



**IMPROVEMENT OF THE WATER SCRUBBING TECHNOLOGY FOR BIOGAS  
UPGRADING**

**BY**

**WALOZI RONALD**

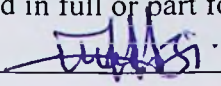
**BSc. Mcc. Eng. (Mak.)**

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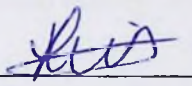
## DECLARATION

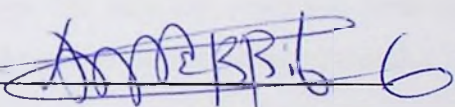
I RONALD WALOZI humbly declare that this report is based on my original work and it has not been submitted in full or part for a degree award in any other university.

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This report has been approved by us the supervisors to have met the examiner's requirements for the award of the degree of Master of Science in Technology Innovation and Industrial Development of Makerere University.

Signed  Date 18/12/2014  
Dr. Betty Nabuuma

Signed  Date 05.01.2015  
Eng. Dr. Adam Sebbit

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## **DEDICATION**

I dedicate this report to my dear Mother, Mrs Mutome Beatrice Naguti and to my Wife, Ms. Norah Acan.

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## ACRONYMS

|           |                                              |
|-----------|----------------------------------------------|
| A: -      | Area                                         |
| AD: -     | Anaerobic digestion                          |
| CHP: -    | Combined heat and power                      |
| $C_p$ : - | CH <sub>4</sub> content in processed biogas  |
| $C_r$ : - | CH <sub>4</sub> in raw biogas                |
| D: -      | External diameter                            |
| DEA: -    | Di-ethanolamine                              |
| $d_i$ : - | Internal diameter                            |
| EU: -     | European Union                               |
| GHG: -    | Greenhouse gas                               |
| l/kgVs: - | Biogas yield per kilogram of volatile solids |
| MEA: -    | Mono-ethanolamine                            |
| ppm: -    | Parts per million                            |
| PSA: -    | Pressure Swing Adsorption                    |
| $y_p$ : - | CO <sub>2</sub> in processed biogas          |
| $y_r$ : - | CO <sub>2</sub> in raw biogas                |

## ABSTRACT

Biogas is a renewable energy resource comprising of mainly methane, carbon dioxide, and hydrogen sulphide. Its range of uses can be increased by removing hydrogen sulphide and enhancing methane content by removal of carbon dioxide. The presence of carbon dioxide reduces the heat value of biogas and also makes it expensive to transport. Additionally, the presence of hydrogen sulphide and its oxides react with water to form corrosive acids. One of the cheapest and simplest biogas upgrading technologies for removal of carbon dioxide and hydrogen sulphide from biogas is water scrubbing. The research reported in this thesis aimed at improving an existing water scrubbing system that could only raise methane content in biogas from 55% to 65% to a system that could upgrade biogas to a methane content of 80% and reduce the hydrogen sulphide to a recommended value of 20ppm for most biogas electricity generation devices.

By operating at a maximum raw biogas pressure of 1.0589 bar and varying the new water scrubbing system operating conditions of packing material type, packing depth, water and gas flow rates, appropriate parameters for upgrading biogas from an initial composition of 71.5ppm hydrogen sulphide, 43% carbon dioxide and 55.85% methane to non-detectable hydrogen sulphide and 80% methane were identified.

Results show that for a column packed with steel-wire mesh to a depth of 0.4m, it is possible to increase the volumetric percentage of  $\text{CH}_4$  in biogas to 80% for water to gas flow rate ratios of 1.9 and above. Increasing the packed depth to 0.8m increases volumetric percentage of  $\text{CH}_4$  in upgraded biogas to 80% at a lower ratio of 0.7. This increase in packed depth resulted in an improvement from 1800 litres to 700 litres of water for every  $\text{m}^3$  of raw biogas upgraded. However, to achieve 80%  $\text{CH}_4$  in marble packed columns of similar depths, the water to gas flow rate ratio has to be raised above 2.

These results imply that although at low biogas pressure methane content could be raised to 80%, the benefit comes at a very high water cost. Water scrubbing should therefore be considered in areas where there are free or very low cost water sources.

## **CHAPTER 1 : INTRODUCTION**

### **1.1 Background**

Industrialization is an important contributor for any country's development goals. It leads to increased employment, more export earnings, wider tax base, increased purchasing power and increased integration with agriculture and product diversification throughout the economy. Although there are several requirements for industrialization, one of the key inputs is energy especially electricity. Insufficient and inconsistent electricity supply constrains the industrialization process. Investors need the assurance of consistent power supply before they can construct new plants and or expand on the existing ones. Currently, Uganda's electricity supply is not sufficient to meet the ever growing demand. In order to support industrialization, there is need to increase the electricity supply base.

With regard to expanding the electricity supply base, several options do exist. One of these would be to increase hydroelectricity power production. However, hydropower plant construction is not only expensive but also limited by the number and location of suitable water bodies. Additionally, the high costs of transmission line construction make it expensive to supply electricity to remote areas.

Another option for electricity generation is use of fossil fuels. These can be used for centralized electricity supply to the main grid or as decentralized energy supply sources as is the case for many industries and small enterprises running on generators. However, since all the fuel used is currently imported, the high exchange rates make this approach expensive for electricity generation. Although Uganda is endowed with oil reserves, exploitation and construction of a refinery is expensive. Also fossil fuels have an uncertain future and their combustion has been reported responsible for global warming and associated environmental effects.

Still another source that can be used for electricity generation is solar. However, electricity needs of many enterprises would require many panels and consequently a large surface area for installation. Besides, there is no guarantee that the sun intensity will be sufficient throughout the

year. Therefore, electricity from solar technology although beneficial is not a sufficient supplement to electricity.

An option that can be a supplementary source of electricity is biomass, particularly biogas. It has been highlighted as a useful source of decentralized energy supply (Haridasan, 2003). Biogas is a renewable energy resource formed by anaerobic digestion of biodegradable matter. On average, raw biogas contains 50-65% methane ( $\text{CH}_4$ ), 30-45% carbon dioxide ( $\text{CO}_2$ ) and traces of hydrogen sulphide ( $\text{H}_2\text{S}$ ), carbon monoxide ( $\text{CO}$ ) and water vapour (Tippayawong and Thanompongchart, 2010). However, although biogas is a good source of electricity, the high percentage of  $\text{CO}_2$  lowers the heat content of the fuel and also makes it expensive to transport (Nordin, Rubiano & Haapanen, 2012). Additionally, the presence of  $\text{H}_2\text{S}$  is highly non desirable in the energy conversion process because it converts to highly corrosive, unhealthy and environmentally hazardous sulphur dioxide ( $\text{SO}_2$ ) and sulphurous acid ( $\text{H}_2\text{SO}_3$ ) (Abatzoglou & Boivin, 2008). In order to optimize the generation of electricity from biogas, there is need to raise the percentage of  $\text{CH}_4$  by reducing the presence of  $\text{CO}_2$ ,  $\text{H}_2\text{S}$  and water vapour.

Various technologies can be used to raise the percentage of  $\text{CH}_4$  in biogas. These include pressure swing adsorption (PSA), water scrubbing, physical absorption, chemical absorption, membrane separation and cryogenic upgrading (Nordin et al., 2012). The current project proposes the use of water scrubbing because a comparative study carried out by Hunter and Oyama (2000) revealed that it is simple, cheap and removes both  $\text{CO}_2$  and  $\text{H}_2\text{S}$ .

