves the efficiency of the cyclone separator.

Cyclone design criteria

i. The diameter of pipe leading from the gasifier outlet to the cyclone inlet should be selected to allow an adequate solids conveying-velocity within the pipe. Typical solids conveying-velocities range from 10m/s-15m/s as shown in Table 6-1.

ii. One should select the cyclone inlet pipe width \( B_c \) equal to the gasifier outlet pipe diameter or set the cyclone inlet velocity equal to the pipe velocity and design the cyclone according to the proportions in Figure 6-6.

**Table 6-1:** Gas Velocity Requirements for Conveying Solids (Dependant on Nature of Contaminant)

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Velocity(m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoke, fumes, very light dust</td>
<td>10</td>
</tr>
<tr>
<td>Dry medium density dust(sawdust, grain)</td>
<td>15</td>
</tr>
<tr>
<td>Heavy dust (metal turnings)</td>
<td>25</td>
</tr>
</tbody>
</table>

Source: Reed & Das [1988]

Gas flow rate at the engine manifold was 0.436m\(^3\)/s (1570.29m\(^3\)/h) and inlet conditions to the engine are assumed to be 25°C (298K) and 1 atm pressure [Kaupp, 1984]. According to Reed & Das [1988], it is desired to reduce the solid particles to 10mg/Nm\(^3\) from raw gas that exits the gasifier at 700°C. In addition cyclone inlet temperature is assumed to be 300°C (573K). Therefore, the volume flow rate at the cyclone inlet was calculated using Equation 6-1 i.e.
\[
\frac{V_1}{T_1} = \frac{V_2}{T_2}
\]

\[
V_1 = 0.436 \text{m}^3/\text{s}; \quad T_1 = 298 \text{K}; \quad T_2 = 573 \text{K}
\]

\[
V_2 = \frac{0.436 \times 573}{298} = 0.839 \text{m}^3/\text{s}(3019.37 \text{m}^3/\text{h})
\]

Figure 6-5 shows the relationship between the cyclone separator cut size \(d_{50}\) and cyclone inlet width \(B_c\) for a given pressure drop. It is also observed that the effect of temperature on cyclone cut size is minimal and this is attributed to the counterbalancing variations of density and viscosity with temperature [Reed & Das, 1988].

![Figure 6-5: High efficiency cyclone-cut size versus inlet width](image)

Source: Reed & Das [1988]

Considering Figure 6-5, it is desired to have a pressure drop between 25mmH\(_2\)O - 100mmH\(_2\)O and from Table 6-1, the recommended minimum velocity for conveying medium density dust is 15m/s. Thus, a pipe of 15cm (0.15m) inside diameter should provide a gas velocity of

\[
V = \frac{4Q}{\pi D^2}
\]

Equation 6-5

From Equation 6-5,
\[
V = \frac{4 \times 0.839}{\pi \times (0.15)^2} = 47.49 \text{ m/s}
\]

The value of 47.49 m/s was well above the minimum. Selecting the cyclone inlet width equal to the gas pipe diameter, the cyclone was designed from the proportions in Figure 6-6.

\[V = \frac{Q}{A} = \frac{0.839}{(15 \times 30) \times 10^{-4}} = 18.64 \text{ m/s}\]
Calculation of the particle cut diameter (particle cut size)

Cyclone cut size is the particle size that will be collected with 50% efficiency. This is given by,

\[
d_{pc} = \frac{9\mu b}{2N_e N_{e1} (\rho_p - \rho_g) \Pi}
\]

**Equation 6-6**

Where:

- \(d_{pc}\) - Particle cut size, \(\mu m\)
- \(b\) - Cyclone inlet width, m
- \(\mu\) - Dynamic gas viscosity, kg/m-s
- \(N_e\) - Effective number of turns in a cyclone; 5 was assumed considering a high efficiency cyclone [Reed & Das, 1988].
- \(N_{e1}\) - Inlet gas velocity, m/s
- \(\rho_p\) - Actual particle density, kg/m\(^3\)
- \(\rho_g\) - Gas density, kg/m\(^3\) at the inlet

Figure 6-7 shows the variation of gas viscosity and density with temperature.

![Figure 6-7: Gas viscosity and density versus temperature](Image)

*Source: Reed & Das [1988]*

From Figure 6-7, using the cyclone inlet temperature of 300\(^0\)C, the density of gas and dynamic gas viscosity are

\[\rho_g = 0.489 kg/m^3\]
\[ \mu = 255 \times 10^{-7} \text{kg/m-s} \]

Assuming ash density, \( \rho_p = 2000 \text{kg/m}^3 \) [Reed & Das, 1988] the cyclone cut size was according to Equation 6-6,

\[
d_{pc} = \sqrt{\frac{9(255 \times 10^{-7})(0.15)}{2(5)(18.64)(2000 - 0.489)(3.14)}} = 5.42 \mu\text{m for ash}
\]

Pressure drop across the cyclone

The pressure drop across the cyclone was estimated from Reed & Das [1988] as

\[
\Delta P = \frac{(6.5)\times(\rho_g)(V_i^2)A_d}{D_e^2}
\]

Equation 6-7

Where:

- \( V_i \) = Gas inlet velocity, m/s
- \( A_d \) = Inlet duct area, m\(^2\)
- \( D_e \) = Diameter of the cyclone exit duct, m
- \( \rho_g \) = Gas density, kg/m\(^3\)

From Equation 6-7,

\[
\Delta P = \frac{(6.5)\times(0.489)(18.64^2)(0.15)(0.3)}{(0.3)^2} = 552.07\text{Nm}^2 (56.28\text{mmH}_2\text{O})
\]

Thus, this cyclone should achieve the desired particulate removal without excessive pressure drop.

6.4.2 Design of the venturi scrubber

Principle of venturi scrubbers

The venturi scrubber is classified under wet scrubbers. It captures by impaction and impingement and also rinses away any deposits that might otherwise form. Some fine particles are also captured here by diffusion. High-velocity flow through the low-pressure throat area atomizes the droplets. The low pressure at the throat causes condensation and the high relative velocity of the droplets with respect to the gas captures larger particles by impaction. The atomized droplets present a considerable surface area for fine particles to be captured by
diffusion. Entrained droplets containing captured contaminants are separated inertially from the cleaned gas. Liquid recycle requires cooling and removal of captured materials or disposal and replenishment.

\[ \frac{V_1}{T_1} = \frac{V_2}{T_2}, \quad V_1 = 0.839 \text{m}^3/\text{s}; \quad T_1 = 573 \text{K}; \quad T_2 = 473 \text{K} \]

\[ V_2 = \frac{(0.839 \times 473)}{573} = 0.692 \text{ m}^3/\text{s} (2492.43 \text{ m}^3/\text{h}) \]

Converting the gas volume flow rate of 0.692 m\(^3\)/s to actual cubic feet per minute (ACFM); \[ \frac{0.692 \times 60}{0.3048^3} = 1466.99 \text{ ACFM}. \]

According to [www.slyinc.com](http://www.slyinc.com) [2009], by knowing the moisture content of a gas stream (generally expressed as pounds of water per pound of dry gas) and the inlet temperature, the saturation temperature and saturated volume content can be calculated. The volume correction chart (Appendix A-2) can then be used for a close approximation of the change in gas volume.