## **1.2 Statement of the Problem**

Uganda's current electricity supply sources are not only expensive but also insufficient. The demand for electricity is also increasing. There is therefore need to explore the use of other sources of electricity such as raw biogas in order to achieve Uganda's industrialization development strategy. However, the presence of  $\text{CO}_2$ ,  $\text{H}_2\text{S}$  and water in raw biogas limits its use for electricity generation. The presence of  $\text{CO}_2$  lowers the heat content of fuel and also makes biogas transportation expensive. The calorific value and potential electricity generation of biogas at  $\text{CH}_4$  concentration of 45, 65 and 90% are 16, 23 and 39MJ/m<sup>3</sup> and 4.4, 6.5 and 11.0kWh/m<sup>3</sup>

(Annon., 2012). Also, the presence of  $H_2S$  is highly non desirable because of its bad smell, energy conversion process produces highly corrosive, unhealthy and environmentally hazardous  $SO_2$  and  $H_2SO_3$  in the presence of water. There is therefore need to remove these impurities in order to widen biogas technology applications. Although there was an attempt in the year 2011/2012 by Mutibwa Simon to develop a water scrubbing system at the College of Engineering, Design, Art and Technology of Makerere University, it was only able to raise the methane concentration from 55% to 65% (Mutibwa, 2012). The research aimed at improving the Water Scrubbing system in order to raise the  $CH_4$  concentration in processed biogas to over 75% so that it can be used for electricity generation.

### **1.3 Main Objective**

The main objective of the project is to upgrade biogas using water scrubbing process.

### **1.4 Research Questions**

The questions for this research were;

- What are the characteristics of raw biogas?
- What are the problems associated with the current water scrubbing system?
- What values of the scrubber system operating parameters would yield the desired methane content?

### **1.5 Specific Objectives**

The specific objectives of the research are:

- To determine the characteristics of raw biogas generated
- To design and construct the new water scrubbing system
- To determine the values of the new scrubbing system operating parameters that would result in  $CH_4$  content in upgraded biogas of 80%.

### **1.6 Significance of the Research**

This research is expected to support Uganda's Renewable Energy Policy goal of increasing the use of modern renewable energy from 4% in 2007 to 61% of the total energy consumption by the

year 2017 (Ministry of Energy and Mineral Development, 2007). The modern renewable energy include: use of biogas, improved energy saving bio mass and charcoal stoves, wind energy, geothermal and solar among others. The results of this research will provide the information required to use biogas as a decentralized alternative source of electricity generation. This research and its findings will also act as a basis for further research in the use of biogas for other applications such as motor vehicle fuel.

### 1.7 Conceptual Framework

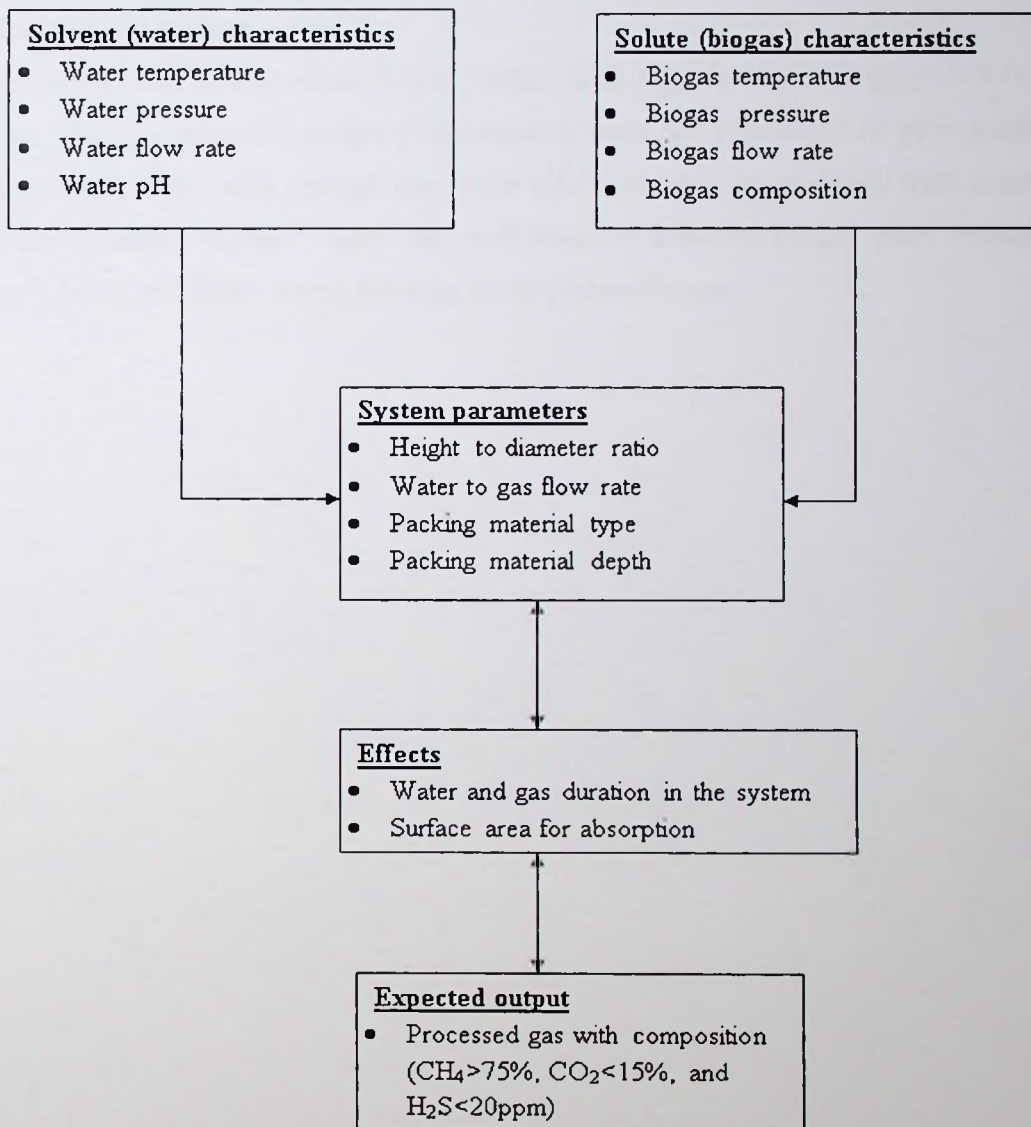


Figure1.1: Conceptual framework

### **1.8 Scope**

While there might be other impurities in the biogas, the research was limited to removal of CO<sub>2</sub> and H<sub>2</sub>S. Experiments were carried out on a single site at Uga Chick Poultry Breeders Ltd since it had sufficient biogas production. They were also able to give the researcher permission to use the plant for a period of three months. Although other researchers have carried out experiments for extensively varying biogas pressures up to a tune of 30 bars, this research used raw biogas at the pressures that had built up in the fixed dome at the time of the experiments.

### **1.9 Ethical Consideration**

The information used in this research was treated with high level of integrity. While obtaining information for this research, biogas plant owners were not persuaded to give information or permission against their will. Instead they were informed on how important their contribution is towards this research. Further, there was collaboration between biogas plant owners and the researcher to avail the plant during the time for experimentation.

## CHAPTER 2 : LITERATURE REVIEW

### 2.0 Introduction

In this chapter, a review of literature related to research on biogas and upgrading technologies and requirements is presented.

### 2.1 Biogas

Renewable energy deriving from biomass has great potential for growth to meet future energy demand (Tippayawong and Thanompongchart, 2010). Biogas is a typical renewable energy resource with a potential for use both for direct heating and lighting as well as for use in several engines (Shirage, Sankpal and Pawar, 2003). It is a renewable energy produced by anaerobic digestion of biodegradable matter (Kapdi, Vijay, Rajesh & Rajendra., 2004). Typical biomass sources for biogas production include energy crops such as castor oil, by-products from production of other fuels such as ethanol and biodiesel, land fill gas, and organic residues from agriculture (Nordin et al., 2012).

In Uganda, biogas is mainly generated from animal, human waste (Ministry of Energy and Mineral Development, 2007), grasses, poultry manure and agricultural residues (Sengendo et al., 2010). Since organic wastes are generated on a renewable basis in Uganda, it would be advantageous to view biogas as a supplementary fuel which can go a long way in meeting part of Uganda's energy needs (Nabuuma, 2005).

Raw biogas contains about 55-65% methane ( $\text{CH}_4$ ), 30-45% carbon dioxide ( $\text{CO}_2$ ), as well as some traces of hydrogen sulphide, water vapour, (Tippayawong and Thanompongchart, 2010), nitrogen, ammonia, siloxane (Abatzoglou & Boivin, 2008; Persson, Jonsson & Wellinger, 2006; Walunj & Pawar, 2003). This composition varies depending on biomass source (substrate), production technology and gas collection (Persson & Wellinger, 2009).

### 2.2 History of Biogas Technology in Uganda

Biogas was introduced in Uganda in the 1950s when the Church Missionary Society (CMS) constructed two floating drum bio digesters (Sengendo et al. 2010; Nabuuma, 2005). These acted

as demonstration units and led to construction of more digesters in Ankole but they later stopped working (Nabuuma, 2005). By 1987, the People's Republic of China in conjunction with the Ministry of Animal Husbandry and Fisheries installed seven digesters and all worked except one failed (Odogola, Kato, Bela & Makumbi, 2001). The number of bio digesters has increased from 100 in 1990 to 700 in 2008 (Sengendo et al., 2010). By increasing the country's awareness of benefits that can be realized through biogas technology use, there is hope that its dissemination and use will continue to increase.

### **2.3 Biogas Technology and its Applications**

Biogas is a good fuel in a number of applications including all or some developed for natural gas. For some applications such as direct heating and steam generation, biogas is often used in its raw form. However, for other applications like electricity generation and motor vehicle fuel use, raw biogas needs to be upgraded (Persson et al., 2006). For heating purposes, biogas is fed into the burner or boiler and heat is transferred to the water and or any other material that needs to be heated. Direct heating finds application in areas such as food preparation, brooders and steam generation for electricity.

Biogas can also be used in automobile after upgrading to natural gas quality and for electricity generation using biogas electricity generators (Persson et al., 2006). Since high methane content is essential for automobile application, CO<sub>2</sub>, H<sub>2</sub>S and water vapor have to be removed from biogas in order to raise the CH<sub>4</sub> concentration (Vijay, Ram, Parchuri & Shyam, 2006; Wellinger & Lindberg, 1997).

Several options exist for generation of electricity using biogas. Firstly, biogas can be used for generation of high quality steam to drive turbines in steam power plants (Abatzoglou & Boivin, 2008). Another alternative would be to convert the chemical energy in biogas to electricity using biogas consuming power generators (Seikkonen, 2006).

Commenting on India, Shirage et al. (2003) observed that the country's rural energy planning choices were limited to centralized energy supply technologies such as power plants based on

hydroelectricity, coal, oil and natural gas. Up until recently, Uganda's scenario has been comparable. However, high investment requirements for centralized energy supply systems have provided an incentive to promote decentralized sources of energy supply.

While biogas statistics show that biogas utilization is successful in Europe and many Asian countries, it is still not fully harnessed and utilized in Africa (Akinbami, Ilori, Oyebisi, Oyebisi & Adoeti, 2001). Although this was reported more than a decade ago, the change appears to be minimal. In Uganda, biogas is mainly used for heating and lighting (Sengendo et al., 2010). There is therefore need to exploit this renewable energy source not only for heating and lighting but also for decentralized electricity supply and automobile uses.

## **2.4 Advantages of Biogas Technologies**

Production and utilization of biogas from anaerobic digestion provides environmental and social-economic benefits to the society as whole as a well as for farmers involved. Utilisation of the internal value chain of biogas production enhances local economic capabilities, safeguards jobs in rural areas and increases regional purchasing power. It improves living standards and contributes to economic and social development (Nabuuma, 2005).

### **2.4.1 Renewable Energy Source**

The current global energy supply is highly dependent on fossil sources. These are fossilised remains of dead plants and animals, which have been exposed to heat and pressure in the Earth's crust over hundreds of millions of years. For this reason, fossil fuels are non-renewable resources whose reserves are being depleted much faster than new ones are being formed (Ministry of Energy and Mineral Development, 2007). Unlike fossil fuels, biogas from anaerobic digestion (AD) is permanently renewable, as it is produced from biomass. Biogas from anaerobic digestion will not only improve the energy balance of a country but also make an important contribution to the preservation of the natural resources and to environmental protection (Teodorita et al., 2008)

#### **2.4.2 Reduced Greenhouse Gas Emissions and Mitigation of Global Warming**

Utilisation of fossil fuels such as lignite, hard coal, crude oil and natural gas converts carbon, stored for millions of years in the Earth's crust, and releases it as carbon dioxide (CO<sub>2</sub>) into the atmosphere. An increase of the current CO<sub>2</sub> concentration in the atmosphere causes global warming as carbon dioxide is a greenhouse gas (GHG). The combustion of biogas also releases CO<sub>2</sub>. However, the main difference, when compared to fossil fuels, is that the carbon in biogas was recently taken up from the atmosphere, by photosynthetic activity of the plants.

The carbon cycle of biogas is thus closed within a very short time (between one and several years). Biogas production by anaerobic digestion also reduces emissions of methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) from storage and utilisation of untreated animal manure as fertiliser. The GHG potential of methane is higher than of carbon dioxide by 23 fold and of nitrous oxide by 296 fold. When biogas displaces fossil fuels from energy production and transport, a reduction of emissions of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O will occur, contributing to mitigate global warming (Elmar 2010, Teodorita et al., 2008).

#### **2.4.3 Reduced Dependency on Imported Fossil Fuels**

Fossil fuels are limited resources, concentrated in few geographical areas of our planet. This creates, for the countries outside this area, a permanent and insecure status of dependency on import of energy. Most countries including Uganda are strongly dependent on fossil energy imports from regions rich in fossil fuel sources such as Russia and the Middle East. Developing and implementing renewable energy systems such as biogas from anaerobic digestion, based on national and regional biomass resources, will increase security of national energy supply and diminish dependency on imported fuels (Ministry of Energy and Mineral Development, 2007).

#### **2.4.4 Waste Reduction**

One of the main advantages of biogas production is the ability to transform waste material into a valuable resource, by using it as substrate for AD. Many European countries are facing enormous problems associated with overproduction of organic wastes from industry, agriculture and households. Biogas production is an excellent way to comply with increasingly restrictive

national and other regulations in this area and to utilise organic wastes for energy production, followed by recycling of the digested substrate as fertiliser. Anaerobic digestion can also contribute to reducing the volume of waste and of costs for waste disposal (Taglia, 2010, Aashish, 2002).

#### **2.4.5 Job Creation**

Production of biogas from anaerobic digestion requires man power for production, collection and transport of AD feedstock, manufacture of technical equipment, construction, operation and maintenance of biogas plants. This means that the development of a national biogas sector contributes to the establishment of new enterprises, some with significant economic potential, increases the income in rural areas and creates new jobs (Teodorita et al., 2008, Ministry of Energy and Mineral Development, 2007).

#### **2.4.6 Flexible and Efficient End Use of Biogas**

Biogas is a flexible energy carrier, suitable for many different applications. One of the simplest applications of biogas is the direct use for cooking and lighting, but in many countries biogas is used nowadays for combined heat and power generation (CHP) or it is upgraded and fed into natural gas grids, used as vehicle fuel or in fuel cells (Elmar, 2010).

#### **2.4.7 Agricultural Benefits**

In the process of anaerobic digestion, the organic nitrogen in the manure is largely converted to ammonium. Ammonium is the primary constituent of commercial fertilizer, which is readily available and utilized by plants. Therefore it can be used as organic fertilizer hence substituting commercial fertilizers (Taglia, 2010).

### **2.5 Properties of Biogas**

Biogas is colourless and before  $H_2S$  is removed, it smells like bad eggs. Since biogas consists mainly of methane, its properties are similar to those of  $CH_4$ . The properties of biogas are: it has calorific value of between 20 and 29 MJ/m<sup>3</sup> with a maximum combustion temperature of 1200°C, has specific gravity of 0.94, critical temperature and pressure of -37°C and 56.6bars

respectively, molecular weight of 16.04 and is high-quality gas fuel and also the critical explosive mixture of standard biogas and air is 8.80%~24.4% (Annon., 2012).