For this design, the inlet volume was 1466.99 ACFM. The inlet temperature was estimated at 200\(^\circ\)C (392\(^\circ\)F). The moisture content of the gas was assumed to be 0.15 lb\(\text{H}_2\text{O}/\text{lb of dry air} \) [www.slyinc.com, 2009]. Thus, for 1466.99 ACFM at
392°F containing 0.15lb H₂O/lb of dry air, the chart (Appendix A-2) shows a correction factor of 0.775. Now, Inlet volume × correction factor = outlet volume

\[ 1466.99 \times 0.775 = 1136.92 \text{ACFM} \]

The scrubber was then sized for this saturated outlet volume using the data from Appendix A-3. The value of 1136.92 ACFM is closest to the Nominal capacity range of 2600/3600 ACFM since this is the smallest available from Appendix A-3 and the scrubber dimensions in Table 6-2 were selected.

**Table 6-2: Scrubber Dimensions Selected for the Gasifier- Engine System**

<table>
<thead>
<tr>
<th>Nominal capacity, saturated CFM</th>
<th>2600/3600</th>
</tr>
</thead>
<tbody>
<tr>
<td>inlet &amp; outlet A</td>
<td>13×13</td>
</tr>
<tr>
<td>separation diameter B</td>
<td>3&quot; - 8&quot;</td>
</tr>
<tr>
<td>separation C1</td>
<td>6&quot; - 6&quot;</td>
</tr>
<tr>
<td>Vent C2</td>
<td>6&quot; -5 11/16&quot;</td>
</tr>
<tr>
<td>Overall height C3</td>
<td>7&quot; -2 3/16&quot;</td>
</tr>
<tr>
<td>overall width D</td>
<td>6&quot; -7 1/2&quot;</td>
</tr>
<tr>
<td>venturi width E</td>
<td>2&quot; - 4&quot;</td>
</tr>
<tr>
<td>Separation cone F</td>
<td>1&quot; -3 1/2&quot;</td>
</tr>
<tr>
<td>drain pipe G</td>
<td>3&quot;</td>
</tr>
<tr>
<td>water pipe H</td>
<td>2&quot;</td>
</tr>
<tr>
<td>venturi depth J</td>
<td>1&quot; -5&quot;</td>
</tr>
</tbody>
</table>
Design of pump for the venturi scrubber

Table 6-3 shows the design characteristics of the venturi scrubber.

### Table 6-3: Design Characteristics of the Venturi Scrubber

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Pressure drop ($\Delta P$)</th>
<th>Liquid-gas-ratio (L/G)</th>
<th>Liquid inlet pressure ($P_L$)</th>
<th>Removal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>50-250cm of water (50-100cm of water most common)</td>
<td>6.7-13.4 L/m³</td>
<td>&lt;7-100kPa</td>
<td>90-99% is typical</td>
</tr>
</tbody>
</table>

Source: Wikimedia [2009]

From Table 6-3, L/G considered was 6.7 L/m³ for efficient scrubbing of the gas. Thus, for a gas volume flow rate of 0.692 m³/s, the corresponding water flow rate would be,

$$Q_L = 0.692 \times 6.7 = 4.64 \text{ L/s (0.00464 m}^3\text{/s})$$

From the sizing data of the venturi scrubber shown in Table 6-2, the water pipe diameter, $d_i = 2''$ (0.0508m) was required.

The frictional pressure drop in pipes is denoted by;

$$\Delta P_{f,f} = f \times \left( \frac{L}{d_i} \right) \times \left( \frac{p \times v^2}{2} \right) \text{ ............................................................Equation 6-8}$$

Where,

- $f$ - Friction factor
- $L$ - Length of the pipe, estimated to a value of 5m.
- $d_i$ - Inside diameter
- $p$ - Density
- $v$ - Velocity

Properties of water used in the analysis;

$$\rho = 741.966 + 1.9613 \times T - 0.00371211 \times T^2 \text{ ........................................Equation 6-9}$$
\[
\mu = 10^{\left[-13.73 + \frac{1830}{T} + 0.0197 \times T - 0.0000147 \times T^2\right]}
\]

.................Equation 6-10

All the temperatures must be in Kelvin.

The U.S Metric Association, USMA [2009] suggests an average room temperature between 20°C – 25°C. The average room temperature considered was,
\[
\frac{(20^\circ \text{C} + 25^\circ \text{C})}{2} = 22.5^\circ \text{C}
\]

Since the water from the scrubber pond is pumped at room temperature of 22.5°C (295.5K) then the following water properties were considered.

From Equation 6-9 and 6-10,
Density, \( \rho = 997.39 \text{ kg/m}^3 \)

Kinematic viscosity, \( \mu = 0.001001 \text{ m}^2/\text{s} \)

\( Q_L = 0.00464 \text{ m}^3/\text{s} \)

\[
A = \frac{\pi \times D^2}{4} = \frac{3.14 \times 0.0508^2}{4} = 0.00203 \text{ m}^2
\]

Water velocity, (m/s) = \( \frac{Q_L}{A} = \frac{0.00464}{0.00203} = 2.29 \text{ m/s} \)

Reynolds number \( Re = \frac{d \times V}{\mu} = \frac{0.0508 \times 2.29}{0.001001} = 116.15 \)

Since \( Re < 2300 \), then the flow is laminar thus the following expression was used to calculate the friction factor;

\[
f = \frac{64}{Re} = \frac{64}{116.15} = 0.55
\]

From Equation 6-8,
\[ \Delta P_{f,f} = f \times \left( \frac{L}{d_i} \right) \times \left( \frac{\rho \times v^2}{2} \right) = 0.55 \times \left( \frac{5}{0.0508} \right) \times \left( \frac{997.39 \times 2.29^2}{2} \right) = 141804.86 \text{ Pa} \]

Assuming a pump efficiency of 50%

Pump power, \( P_{pump} = \frac{Q_L \times \Delta P_{pump}}{\eta_{pump}} \) \hspace{1cm} \text{Equation 6-11}

Where, \( \Delta P_{pump} = \Delta P_{f,f} \)

\[ P_{pump} = \frac{0.00464 \times 141804.86}{0.5} = 1315.58 \text{ W (1.316 kW)} \]

This power can be supplied from the net power output of 425.17 kW obtained from a single gasifier-engine system.

6.4.3 Design of the fine filter

Filter parameters like bed height, filtering material, retention time, gas flow with respect to tar absorption and tar content were important considerations. Retention time is a time requirement to pass the gas from filter materials filled in the filter. This factor was very important in designing the filter system. This was calculated by using the following formula [Mandwe, Gadge, Dubey, Khambalkar, 2006];

\[ RT = \frac{BH}{V_g} \] \hspace{1cm} \text{Equation 6-12}

Where, \( RT = \) Retention time, s

\( BH = \) Bed height, m

\( V_g = \) Velocity of gas, m/s

The dimension of the dry filter was calculated on the basis of experimental data published by PAU Ludhiana during their filtration study [Mandwe, Gadge, Dubey, Khambalkar, 2006]. The experiment carried out for a dry filter by PAU Ludhiana obtained a retention time of 10 seconds for a gas in the filter bed height of 50cm.
The velocity in the filter was estimated as:

\[ V_g = \frac{0.5}{10} = 0.05 \text{m/s} \]

Gas flow rate at the engine manifold was 0.436 m³/s (1570.29 m³/h) and this was also taken as the gas flow rate in the fine filter.

The diameter of the filter with 0.05 m/s velocity was estimated as:

\[ D^2 = \frac{0.436}{0.05 \times \frac{\pi}{4}} = 11.11 \text{m}^2 \]

\[ D = 3.334 \text{m (3334mm)} \]

Thus, with this design the pressure drop is expected to be within the safe limits.

**Figure 6-9:** Sketch of the fine filter (all dimensions in mm)

The filtering material recommended for the fine filter was rice husks since these can readily be obtained locally and at an affordable price.

### 6.4.4 Design of fabric filter / baghouse filter

**Principle of baghouse filters**

Baghouse filters are used to capture fine dust particles and to separate fly ash from combustion gases. The baghouse filter will consist of a fibrous filter bag supported on metal cases enclosed in a chamber through which the gases must pass. A deposit of the separated particles soon builds up on the bag and establishes a dust cake of appropriate pore size through which additional
particles can’t pass. As more dust is accumulated, the pressure drop increases. When the cake is an optimal thickness for removal, the bag is agitated either by gas pressure or by mechanical means causing the excess cake to drop to the bottom of the housing where it is eventually removed. Figure 6-10 illustrates this principle.

A number of cleaning mechanisms are used to remove caked particles from bags. The four most common are shaking, reverse air, pulse jet, and sonic. For the project design, a manual shaking mechanism was considered i.e. the baghouse filter would be removed from the housing when it is due for cleaning, shaken to remove the cake and then placed back.

**Design of fabric filter**

The design of a baghouse involved many considerations such as space restriction, cleaning method, fabric construction, fiber, air-to-cloth ratio.

![Woven filter](image)

*Figure 6-10: Sieving (on a woven filter)*

*Source: David, Jerry, Mick [2009]*

a) Design criteria

The design of the baghouse considered the following factors;

i. Physical and chemical properties of the dust

These include size, type, shape, and density of dust; average and maximum concentrations; chemical and physical properties such as abrasiveness, explosiveness, electrostatic charge, and agglomerating tendencies.
ii. Predicting the gas flow rate

This is essential for good baghouse design. The average and maximum flow rate, temperature, moisture content, chemical properties such as dew point, corrosiveness, and combustibility should be identified prior to the final design.

iii. Fabric construction design features

These include woven or felt filters, filter thickness, fiber size, fiber density, filter treatments such as napping, resin and heat setting, and special coatings.

iv. Proper air-to-cloth (A/C) ratio

This is the key parameter for proper design. Reverse-air fabric filters have the lowest A/C ratios, then shakers, and pulse-jet.

v. Once the bag material is selected, the bag cleaning methods must be properly matched with the chosen bags. The cost of the bag, filter construction, and the normal operating pressure drop across the baghouse help dictate which cleaning method is most appropriate.

vi. The ratio of filtering time to cleaning time is the measure of the percent of time the filters are performing. This general, “rule-of-thumb” ratio should be at least 10:1 or greater [David, Jerry, Mick, 2009]

vii. Cleaning and filtering stress is very important to minimize bag failures. The amount of flexing and creasing to the fabric must be matched with the cleaning mechanism and the A/C ratio; reverse-air is the gentlest, shaking and pulse-jet place the most vigorous stress on the fabric.

viii. Bag spacing is very important for good operation and ease of maintenance. Bag spacing affects the velocity at which the flue gas moves through the baghouse compartment.

ix. Space and cost requirements are also considered in the design. Baghouses require a good deal of installation space; initial costs and operating and maintenance costs can be high.
b) Process information and bag dimensions

i. The material recommended for the baghouse filter is cloth since it is locally available.

From the engine design, the real gas flow rate to the engine was, \( Q = 0.436 \text{m}^3/\text{s} \) (436000 cm\(^3\)/s) and this was considered to be the process gas flow rate i.e. the gas flow rate through the baghouse filter.

Reed & Das [1988] recommend using a conservatively designed fabric filter; 5-10cfm/ft\(^2\) (2.54-5.08 (cm\(^3\)/s)/cm\(^2\)). According to David, Jerry, Mick [2009], the values quoted by Reed & Das [1988] are referred to as gross air-to-cloth-ratio or filtration velocity. David, Jerry, Mick [2009] give values for gross air-to-cloth ratio and filtration velocity as shown in Table 6-4.

**Table 6-4: Typical Air-cloth- ratio (Filtration Velocity) Comparisons for Three Cleaning Mechanisms**

<table>
<thead>
<tr>
<th>Cleaning mechanisms</th>
<th>Air-to-cloth ratio (cm(^3)/sec)/cm(^2))</th>
<th>Filtration velocity (ft(^3)/min)/ft(^2))</th>
<th>cm/sec</th>
<th>ft/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaking</td>
<td>1 to 3:1</td>
<td>2 to 6:1</td>
<td>1 to 3:1</td>
<td>2 to 6:1</td>
</tr>
<tr>
<td>Reverse-air</td>
<td>0.5 to 2:1</td>
<td>1 to 4:1</td>
<td>0.5 to 2:1</td>
<td>1 to 4:1</td>
</tr>
<tr>
<td>Pulse-jet</td>
<td>1 to 7.5:1</td>
<td>2 to 15:1</td>
<td>1 to 7.5:1</td>
<td>2 to 15:1</td>
</tr>
</tbody>
</table>

Source: David, Jerry, Mick [2009]

From Table 6-4,

Since the shaking mechanism was considered for this design then,

Gross air-cloth ratio, \( \text{A/C} = 3 \text{ (cm}^3/\text{s)}/\text{cm}^2 \) or filtration velocity, \( V_f = 3 \text{ cm/s} \)

ii. Bag dimensions

For space considerations the following bag dimensions were selected from Appendix A-5.