## **2.6 Contaminants in Biogas**

For both motor vehicle use and power generation, biogas quality is very crucial (Persson et al., 2006; Abatzoglou & Boivin, 2008). It is therefore essential to remove as much of the contaminants as possible to levels specified by energy conversion equipment manufacturers. The typical contaminants in biogas are  $H_2S$ ,  $CO_2$ ,  $NH_3$ , Siloxanes and water and their quantities depend on the substrate (Persson & Wellinger, 2009; Abatzoglou & Boivin, 2008). The presence of  $H_2S$ ,  $CO_2$  and  $H_2O$  greatly affects engine performance (Tippayawong & Thanompongchart, 2010).  $H_2S$  is poisonous and corrosive as well as environmentally hazardous. During combustion, it's converted to a more poisonous gas,  $SO_2$ . Additionally, it reacts with  $H_2O$  to form corrosive sulphurous acid ( $H_2SO_3$ ) which reduces the life of the equipment (Kapdi et al., 2005). Therefore,  $H_2S$  removal is a must for any ultimate utilization of biogas (Abatzoglou & Boivin, 2008). The presence of  $CO_2$  in biogas lowers the calorific value and makes transportation of biogas expensive (Kapdi et al., 2005). This should therefore be removed to improve the heat content of the fuel (Tippayawong & Thanompongchart, 2010; Walunj & Pawar, 2003) and where biogas production location is far from the place where it is to be utilized, removal of  $CO_2$  can reduce transportation costs.

## **2.7 Biogas Upgrading**

Biogas upgrading involves the removal of  $CO_2$  (Persson & Wellinger, 2009),  $H_2S$ ,  $H_2O$  (Walunj & Pawar, 2003) and any other impurities from biogas (De Hullu et al., 2008). To increase the percentage of  $CH_4$ , different upgrading methods are available and the choice of the compound to be removed and upgrading method depends on the end use of biogas (Walunj & Pawar, 2003).

The technologies for removal of  $CO_2$  include absorption by chemical solvent, physical absorption, cryogenic, membrane separation,  $CO_2$  fixation by biological or chemical means (Tippayawong & Thanompongchart, 2010), adsorption on a solid surface/ pressure swing Adsorption (Kapdi et al., 2005), and water scrubbing (Beil, Hoffstede & Hahn, 2010).

### **2.7.1 Pressure Swing Adsorption (PSA)**

This technique is used to remove  $\text{CO}_2$  from biogas. In this technique,  $\text{CO}_2$  is separated from biogas by adsorption on a surface under elevated pressure. Activated carbon or zeolites is the adsorbing material which is regenerated by a sequential decrease in pressure before the column is loaded. The operating pressure is in the range of 4 to 6 bars and is able to give a methane yield of over 96% (Kapdi et al., 2005). The limitation with this method is that it requires biogas free from organic solvents,  $\text{H}_2\text{S}$  and  $\text{H}_2\text{O}$  since this can destroy the structure of the adsorption surface (Beil et al., 2010). This means that  $\text{H}_2\text{S}$  has to be removed in a separate process thereby increasing the number of upgrading stages. This method requires more than one column and is therefore expensive.

### **2.7.2 Chemical Absorption**

This technique is used to remove  $\text{CO}_2$  and it involves the use of mono-, di- or tri-ethanol amine or aqueous solutions of alkaline salts such as sodium and potassium hydroxide (Kapdi et al., 2005). The technique can give a  $\text{CH}_4$  yield of 99% (Beil et al., 2010). The disadvantage is that  $\text{H}_2\text{S}$  has to be removed and then followed by  $\text{CO}_2$  in a separate adsorption column (De Hullu et al., 2008; Beil et al., 2010). It removes both  $\text{CO}_2$  and  $\text{H}_2\text{S}$  though it requires more than one column and therefore expensive.

### **2.7.3 Cryogenic Separation**

This process is used for removal of  $\text{CO}_2$  and involves the separation of gas mixtures by fractional condensation and distillations at low temperatures since  $\text{CO}_2$  liquefies at low temperatures. Therefore pure methane can be obtained. This technique operates at a temperature of  $-170^\circ\text{C}$  and pressure of 80 bars. This process can give a  $\text{CH}_4$  yield of about 97% and does not require use of any chemicals. The limitation with this technique is that it requires complex equipment and is therefore expensive (De Hullu et al., 2008).

compared to water scrubbing since stripping sulphur from the solvent is not recommended (Wellinger & Lindberg, 1997). This method does not remove CO<sub>2</sub> and H<sub>2</sub>S simultaneously like water scrubbing therefore H<sub>2</sub>S has to be removed in a separate column before CO<sub>2</sub> is removed. This also makes it expensive.

#### **2.7.7 Dry Oxidation Process**

This is used for removal of H<sub>2</sub>S from biogas by converting it to either sulphur or its oxides. This category has two methods namely introduction of air/oxygen into the biogas system and adsorption using iron oxide. When oxygen is introduced into a biogas system using an air pump, H<sub>2</sub>S is converted to sulphur hence lowering the concentration of H<sub>2</sub>S as shown in the chemical equation below.



This method can reduce H<sub>2</sub>S by 95% to less than 50 ppm. A small amount of oxygen (6-12%) should be added since biogas is explosive in air (Wellinger & Lindeberg, 1999). This method does not remove CO<sub>2</sub>, therefore it is not the best when removing both CO<sub>2</sub> and H<sub>2</sub>S.

In adsorption using iron oxide method, biogas is passed through iron oxide pallets to remove H<sub>2</sub>S. Here, H<sub>2</sub>S in biogas reacts with iron oxide to form iron sulphide. This method is simple, only that a lot of heat is generated during regeneration. Also the dust packing contains a toxic component and the method is also sensitive to high water content of biogas (Kapdi et al., 2005). It also removes H<sub>2</sub>S and does not remove CO<sub>2</sub>.

#### **2.7.8 Liquid Phase Oxidation Process**

This is used for removal of H<sub>2</sub>S from gases with low H<sub>2</sub>S content and is through physical absorption process or chemical absorption process. In physical absorption process, solvents such as water are used to absorb H<sub>2</sub>S. The only limitation with using water is the very high water consumption for small amount of H<sub>2</sub>S. Therefore, sodium hydroxide is added in water to enhance the absorption process though the process forms sodium hydrosulphide which is not regenerated and poses disposal problems.

For the chemical absorption process, iron salts like iron chloride is used. This is extremely effective in reducing high  $\text{H}_2\text{S}$  levels and is based on the principle of formation of insoluble precipitates which need to be removed (Kapid et al., 2005; Ryckebosch, Drouillon & Vervaeren, 2011). If iron (III) hydroxide is used, regeneration can be done with oxygen or air (Ryckebosch et al., 2011). In case water is used as the solvent, this method is comparable to water scrubbing since  $\text{H}_2\text{S}$  as well as  $\text{CO}_2$  are removed.

## **2.8 Summary of the Water Scrubbing Techniques**

Among all the above mentioned techniques, water scrubbing appears to have more advantages. Some researchers have highlighted it as being simple and cheap (Krich et al., 2005). It can be used at relatively low pressures and therefore does not require a lot of power for compression like membrane separation and organic scrubbing (Vijay et al., 2006; Hagen & Polman, 2001). Additionally unlike chemical absorption, organic scrubbing, membrane separation, pressure swing adsorption, liquid phase oxidation and dry phase oxidation where  $\text{CO}_2$  and  $\text{H}_2\text{S}$  are removed in two separate stages, water scrubbing has the benefit of simultaneously removing  $\text{CO}_2$  and  $\text{H}_2\text{S}$  in a single stage (Ryckebosch et al., 2011; Kapdi et al., 2005). It has low  $\text{CH}_4$  losses especially when the water temperatures are controlled, because  $\text{CH}_4$  solubility in water is less than that of  $\text{CO}_2$  and  $\text{H}_2\text{S}$  for the same temperatures (Persson & Wellinger, 2009; Ryckebosch et al., 2011; Schomaker, Boerboom, Visser & Pfeifer, 2000). Based on these observations, water scrubbing appears to be, as noted by Krich et al. (2005) a simple and cheap means of upgrading biogas. However, to popularize its use, there is need to establish the appropriate way of operating water scrubbing systems under given circumstances.