Bag diameter = 12 inches (30.48 cm)

Bag height = 8 ft (2.44 m)
C) Calculating total gross cloth area

\[ A_C = \frac{Q}{V_f} \]  

Equation 6-13

Where,

- \( A_c \) - cloth area, cm\(^2\)
- \( Q \) - process gas flow rate, cm\(^3\)/s
- \( V_f \) - filtration velocity, cm/s

From Equation 6-13,

\[ A_C = \frac{436000}{3} = 145396.8 \text{ cm}^2 \]

The pressure drop across the fabric filter would be monitored using a manometer. When the pressure goes above the expected value, the system would be stopped, the cloth cleaned manually and placed back in the hopper.

6.5 Waste heat recovery

This involves using part of the greater than 70% of fuel energy that is otherwise lost as exhaust heat and engine heat during engine operation. A water cooled engine is both convenient and safe to recover the heat. One of the applications is drying the waste.

Drying the waste

Heat from the exhaust gas can be recovered with a compact water cooled heat exchanger or put to direct contact use. Because the engine exhaust gas is hot enough (600\(^\circ\)C–700\(^\circ\)C) to decompose biomass, it must be tempered (substantially diluted with cooler gas) before being used [Reed & Das, 1988]. One of the best ways to dilute is to take the humid gas leaving the outlet of the biomass dryer, add about 10% by volume of engine exhaust gas, and recycle the mixture to the gas entry port of the dryer.
Advantages

The advantages of drying the waste using heat from the exhaust are;

i. It's already warm, thus more of it must be used to dilute (and cool) the engine exhaust gas to a given tempered temperature. Thus, more gas is available for drying the feedstock; more gas increases the capacity of the feedstock drying process.

ii. The humidity in the dryer flue gases reduces the chance for pyrolysis of the feedstock when the gas recycles to the dryer.

iii. The gas from the dryer is essentially engine exhaust gas; as such it is non oxidizing and tends to quench any incipient fires in the dryer.

The layout of the gasifier-engine system was drawn using SOLID-EDGE software and it is shown in Figure 6-11.

Figure 6-11: Layout of the gasifier-engine system run on producer gas from MSW
6.6 Environmental aspects of electricity generation from gasifier-engine systems

6.6.1 Exhaust emissions

Carbon monoxide exhaust emissions from a properly running producer-gas-fueled engine are low due to the lean mixture combusted in the engine. Hydrocarbon emissions are also low due to the absence of hydrocarbons in the producer gas. The lower flame temperature of the producer gas, along with the excellent antiknock characteristics and low prompt nitrogen content of producer gas leads to reduced $N_0x$ emissions.

6.6.2 Toxic hazards

Carbon monoxide (CO)

CO is an insidious poison because it is colourless and tasteless. It is the principle fuel component of gasification and can lead to death by suffocation. Lesser exposures cause headaches, nausea, dizziness and irritability. The Carbon monoxide exposure standards include the threshold limit value (TLV) of 50ppm CO in the workplace time weighted average for an 8h work day. Short term exposure limit (STL) is 400ppm. Atmospheric concentrations above 1% (10,000ppm) CO may cause unconsciousness in only a few minutes [Reed & Das 1988].

Creosote

The major pollutant source from producer gas is the necessary disposal of cleaning condensate, which may be high in tars especially phenols. This can be minimized by using the driest fuels possible and by using the best low tar gasifier design available to prevent tar and condensate production.

Safe operating procedures should be strictly observed to ensure safety of operating personnel and also reliability of equipment. These include; operating at negative pressure (suction gasifiers), checking the entire system for leakages upon installation and regularly with engine service thereafter and adequate ventilation. Alarms are available for measuring and signaling excessive CO levels in ambient air.
6.6.3 Char/ash mixture

Is free of dangerous materials and can be burned or safely disposed off in a landfill. Char/ash mixture can also be used to supplement soil nutrients or animal feeds. Larger char material may be saleable for further charcoal gasification, combustion or briquetting.

6.6.4 Comparison of environmental impact of methane generated from landfills to Carbon monoxide from gasifier-engine systems

The methane generated from landfills is 21 times more potent as a greenhouse gas than Carbon dioxide and thus it contributes greatly to global warming. On the contrary Carbon monoxide generated from gasifier-engine systems is not a greenhouse gas thus does not contribute to global warming. Nevertheless the environmental impacts of Carbon monoxide previously discussed should not be undermined.

Considering that the methane from landfills is not currently being utilized, these enormous emissions pose a serious threat to the environment. With proper gasifier–engine installations and following the safety precautions the threat of Carbon monoxide can be minimized considerably. Furthermore, the methane generated from gasification is too low thus its effect as a greenhouse gas can be considered negligible.
CHAPTER SEVEN: ECONOMIC ANALYSIS

7.0 Introduction

This chapter investigates the economics of the gasifier–engine system. The objective of the economic analysis is to determine the technical solution that will provide electricity at an affordable price subject to various restrictions such as laws and environmental regulations.

Economic evaluations must often cover a long period of time; at least 10 years and often up to 25-40 years [Kjellström, 2007]. This leads to uncertainties such as

i. Future inflation rate.
ii. Future fuel prices.
iii. Future taxes.
iv. More strict environmental laws.
v. Economic lifetime, maintenance/repair costs and reliability for new technologies.

7.1 Costs to be considered

The costs to be considered can be categorized in the following three broad categories.

i. Initial Investment
ii. Fixed re-current costs (Crf)
iii. Variable recurrent costs (Crv)

7.1.1 Initial investment (I)

This includes all expenditure before commercial operation such as equipment purchase, transportation, installation, commissioning.

7.1.2 Fixed re-current costs (Crf)

This is expenditure incurred during the operating period and they are independent of the plant output. Examples include;

i. Insurance.
ii. Salaries to operators.
iii. Some maintenance costs.
iv. Depreciation.
v. Interest on invested capital.
vi. Some taxes.

Annual fixed re-current costs are often expressed as a fraction of the initial investment, I.
\[ C_{\text{rf}} = c \cdot I \] where c is often in the range 1–3% [Kjellström, 2007].

### 7.1.3 Variable re-current costs (Crv)

This is expenditure during operating period that depends on the plant output. Examples include:

i. Fuel costs.
ii. Lubricants.
iii. Some maintenance costs.
iv. Some taxes.
v. Waste handling costs.

According to Kjellström [2007], annual variable re-current costs can be expressed as
\[ C_{\text{rv}} = \frac{b + \Psi}{\eta} \cdot P_{\text{rated}} \cdot \tau \] \[ \text{Equation 7-1} \]

Where,
- \( P_{\text{rated}} \) is the rated output of the plant.
- \( \eta \) - The average efficiency.
- \( b \) - Fuel cost (\$/MWh_{\text{fuel}}).
- \( \Psi \) - Maintenance costs (\$/MWh).
- \( \tau \) - Utilization time.

\[ \tau = \frac{Q}{P_{\text{max}}} \] \[ \text{Equation 7-2} \]

Where,
- \( Q \) - Energy demand
- \( P_{\text{max}} \) - Peak power demand

An assessment of the overall economic feasibility of using biomass to generate electric power should consider the following factors when considering a specific project.
i. The cost of biomass fuel.

ii. The cost of the gasifier system, including fuel storage bins, fuel feeding devices, gas clean up systems, a utility connection, switch gear and installation costs.

iii. The cost of money at prevailing interest rates.

iv. The cost of operating labour.

v. Overhaul and replacement costs.

vi. Design life of the equipment between overhauls or replacement.

vii. The value of the power produced.

viii. The cost of ash and tar disposal after clean up.

ix. Retail cost of buying electricity.

x. Benefits of using renewable energy e.g. Job creation and economic benefit to the community.