## **2.9 Factors Affecting the Water Scrubbing Technique**

There are a number of factors that influence the efficiency and effectiveness of the water scrubbing process. These include temperature and pressure of the raw biogas gas, flow rate and purity of water, dimensions of the scrubber, type and depth of packing in the scrubber (Bhattacharya, Mishra and Singh, 1988).

The water scrubbing works on the principle that different gases have different solubility in water. The solubility of gases in water is governed by pressure, temperature, liquid/gas ratio among others. Figure 2.1, 2.2 and 2.3 shows the solubility of CH<sub>4</sub>, CO<sub>2</sub> and H<sub>2</sub>S in water at constant pressure and varying temperature.

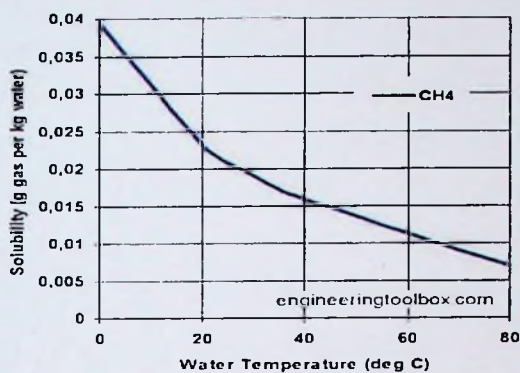


Figure 2.1: Solubility of CH<sub>4</sub> in water

Source: [engineeringtoolbox.com](http://engineeringtoolbox.com), accessed on 12/June/2013

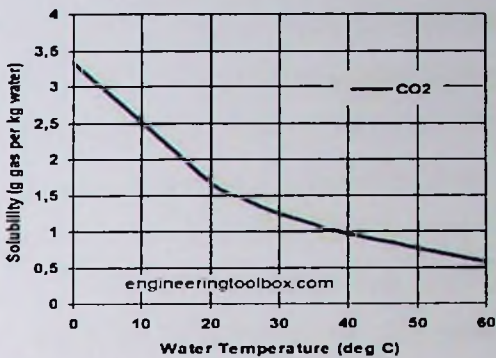


Figure 2.2: Solubility of CO<sub>2</sub> in water

Source: [engineeringtoolbox.com](http://engineeringtoolbox.com), accessed on 12/June/2013

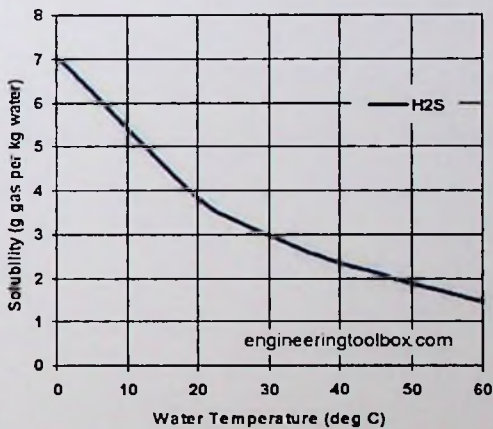


Figure 2.3: Solubility of H<sub>2</sub>S in water

Source: [engineeringtoolbox.com](http://engineeringtoolbox.com), accessed on 12/June/2013

The CH<sub>4</sub> yield increases with increase in pressure at fixed water flow rate and also increases with flow rate fixed gas pressure (Dubey, 2000; Khapre, 1989; Wellinger & Lindberg (1999).

However there is a maximum value for gas pressure and water flow rate beyond which there is no significant increase in CH<sub>4</sub> yield. Also the CH<sub>4</sub> yield is enhanced when the absorption column is filled with packing (Vijay et al., 2006; Vijay, 1989). The higher the packing height the greater the CH<sub>4</sub> yield though there is a maximum packing height for highest CH<sub>4</sub> yield (Shyam, 2002). The nature of packing material used also influences the CH<sub>4</sub> content in upgraded gas. Therefore, packing materials have to meet specific requirements. According to Rasi, Lantela, Veijanen & Rintala (2008), packing material should have: large voids to reduce pressure drop during scrubbing process; good wettability such that the gas is in contact with the wet surface during the scrubbing process, uniform distribution of water and gas across the column, less than 1/8<sup>th</sup> of column diameter since too large sizes in a small column can cause poor liquid distribution, light weight and large surface area per unit volume of packing. Also the CH<sub>4</sub> yield increase with decrease in temperature since the solubility of CO<sub>2</sub> and H<sub>2</sub>S in water increases with decrease in temperature than that of CH<sub>4</sub> (Rasi et al., 2008). The effect of these factors on CH<sub>4</sub> yield was investigated during this project research.

From literature reviewed, it can be concluded that the efficiency and effectiveness of the biogas upgrading using water scrubbing technology is a function of scrubbing column height to diameter ratio; water temperature, pressure and flow rate; biogas pressure and flow rate and nature and type of packing material. Therefore, these are the parameters which need to be tested. Chapter Three below describes the methods which were used to determine the parameters for efficient and effective upgrading of biogas using the water scrubbing technology.

## CHAPTER 3 : METHODOLOGY

### 3.1 Introduction

This chapter describes how the research was carried out in order to achieve the research objectives stated in chapter 1. The chart in figure 3.1 is a summary of the steps that were followed.

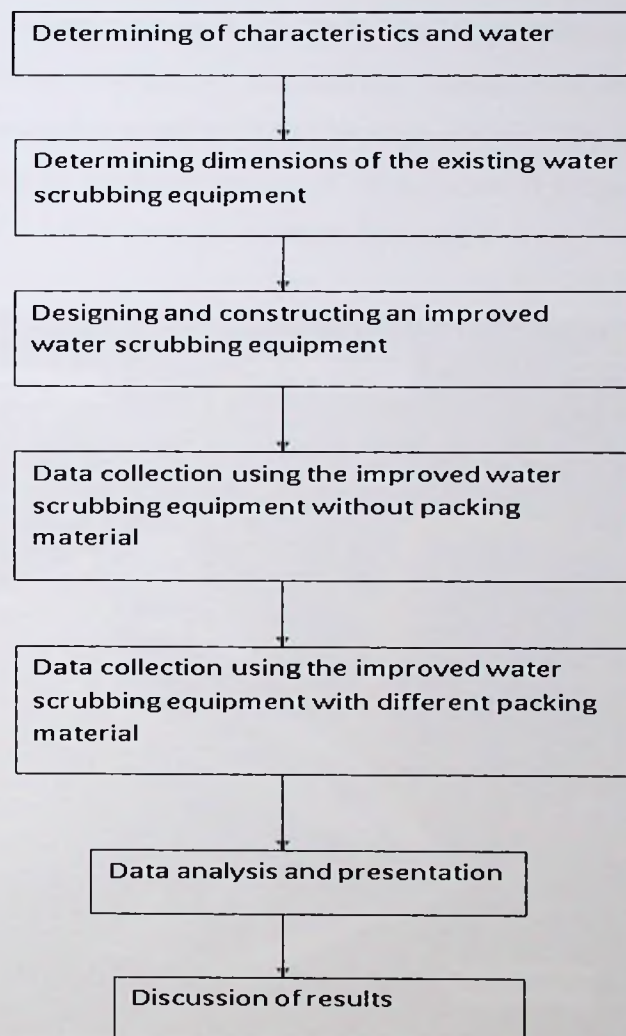


Figure 3.1: Summary of research steps

### 3.2 Determining the Characteristics of Raw Biogas

The characteristics of raw biogas which include: biogas composition, pressure, and temperature and maximum achievable flow rate were determined. The procedure for measurement of each of these is described in the following sections.