Since neither moisture nor ash contributes to fuel value, biomass fuel is mostly quoted in dollars per ton MAF ($/tonMAF) where MAF denotes moisture-and ash-free-basis (i.e. as if the biomass had its moisture and ash removed) [Reed & Das, 1988].

\[
\text{Biomass cost ($/tonMAF) = } \frac{\text{Actualcost}}{(1-M-A)} \]

Equation 7-3

Where,

M is the fraction of moisture in the biomass.

A is the fraction of ash in the biomass.

The costs of biomass depend on

i. Quantities available.

ii. Whether the biomass is a byproduct or principal product.

iii. Distance that the biomass must be hauled.

iv. Amount of pretreatment sizing, drying and storage needed.

v. Tax benefits for biomass.
Equipment cost

The cost of a gasifier ranges from $40-$200/kWh [Reed & Das, 1988]. Furthermore, a gasifier system for generating process heat or power may cost two to eight times this amount, depending on the auxiliary equipment required including;

i. Fuel storage bins.

ii. Fuel drying, screening and pretreatment systems.

iii. Devices to deliver and meter fuel fed to the gasifier.

iv. The gasifier itself.

v. Ash removal.

vi. A gas cleanup system.

vii. Gasifier operational controls.

Conversion efficiency and fuel consumption

The efficiency with which the gasifier converts biomass fuel to final product is an important factor for calculating operating costs.

The cost of operating labour

Batch-fed gasifiers can be used in the lowest cost system designs. Batch-fed gasifiers are suitable for many situations especially in the context of the workplace where change of shifts, lunch and breaks serve as natural intervals for fuelling and ash removal. Thus, batch-feeding was considered.

Maintenance costs

Maintenance costs (as well as original equipment costs) increase rapidly as engine size increases. For instance a major overhaul on a 1000KW (1MW) diesel engine costs about $4500(9000000Ugshs) [Africa Motors and Machinery, 2010]

The economic analysis was evaluated for the installation of a single gasifier-engine system.
7.2 Calculation of the payback time of the project

This is the period of time it will take for the benefits from the project to equal the investment capital.

\[
\text{Payback} = \frac{\text{Investment}}{\text{uniform annual benefits}} \\
\text{Equation 7-4}
\]

Where,

Annual benefits = revenue – electricity production costs

7.2.1 Investment

The cost of a single gasifier-engine system (equipment) including the engine was taken as $2087/kW [Thomas and Timothy, 2007]. Each gasifier-engine system is to generate 425.17kW of electrical power.

Thus,

Total cost of equipment (initial investment), \( (425.17) \times (2087) = $887333.01 \)

7.2.2 Annual benefits

The formula for computing the annual benefits is;

Annual benefits = Revenue - Electricity production costs.

Revenue

The annual revenue was computed as follows.

Assuming a duty cycle of 80%,

Operating hours a year = \( \frac{80}{100} \times (365\text{days/yr}) \times (24\text{hrs/day}) \)

= 7008 h/yr

Annual electricity generation from one (1) gasifier-engine system,

\[ = 1 \times 425.17\text{kW} \times 7008 \frac{\text{h}}{\text{yr}} = 2979602.2 \text{ kWh/yr} \]
Auxiliary annual energy consumption from 0ne (1) pump,
\[ = 1 \times 1.316 \text{kW} \times 7008 \frac{\text{h}}{\text{yr}} = 9219.58 \text{kWh/yr} \]

Net annual energy production = (2979602.2 - 9219.58)
\[ = 2970382.6 \text{kWh/yr} \]

The renewable energy policy for Uganda [www.rea.or.ug, 2010] provides two schedules of feed-in tariffs for renewable energy generators i.e. one for hydropower and one for cogeneration with bagasse. The schedule for cogeneration with bagasse was considered since bagasse and MSW fall in the same category of biomass and it is shown in Table 7-1.

<table>
<thead>
<tr>
<th>Table 7-1: Feed-in Tariffs for Uganda</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Peak</td>
</tr>
<tr>
<td>(US $/kWh)</td>
</tr>
<tr>
<td>Years 1-6</td>
</tr>
<tr>
<td>12.0</td>
</tr>
<tr>
<td>Years 6-15</td>
</tr>
<tr>
<td>8.00</td>
</tr>
<tr>
<td>Simple Average (US$ /kWh)</td>
</tr>
<tr>
<td>9.60</td>
</tr>
<tr>
<td>Weighted Average (US$ /kWh)</td>
</tr>
<tr>
<td>5.96</td>
</tr>
<tr>
<td>Shoulder</td>
</tr>
<tr>
<td>(US $/kWh)</td>
</tr>
<tr>
<td>Average</td>
</tr>
<tr>
<td>7.03</td>
</tr>
<tr>
<td>5.25</td>
</tr>
<tr>
<td>5.96</td>
</tr>
</tbody>
</table>

Source: Ministry of Energy [2010]

The simple weighted average of 5.96 US $/kWh (0.0596 $/kWh) will be used. Thus, the annual revenue is 2970382.6 kWh/yr \times 0.0596 $/kWh = 177034.80 $/yr

Electricity production costs

Table 7-2 shows typical fuel costs for various forms of biomass. From Table 7-2 the cost of municipal solid waste is estimated in the range, negative (0-20) $/dry ton.

[www.bou.or.ug] [2010] gives an interest rate of 21.9% as the commercial bank rate for January 2010. However, use of this interest rate for the economic analysis resulted in a payback time of 347 years which was not feasible. [www.bou.or.ug] [2010] also gives commercial banks interest rates in the range 16%- 21% as at January, 26th-2007. Considering the interest rate of 16% resulted in a payback of 19 years. This is still quite long considering that this is a small scale power generation project.
Table 7-2: Typical Fuel Costs for Various Forms of Biomass (1986$)

<table>
<thead>
<tr>
<th>Form</th>
<th>Shape</th>
<th>Cost ($/ton)</th>
<th>Cost ($/MBtu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet chips from tree service</td>
<td>Chips with twigs and bark</td>
<td>0-20</td>
<td>0-1.25</td>
</tr>
<tr>
<td>Demolition hammer milled dry</td>
<td>Chips with slivers</td>
<td>10-20</td>
<td></td>
</tr>
<tr>
<td>Dry chips – whole tree</td>
<td>Chips, uniform size, no twigs or slivers</td>
<td>20-40</td>
<td>1.25 – 2.50</td>
</tr>
<tr>
<td>Densified biomass(pellets, cubes)</td>
<td>Uniform cubes</td>
<td>40-60</td>
<td>2.5-3.75</td>
</tr>
<tr>
<td>Cord wood</td>
<td>Large 2ft long irregular diameter</td>
<td>100-150</td>
<td>6.25-10.00</td>
</tr>
<tr>
<td>Municipal solid waste</td>
<td>Very irregular shape with high-ash, mixed composition</td>
<td>Credit -(0-20)</td>
<td>Credit -(0-1.25)</td>
</tr>
<tr>
<td>Refuse- derived fuel</td>
<td>Irregular shape, composition more predictable than MSW</td>
<td>0-20</td>
<td>0-1.25</td>
</tr>
</tbody>
</table>

Source: Reed & Das [1988]

Boyle [2004] suggests that evaluation of economics of renewable energy projects have used discount rates of 8% and even 15%. However, many critics suggest that these values are too high and instead a value of 6% is more favoured. For this economic analysis an interest rate of 8% was considered.