#### 3.2.1 Composition of Biogas

This was determined using a Geotech GA 2000 Plus biogas analyzer which is available at the School of Engineering, College of Engineering, Design, Art and Technology, Makerere University. This was used to establish the percentage of  $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{H}_2\text{S}$  and oxygen in the raw biogas. The requirements for determination of composition of biogas were: biogas bag, biogas analyzer, rubber tubes. The following procedure was used.

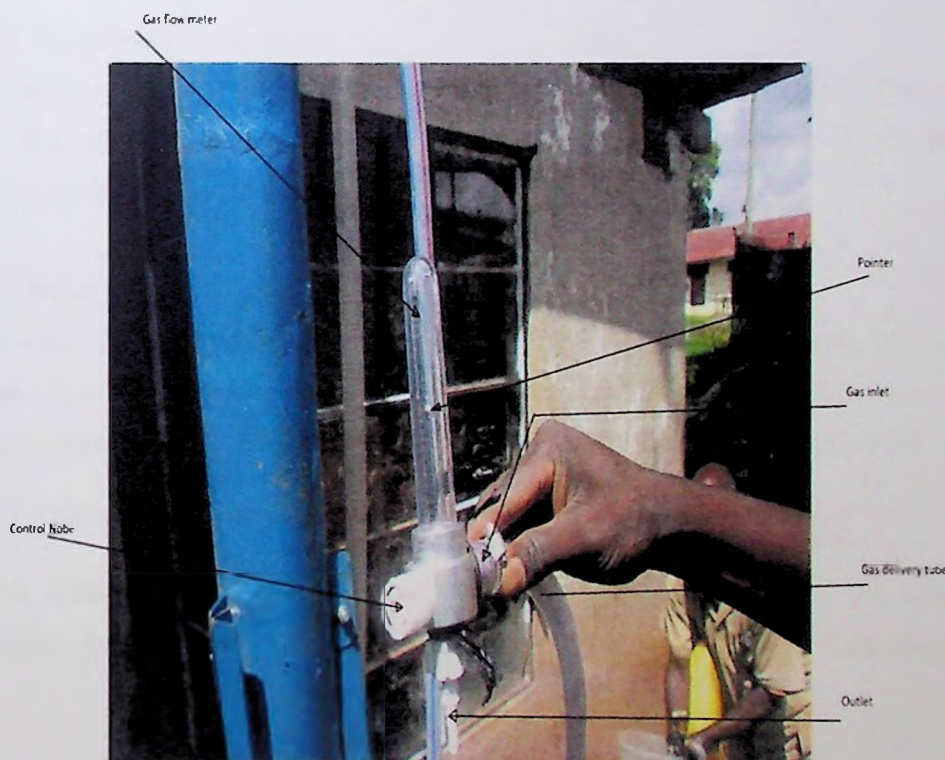


Figure 3.2: Biogas Analyzer setup

- The biogas bag was completely opened by opening the valve on it and biogas was collected into the biogas bag. When enough gas had been collected, the valve on the biogas bag was closed followed by the biogas delivery valve.
- The bag was then connected through the hydrogen sulphide filter to the suction side of the biogas analyzer using rubber tubes as shown in Figure 3.2.
- The biogas analyzer was started by switching on the pump and the valve on the bag was opened to allow the biogas flow through the analyzer.
- The experiment was allowed to run until readings on the analyzer stabilized. The reading were noted and recorded in the table. This was repeated three times.

### 3.2.2 Determining the Flow Rate of the Biogas

The flow rate of the biogas was determined using an MEC CE0120 LU55BQ flow meter (German make) connected to the delivery pipe of the biogas plant using a hose pipe and hose pipe clips. The following procedure was used to determine the flow rate of biogas.



**Figure 3.3: Gas flow meter setup**

- The inlet side of the gas flow meter was connected to the delivery side of the biogas digester using hose pipes and hose clips as shown in the Figure 3.3.
- The biogas delivery valve was opened fully for the gas to flow through the flow meter.
- The valve on the flow meter was opened fully using the control knob to measure the maximum flow rate of the biogas. After the pointer had stabilized, the pointer reading was noted and recorded in liters per minute (litres/minute). The gas flow meter was adjusted to give the required flow rate using the control knob shown in Figure 3.3.

### 3.2.3 Pressure of the Gas as it Leaves the Digester

Pressure of the raw biogas was determined as it leaves the digester using a manometer. The relative pressure of the gas was determined in centimeters of H<sub>2</sub>O. The absolute pressure was determined by adding the relative pressure to atmospheric pressure.

## 3.3 Determining Characteristics of Water

The water characteristics include temperature, flow rate and pH.

### 3.3.1 Temperature of Water

The temperature of water was measured using an infrared thermometer. Three values were taken and the average temperature was determined. This was done at the beginning of each experimental day for 15 days.

### 3.3.2 Flow Rate of Water

The water flow rate was determined by using a tank filled with water, 20 litre jerican and stop clock. The 20 litre jerican was filled three times and the different time taken was recorded and the average time determined. The flow rate was computed using equation 3.1

$$\text{Water flow rate (litre/minute)} = \frac{20 \text{ (litres)}}{\text{average filling time (minutes)}} \quad 3.1$$

Since different valve openings lead to different water flow rates, the valve was opened to different angles and the corresponding flow rates were determined following the same steps as

explained above. The valve was opened to angles of 360, 540, 720, 900, 1080 and 1260° and the corresponding water flow rates were; 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 respectively.

### 3.3.3 pH of Water

The pH of water was determined using a pH meter. The pH was determined three times and the average pH was determined and recorded.

### 3.4 Determining the methane enrichment and carbon dioxide reduction

The methane enrichment and carbon dioxide reduction were determined at different raw biogas flow rates using equation 3.2 and 3.3 as provided in Rasi et al. (2008).

$$\text{CH}_4 \text{ enrichment} = \frac{C_p - C_r}{C_r} \times 100 \quad 3.2$$

where  $C_p$  and  $C_r$  is  $\text{CH}_4$  content in processed and raw biogas respectively

$$\text{Carbon dioxide reduction} = \frac{y_r - y_p}{y_r} \times 100 \quad 3.3$$

where  $y_p$  = carbon dioxide content in processed gas

$y_r$  = carbon dioxide content in raw biogas

### 3.5 Dimensions of the Old Water Scrubbing System

The height and diameter of the scrubbing column were measured using a tape measure and the height to diameter ratio was computed. The inlet and outlet pipe diameter of water were measured using a vernier caliper. In addition, the size of the valves was determined from the specifications.

### 3.6 Designing an Improved Water Scrubbing System

After establishing the problems associated with the existing system, an improved system was designed to correct the problems and improve the system. The problems associated with existing system are small height to diameter ratio; difficulty to change the packing material, flooding and leakages. The following factors were considered during the design of an improved water scrubbing equipment:

- Scrubber column diameter and height

- Free from leakage
- Ease of operation
- Light weight for portability
- Small operational space
- Safety of the machine
- Gas pressure and flow rate at the inlet
- Water flow rate at the inlet
- packing material provision such that different packing materials can be used and their effects investigated
- Ease of maintenance.

According to Dubey (2000), the height to diameter ratio of the scrubber column should be between 10 -133. From Dubey (2000) and Vijay et al. (2006), a column with higher height to diameter ratio performs better. The existing system is within the ratio range but at a lower side. The new system was therefore adjusted from a height to diameter ratio of 10.3 to 17 because of it being at a relatively higher side yet affordable. Although a high height to diameter ratio system performs better, it also means extra costs in construction material. Additionally it would also mean that one needs to incorporate a water pump in order to raise water from a low water source to a very high height. Therefore in order to improve performance while keeping the costs low, the height to diameter ratio was adjusted from 10.3 to 17. This was because no pump was going to be used, there was need to keep the diameter relatively small so that the water spray from the overhead tank could cover the entire diameter of the column. When the diameter is very large, there is a possibility of having water not reaching the walls of the scrubber column.

### 3.6.1 Sizing of the Scrubber Column

The diameter,  $d$  and height,  $h$  of the scrubber column was sized using equation 3.4 below.

$$r = \frac{h}{d} \quad 3.4$$

where  $r$  is the ratio of height to diameter

The diameter  $d$  of the scrubber column was 150mm based on Vijay et al. (2006) and Chandra, Vijay and Subbaraet (2012). The ratio,  $r$  of height to diameter is 17. Using equation 3.4, the height,  $h$  was calculated as shown below.

$$r = \frac{h}{d}$$

$$bh = 17 \times 150$$

$$h = 2550\text{mm} \approx 2600\text{mm}$$

Therefore the height of the column was 2600mm.

### 3.6.2 Partitioning of the Column

This was based on the design by Chandra et.al (2012). This design was selected because the system was incorporated with different packing material and it was also designed to absorb  $\text{CO}_2$  to over 99%. The equipment was partitioned for easy maintenance and changing of packing material. He designed a scrubber column and partitioned it into three sections namely: top, middle and bottom sections of height 500, 3500 and 1000mm respectively as shown in Figure 3.4.

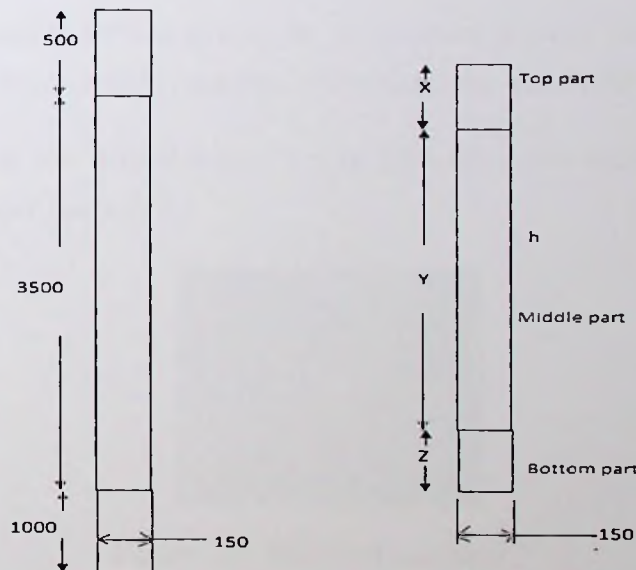


Figure 3.4: Schematic diagram of the column partition

The scrubber column is of height  $h$ , partitioned into top, middle and bottom parts of height  $X$ ,  $Y$  and  $Z$ , respectively. Since the two columns are similar, they can be compared and the following equations were used to determine  $X$ ,  $Y$  and  $Z$ .

$$X = \frac{500}{5000} \times h \quad 3.5$$

$$Y = h - X - Z \quad 3.6$$

$$Z = \frac{800}{5000} \times h \quad 3.7$$

The height of the top part was calculated using equation 3.5 as shown below.

$$\begin{aligned} X &= \frac{500}{5000} \times h \\ \text{but } h &= 2600 \\ X &= \frac{500}{5000} \times 2600 \\ X &= 260\text{mm} \approx 400\text{mm} \end{aligned}$$

This was approximated to 400mm to ease the construction process. The top section has a gas  $\frac{1}{4}$ " outlet pipe onto which a  $\frac{1}{4}$ " horse pipe is clipped and a water inlet pipe of 1" diameter.

The model of the top part is as shown in Figure 3.5 while the working drawing for the top section is as shown in Appendix 7.



**Figure 3.5: Model of top part**

The size of the bottom part  $Z$  was determined using equation 3.7 as shown below.

$$Z = \frac{1000}{5000} \times h$$

where  $h = 2600\text{mm}$

$$Z = \frac{1000}{3500} \times 2600$$

$$Z = 520\text{m} \approx 600\text{mm}$$

The position of gas inlet pipe ( $h_2$ ) was determined using equation 3.8 based on the assumption that the column should be able to contain 8 litres of water before flooding occurs.

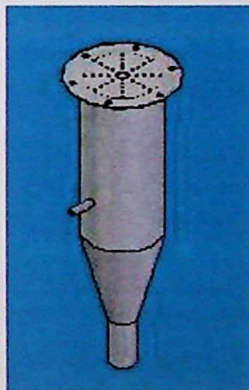
$$h_2 = \frac{(0.008)}{4\pi r^2} \quad 3.8$$

The height at which the gas inlet pipe was positioned was estimated as shown below.

$$h_2 = \frac{0.008}{\pi \times 0.075^2 \times 4}$$

$$h_2 = 0.114\text{m} \approx 200\text{mm}$$

This was approximated to 600 mm. The bottom section has a water outlet valve and pipe of diameter 50mm and a gas inlet pipe of diameter 12.5mm. The gas inlet pipe is situated at a height of 200mm such that at least 8liters can accumulate in the column before flooding occurs. Figure 3.6 shows a model of the bottom section of the scrubbing column.



**Figure 3.6: Model of bottom section**

The working drawing of the bottom section is as shown in Appendix 8.

### 3.6.2.3 Size of the Middle Part

The size, Y of middle partition was determined using equation 3.6 as shown below.

$$Y = h - X - Z$$

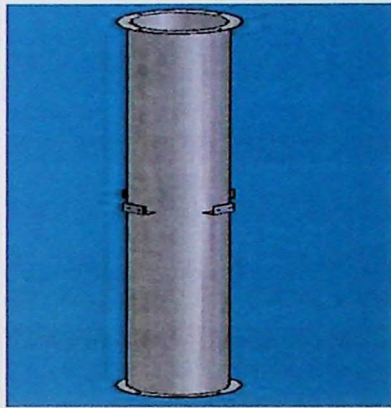
$$\text{where } h = 2500\text{mm}, X = 400, Z = 600\text{mm}$$

$$Y = 2500 - 400 - 600$$

$$Y = 1600\text{mm}$$

The size of the middle section is 1600 mm. The middle part is incorporated with packing different packing material.

Figure 3.7 is the model of the middle section.

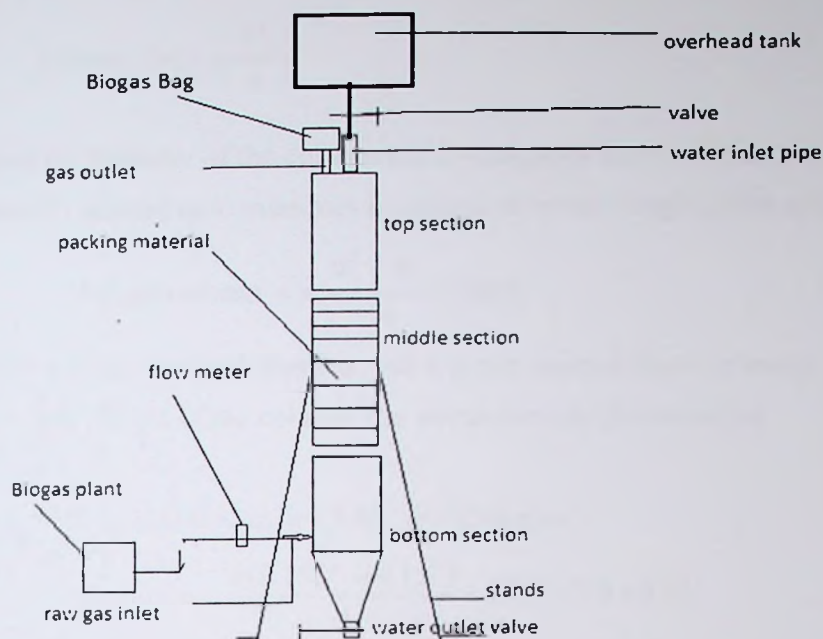


**Figure 3.7: Model of middle section**

The working drawing of the middle section is as shown in Appendix 9. The assembly drawing is as shown in Appendix 11

### **3.6.3 Water Scrubbing System Components**

The overall water scrubbing system consists of biogas plant, water delivery system, scrubbing column, supports pipes and fittings. Figure 3.8 is a schematic of the water scrubbing system.