The electricity production costs can be estimated from Appendix A-6 or calculated using the formulae below [Reed & Das, 1988].

At $2087/kW equipment cost, 8% interest, operating at 80%duty cycle [Thomas and Timothy, 2007; Boyle, 2004; Reed & Das, 1988]

\[
\text{Interest} = C_{\text{int}} = \frac{(\text{Equipment cost,}\$/\text{kW}) \times (\text{loan interest,}\%/\text{yr})}{(\text{duty cycle,}\%) \times (365\text{days}/\text{yr}) \times (24\text{hr}/\text{day})} = \frac{2087 \times 8}{80 \times 365 \times 24}
\]

\[
= 0.02382$/\text{kWh (2.382 US¢/kWh)}
\]

For MSW at -$2/ton (Table 7-2), 11.8%H₂O, specific fuel consumption of 1.913 kg/kWh (4.218 lb/kWh), we get fuel cost;
\[ C_{\text{fuel}} = \frac{\text{fuel price, } \$/\text{ton} \times (\text{specific fuel consumption, lb/kWh})}{(2000 \text{ lb/ton})(1 - (\text{moisture}/100))} \]

\[ = -2 \times 4.218 \times \frac{1}{2000 \times \left(1 - \left(11.8/100\right)\right)} = -0.00478$/\text{kWh} (-0.478 \text{ US¢/kWh}) \]

The cost of engine wear for a 1250kW (1.25MW) engine with 10,000h engine life and $4500 rebuild cost [Africa Motors and Machinery, 2010]

\[ C_{\text{wear}} = \frac{\text{rebuild cost } \$}{(\text{kW})(\text{engine life})} = \frac{($4500)}{(1250)(10000)} = 0.00036$/\text{kWh} (0.036 US¢/kWh) \]

Labour cost for \(\frac{1}{2}\)h per 8hr shift at $0.5/h wage rate

\[ C_{\text{labor}} = \frac{\text{wage rate } \$/\text{h} \times (\text{Attention Hours/shift})}{(\text{capacity kW})(\text{Hours/shift})} = \frac{0.5 \times 0.5}{(1250)(8)} \]

\[ = 0.000025$/\text{kWh} (0.0025 \text{ US¢/kWh}) \]

Normal maintenance; $82.9 for 20L oil capacity, $15 oil analysis, $15 plugs, 1h labour ($37), 200h maintenance interval [Africa Motors and Machinery, 2010; Reed & Das, 1988],

\[ C_{\text{maint}} = \frac{\text{parts + labour + oil analysis}}{(\text{kW})(\text{maintenance interval})} = \frac{(82.9 + 15) + (37) + 15}{(1250)(200)} \]

\[ = 0.00060$/\text{kWh} (0.06 \text{ US¢/kWh}) \]

The total cost of electricity generation is the sum of the above components of production cost;

\[ C_{\text{total}} = C_{\text{int}} + C_{\text{fuel}} + C_{\text{wear}} + C_{\text{labor}} + C_{\text{maint}} \]

\[ = 0.02382 + -0.00478 + 0.00036 + 0.000025 + 0.00060 \]

\[ = 0.020$/\text{kWh} (2.0 \text{ US¢/kWh}) \]

Thus,

annual electricity generation costs =

net annual electricity generation \times \text{cost of electricity generation}

\[ = 2965196.59 \text{kWh/yr} \times 0.02$/\text{kWh} = 59486.33 \$/\text{yr} \]

Benefits = Revenue - Electricity production costs

\[ = 177034.80 \$/\text{yr} - 59486.33 \$/\text{yr} \]
From Equation 7-4,

\[
\text{Payback} = \frac{\text{Investment}}{\text{uniform annual benefits}} = \frac{887333.01}{117548.47} \approx 7.55 \text{ years}
\]

7.3 Net present value (NPV) of the project

The NPV gives the sum of the present values of the individual amounts in the income stream of the project where each income in the stream is discounted. The income stream has only the net profits (Revenues minus Costs). A positive net present value means the investment is better, whereas a negative NPV implies the alternative or not borrowing money is better.

It can be calculated from,

\[
\text{NPV} = \sum_{j=0}^{\infty} \frac{R_j - C_j}{(1+i)^n} \quad \text{Equation 7-5}
\]

Where,

- \( R \) – Revenues
- \( C \) - Cost, including investment

Or

\[
\text{NPV} = I_0 + \frac{I_1}{(1+r)} + \frac{I_2}{(1+r)^2} + \ldots + \frac{I_n}{(1+r)^n} \quad \text{Equation 7-6}
\]

Where; \( I \) - Is each income amount for a specific year

- 0, 1, n - year numbers, where \( I_0 \) is negative for investment costs
- \( r \) - Constant discount rate (interest rate)

The uniform annual benefits of $117548.47 were considered. Using Microsoft Excel, the NPV was computed for values of interest rates from 0% to 21% while varying the number of years. The graph in Figure 7-1 was obtained.
Figure 7-1: Net present value at different interest rates for 13 years

From Figure 7-1, at 8% interest rate, the NPV of the project is positive after 13 years with a value of $41743.76. This implies that after 13 years the project would have paid the $16853477 investment and generated a net profit of $41743.76. It is also noted that at interest rates below 8% NPV is positive and above 8% NPV is negative considering a time frame of 13 years.

7.4 Other considerations for project implementation

Job creation and economic benefit to the community

Jobs would be created when the MSW gasifier-engine system project is implemented. Furthermore, payments would be done to the local community through fuel purchases such as collection, preparation, handling and transport and equipment operation and maintenance. Engine overhaul and investment earnings could also be realized.
CHAPTER EIGHT: CONCLUSION AND RECOMMENDATIONS

8.1 Conclusion

There is a great potential in MSW collected in Kampala approximating to 523 tonnes/day (6.052 kg/s) as recorded at Mpererwe landfill. The waste generation is expected to increase as the population of Kampala increases. The biomass component of the waste is approximately 87.85% (5.317 kg/s) with a moisture content of 71.09% on a wet basis. Thus, the biomass component of MSW represents a great potential for possible gasifier-engine applications.

The various experimental studies carried out at Makerere University revealed the following biomass characteristics of MSW required for possible gasification; moisture content of 11.8%, total solids of 88.2%, ash content of 25.9%, bulk density of 57.7 kg/m$^3$. The gasified MSW had the following normalized gas composition; 11.64%$H_2$, 13.70%$CO$, 16.64%$CO_2$, 54.12%$N_2$, 4.45%$CH_4$ with a heating value of 4.75 MJ/Nm$^3$.

An integrated gasifier-engine system was then designed to consume the biomass component of MSW generated in Kampala. The gasifier–engine system comprised a gasifier, gas cleaning and conditioning system (cyclone, venturi scrubber, fine filter, baghouse/cloth filter) and a spark-ignited gas engine. The generated biomass fuel flow of 5.317 kg/s with 71.09% moisture content was converted to a fuel flow of 1.743 kg/s with 11.8% moisture content suitable for gasification. The fuel consumption of a single gasifier-engine system was 813.47 kg/h (0.226 kg/s) with a SGR of 5089.29 kg/h-m$^2$ and specific energy demand of 42.75 GJ/m$^2$-h leading to a net power output of 425.17 kW and overall gasifier-engine system efficiency of 15.68%. Hence, to consume all the biomass waste collected in Kampala a total of 8 gasifier-engine systems was determined. The net annual energy generated from a single gasifier-engine system was 2.97 GWh/yr.

An economic analysis carried out to assess the feasibility of the study showed a pay-back period of 7.55 years if the electricity was sold to the grid at the feed-in tariff of 5.96 USc/kWh quoted in the new and renewable energy policy for Uganda. The NPV at 8% interest rate was found to be positive after 13 years with a value of $41743.76 which showed that the project was worth the investment. Furthermore, the project could be implemented considering other factors such as increasing the energy supply for Uganda and provision of employment.
The implementation of the project could consider installation of one gasifier-engine system in each of the five divisions of Kampala district (Kawempe, Rubaga, Makindye, Nakawa and Kampala Central leading to a total of 5 gasifier-engine systems and the consumption of the extra 3 gasifier-engine systems would be reserved for supply in case of shortage of fuel. Thus, this would greatly reduce on the costs of transporting the waste over long distances to a single location as well as minimize on the resulting emissions from the transport facilities. Furthermore, employment opportunities would be provided to people in each locality which would greatly improve their standards of living.

The study has thus assessed the possibility of generating electricity from MSW using a gasifier-engine system and the project implementation largely depends on collaboration of the government of Uganda, NGO'S, Research Institutions and local community.

8.2 Recommendations

Suggestions for further research include;

i. Pelletization / briquetting of MSW to enhance its handling for gasifier-engine applications.

ii. Modeling of the gasifier-engine system run on MSW.

iii. Co-firing of MSW with other fuels.

iv. Design of a heat recovery system for gasifier-engine applications with MSW.

v. Producer gas from MSW to be used for heat applications

vi. Design of a gas cleaning and engine system to be coupled to the Makerere University gasifier test rig.

vii. Assessing the opportunities for recycling plants at Mpererwe landfill.

viii. Improved handling of MSW by separating the biomass component from other components such as, metal, plastics, and glass.
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APPENDICES

APPENDIX A

A-1: Part of the Gas Analysis Excel Sheet Used to Calculate the LHV of Producer Gas from MSW

<table>
<thead>
<tr>
<th>Sample</th>
<th>Attenuat on mV</th>
<th>fl mm</th>
<th>H₂ Concentration</th>
<th>Concentration %</th>
<th>O₂ Attenuat on mV</th>
<th>fl mm</th>
<th>Height at fl mm</th>
<th>Concentration %</th>
<th>N₂ Attenuat on mV</th>
<th>fl mm</th>
<th>Height at fl mm</th>
<th>Concentration %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date: 6th May 2005 (Main code)</td>
<td>8</td>
<td>1440</td>
<td>1788</td>
<td>8.05%</td>
<td>8</td>
<td>40</td>
<td>320</td>
<td>-</td>
<td>64</td>
<td>mm</td>
<td>55</td>
<td>58.97%</td>
</tr>
<tr>
<td>Normal Air</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>84</td>
<td>990</td>
<td>-</td>
<td>-</td>
<td>64</td>
<td>mm</td>
<td>55</td>
<td>78.00%</td>
</tr>
</tbody>
</table>

| Date: 9th 11 2009 (MSW-Downstream) | | | | | | | | | | | | |

A-2: Volume Collection Chart for Sizing a Venturi Scrubber

Source: SLY INC [2009]
A-3: Venturi Scrubber Capacities and Dimensions

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2,000/5,600</td>
<td>12x13</td>
<td>2'-8&quot;</td>
<td>6'-6&quot;</td>
<td>6'-5&quot;</td>
<td>7'-2&quot;</td>
<td>2'-4&quot;</td>
<td>3'</td>
<td>2&quot;</td>
<td>1'-5&quot;</td>
</tr>
<tr>
<td>2</td>
<td>3,000/4,700</td>
<td>16x15</td>
<td>4'-4&quot;</td>
<td>7'-2&quot;</td>
<td>6'-6&quot;</td>
<td>7'-2&quot;</td>
<td>2'-5&quot;</td>
<td>4&quot;</td>
<td>2&quot;</td>
<td>1'-5&quot;</td>
</tr>
<tr>
<td>3</td>
<td>4,700/6,300</td>
<td>17x17</td>
<td>4'-8&quot;</td>
<td>7'-2&quot;</td>
<td>6'-2&quot;</td>
<td>7'-11&quot;</td>
<td>2'-11&quot;</td>
<td>2&quot;</td>
<td>1'-7&quot;</td>
<td>2&quot;</td>
</tr>
<tr>
<td>4</td>
<td>6,300/6,500</td>
<td>26x20</td>
<td>6'-2&quot;</td>
<td>7'-8&quot;</td>
<td>6'-10&quot;</td>
<td>8'-10&quot;</td>
<td>3'-2&quot;</td>
<td>4&quot;</td>
<td>2&quot;</td>
<td>1'-9&quot;</td>
</tr>
<tr>
<td>5</td>
<td>8,000/11,500</td>
<td>23x23</td>
<td>5'-11&quot;</td>
<td>10'-4&quot;</td>
<td>8'-9&quot;</td>
<td>9'-10&quot;</td>
<td>3'-7&quot;</td>
<td>5&quot;</td>
<td>2'-4&quot;</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>11,000/16,000</td>
<td>26x20</td>
<td>6'-7&quot;</td>
<td>12'-1&quot;</td>
<td>9'-6&quot;</td>
<td>10'-11&quot;</td>
<td>3'-10&quot;</td>
<td>6&quot;</td>
<td>2&quot;</td>
<td>2'-4&quot;</td>
</tr>
<tr>
<td>7</td>
<td>15,000/20,000</td>
<td>30x20</td>
<td>7'-5&quot;</td>
<td>14'-1&quot;</td>
<td>11'-3&quot;</td>
<td>13'-6&quot;</td>
<td>5'-3&quot;</td>
<td>6&quot;</td>
<td>3&quot;</td>
<td>3'-4&quot;</td>
</tr>
<tr>
<td>8</td>
<td>20,000/27,000</td>
<td>35x25</td>
<td>8'-4&quot;</td>
<td>16'-6&quot;</td>
<td>11'-10&quot;</td>
<td>14'-1&quot;</td>
<td>5'-1&quot;</td>
<td>8&quot;</td>
<td>4&quot;</td>
<td>3'-4&quot;</td>
</tr>
<tr>
<td>9</td>
<td>27,000/36,000</td>
<td>40x30</td>
<td>9'-4&quot;</td>
<td>19'-9&quot;</td>
<td>14'-6&quot;</td>
<td>15'-7&quot;</td>
<td>8'-1&quot;</td>
<td>8&quot;</td>
<td>4&quot;</td>
<td>4'-4&quot;</td>
</tr>
<tr>
<td>10</td>
<td>35,000/48,000</td>
<td>46x46</td>
<td>10'-6&quot;</td>
<td>22'-11&quot;</td>
<td>16'-6&quot;</td>
<td>17'-2&quot;</td>
<td>9'-5&quot;</td>
<td>10&quot;</td>
<td>6&quot;</td>
<td>4'-4&quot;</td>
</tr>
<tr>
<td>11</td>
<td>48,000/60,000</td>
<td>52x52</td>
<td>11'-10&quot;</td>
<td>25'-7&quot;</td>
<td>17'-5&quot;</td>
<td>20'-7&quot;</td>
<td>9'-5&quot;</td>
<td>10&quot;</td>
<td>6&quot;</td>
<td>5'-10&quot;</td>
</tr>
</tbody>
</table>

Source: SLY INC [2009]
### A-4: General Information for a Spark Ignited Gas Engine (1250kW-2000kW)

<table>
<thead>
<tr>
<th>Design</th>
<th>4Cycle, V-block, Turbocharged Low Temperature after Cooled.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore</td>
<td>180mm (7.09 in)</td>
</tr>
<tr>
<td>Stroke</td>
<td>200mm (7.87 in)</td>
</tr>
<tr>
<td>Displacement</td>
<td>91.6 liters (5590 in³)</td>
</tr>
<tr>
<td>Cylinder block</td>
<td>Cast iron, V18</td>
</tr>
<tr>
<td>Battery charging alternator</td>
<td>None</td>
</tr>
<tr>
<td>Starting voltage</td>
<td>24 volt negative ground</td>
</tr>
<tr>
<td>Fuel system</td>
<td>Lean burn</td>
</tr>
<tr>
<td>Ignition system</td>
<td>Individual coil on plug</td>
</tr>
<tr>
<td>Air cleaner type</td>
<td>Dry replaceable element</td>
</tr>
<tr>
<td>Lube oil filter type(s)</td>
<td>Full flow and bypass filters</td>
</tr>
<tr>
<td>Breather</td>
<td>Breather filters</td>
</tr>
</tbody>
</table>

Source: Cummins Power Generation inc. [2008]
### A-5: Comparison of Bag Cleaning Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Shake cleaning</th>
<th>Reverse-air cleaning</th>
<th>Pulse-jet cleaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Usually several cycles/second; adjustable</td>
<td>Cleaned one compartment at a time, sequencing one compartment after another; can be continuous or initiated by a maximum-pressure-drop switch</td>
<td>Usually, a row of bags at a time, sequenced one row after another; can sequence such that no adjacent rows clean one after another; initiation of cleaning can be triggered by maximum-pressure-drop switch or may be continuous</td>
</tr>
<tr>
<td>Motion</td>
<td>Simple harmonic or sinusoidal</td>
<td>Gentle collapse of bag (concave inward) upon deflation; slowly repressurize a compartment after completion of a backflush</td>
<td>Shock wave passes down bag, bag distends from cage momentarily</td>
</tr>
<tr>
<td>Peak acceleration</td>
<td>4 to 8 g</td>
<td>1 - 2 g</td>
<td>30 - 60 g</td>
</tr>
<tr>
<td>Amplitude</td>
<td>Fraction of an inch to few inches</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Mode</td>
<td>Off-stream</td>
<td>Off-stream</td>
<td>On-stream: in difficult-to-clean applications such as coal-fired boilers, off-stream compartment cleaning being studied</td>
</tr>
<tr>
<td>Duration</td>
<td>10 to 100 cycles, 30 sec to few minutes</td>
<td>1 to 2 min. including valve opening and closing and dust settling periods; reverse-air flow itself normally 10-30 sec</td>
<td>Compressed-air (40 - 100 psi) pulse duration 0.1 sec; bag row effectively off-line</td>
</tr>
<tr>
<td>Common bag dimensions</td>
<td>5, 8, 12 in. diam; 8 to 10, 26, 30 ft length</td>
<td>8, 12 in. diam; 22, 30, 40 ft length</td>
<td>6 to 8 in. diam; 8 to 20 ft length</td>
</tr>
<tr>
<td>Bag tension</td>
<td>NA</td>
<td>50 to 120 lbs typical; optimum varies: adjusted after on-stream</td>
<td>NA</td>
</tr>
</tbody>
</table>

Source: David, S. B.; Jerry, J.; Mick, P. [2009]
A-6: Electricity Generation Costs: Graphic Calculations for Interest, wear, Maintenance, Fuel and Labour

Source: Reed & Das [1988]
APPENDIX B: EXPERIMENTAL INVESTIGATIONS

B-1 MSW, sorted, dried and packed for gasification

(a) Weighing MSW before batch-feeding to the gasifier, (b) Starting the gasifier
B-3 (a) Producer gas burning with a blue flame, (b) Producer gas burning with a yellow flame

B-4 (a) Sampling unit, (b) Gasifier, sampling unit and laptop
B- 4 (a) Gas sampling bags, (b) The chief technician recording results

B- 4 (a) G.C recorder (b) The author participating in data collection
APPENDIX C: MSW MANAGEMENT AT MPERERWE LANDFILL

C-1(a) Electronic weighing bridge (b) Truck carrying MSW arriving at the weighing bridge

C-2 (a) Empty truck at weighing bridge after offloading MSW, (b) Dumping site
C-3 (a) Caterpillar moving earth (b) Caterpillar covering the dumped MSW with earth

C-4 (a) Paper sorted from MSW, (b) Polyethylene bags sorted from MSW
C-5 (a) and (b); plastics sorted from MSW

C-6 (a) and (b); Metallic containers sorted from MSW