**Figure 3.8: Schematic drawing of the water scrubbing system**

### 3.6.3.1 Supporting Frames

These consist of three stands fabricated from mild steel angle bars of size 25×25×3mm. The stands are fixed onto the absorption column with bolts and nuts.

The size of the angle bar was determined as shown below.

- a) Force exerted onto the supporting frame is the weight of the column and its content.  
During the design stones were considered as packing material since they are heavier than steel wool and marble.

The weight of stones was determined by the first determining the mass,  $m$  (kg) of the stones that can fill middle section of the column using a beam balance. The weight,  $W$  was determined as shown below.

$$W = mg; \text{ where } m = 50\text{kg}; g = 9.81\text{m/s}^2 \text{ (acceleration due to gravity)}$$

$$W = 50 \times 9.81$$

$$W = 490.5\text{N}$$

Weight of the column

The volume of the column

$$\text{Volume (v)} = \pi \frac{d^2}{4} h. \quad 3.9$$

Where d= diameter of the column and h= height of the middle section

Force (F) exerted onto members is equivalent to the weight of the column and contents.

$$\text{Weight column} = \pi \left( \frac{d^2 - d_i^2}{4} \right) h \beta h \beta \quad 3.10$$

Where d is the external diameter and d<sub>i</sub> is the internal diameter and β is the density of steel. The weight of the column was determined as shown below.

$$d = 0.155\text{m and } d_i = 0.15\text{m, } h = 2.6\text{m, } \beta = 7850\text{kg/m}^3$$

$$\begin{aligned} \text{weight of column} &= \frac{\pi(0.155^2 - 0.15^2)}{4} \times 7850 \times 2.6 \times 9.81 \\ &= 239.8\text{N} \end{aligned}$$

Weight of water

The weight of water was determined using equation below

$$\text{weight of water} = \pi \frac{d^2}{4} h_r \eta g \quad 3.11$$

where

$$h_r = \text{height of the system that was filled with water} = 0.4\text{m; } d = 0.15\text{m, } \eta = 1000\text{kg/m}^3$$

The weight was determined as shown below.

$$\text{weight of water} = \frac{\pi \times 0.15^2 \times 0.4 \times 1000 \times 9.81}{4}$$

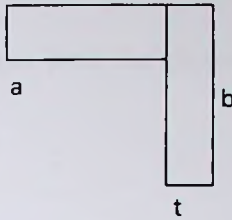
$$\text{weight of water} = 70\text{N}$$

$$\text{Total weight of the system} = 239.8 + 490.5 + 70 = 800.3\text{N.}$$

Taking an angle line of thickness 3mm, the size was determined by assuming supports can with stand at least 50% of the ultimate stress.

$$\text{Maximum allowable stress} = \text{ultimate stress} = 841\text{Mpa.}$$

b) The size a by b of the angle line to be used for the frame was determined as follows



**Figure 3.9: Cross Section of support member**

$$\text{Area, } A = t(a + b)$$

3.11

Using equation 3.11 above

$$\text{But } a = (b - 0.003) \text{ m,}$$

$$A = 0.003(b - 0.003 + b) = 0.003(2b - 0.003)$$

$$\text{Stress experienced by each member of the frame} = \frac{800.3}{0.003 \times (2b - 0.003)}$$

$$841 \times 10^6 \times 0.5 = \frac{800.3 \times 3}{0.003(2b - 0.003)}$$

$$b = 0.02 \text{ m}$$

Therefore an angle bar of 25 × 25 × 3 mm was selected for easy construction

### 3.6.3.2 Gas Supply System

This consists of the biogas plant, pipe fitting and accessories.

#### a) Biogas plant

Raw biogas is fed to the scrubber from cattle dung based fixed dome type digester. The raw biogas is supplied to the scrubbing column through a 12.5 mm hose pipe fixed by hose clips.

#### b) Pipes and fitting

12.5mm hose pipe was used to supply gas from the digester to the Scrubbing unit while water was supplied by a 25.0mm hose pipe.

#### 3.6.3.3 Water Delivery System

This consists of an overhead tank of capacity 120 litres with a 19.0mm valve connected at the bottom of the tank. A 120 litre tank was selected because it is affordable yet with a relatively high capacity to sustain the water consumption during the experiment. The tank was raised to a height of 5.6m from the ground. From the tank through a valve is connected a 25.0mm horse pipe to the water inlet pipe of the Scrubber.

#### 3.6.4 Materials Selection

The following criterion was used to select materials for the design. These were: availability, cost, durability and applicability. The selection was also based on Chandra et.al (2012) and Vijay et al. (2006). Materials that were selected for each of the components are as shown in Table 3.1.

**Table 3.1: Materials for each part of the system**

| Part            | Material        | Reason                                                                                                                                                                                |
|-----------------|-----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Scrubber column | Mild steel      | <ul style="list-style-type: none"><li>• Readily available</li><li>• Durable when painted</li><li>• Easy to use fabrication and welding</li></ul>                                      |
| Pipes           | Mild steel      | <ul style="list-style-type: none"><li>• Readily available</li><li>• Cheap</li><li>• Ease of joining to the scrubber since they are of the same properties</li></ul>                   |
| Bolts and nuts  | Stainless steel | <ul style="list-style-type: none"><li>• Cheap</li><li>• Readily available</li><li>• Corrosion resistant</li></ul>                                                                     |
| Stands          | Mild steel      | <ul style="list-style-type: none"><li>• Cheap</li><li>• Readily available</li><li>• Easy to fabricate to the Scrubber column</li><li>• It is able to with stands high loads</li></ul> |
| Seals           | Rubber          | <ul style="list-style-type: none"><li>• Better sealing</li><li>• Readily available</li></ul>                                                                                          |

### 3.6.5 Selection of packing materials

Various materials can be used as packing material. These include: round plastic balls, white stones, marble, and steel wool. Table 3.2 shows the properties of each of packing materials.

**Table 3.2: Major characteristics of the different packing materials**

| Packing material | Properties                                                      | Materials from which packing is made | Picture of packing material                                                          |
|------------------|-----------------------------------------------------------------|--------------------------------------|--------------------------------------------------------------------------------------|
| Plastic balls    | Density- $800\text{kg/m}^3$ .<br>Round shaped.<br>diameter-75mm | Plastic                              |    |
| White Stones     | Density- $1500\text{kg/m}^3$ ,<br>irregular in shape            | Granite                              |   |
| Marble           | Density- $2500\text{kg/m}^3$ ,<br>round shaped, diameter-20mm   | Calcite                              |  |
| Candlenut seeds  | Density- $889\text{kg/m}^3$ ,<br>irregular in shape             |                                      |  |
| Steel wool       | Density- $178\text{kg/m}^3$ ,<br>coarse texture                 | Steel                                |  |

From preliminary tests, candlenut seeds, and white stone gave a  $\text{CH}_4$  content of 60 and 58% in processed gas at water to gas flow rate ratio of 0.75 which was very low compared to steel and marble which gave 74 and 72 respectively. These were packed to a depth of 0.4m. The poor performance of white stones and candle nuts is due to the following reasons

- For the case of white stones and candlenut seeds, the shape and their distribution within the packing column could have limited effective contact between gas and water, also caused high pressure drop and resistance to gas flow.
- In the case of plastic balls, the poor wetting characteristics (adherence of water to their surfaces,) large size as compared to the Scrubbing column diameter and inability to uniformly distribute water evenly in the column.

The best two materials were marble and steel wool. These were subjected to further tests to establish the effect of water and gas flow rate as well as packing depth on the effectiveness and efficiency of the upgrading process.

### **3.6.6 Testing for Leakage**

After construction of the Scrubbing column, it was crucial to test for any leakages between welded joints. This was done by accumulating the gas in the Scrubber column with the gas inlet, water inlet, and water inlet valves closed and smearing soapy water around the welded joints. It was observed that no soap bubbles were formed indicating no leakage.

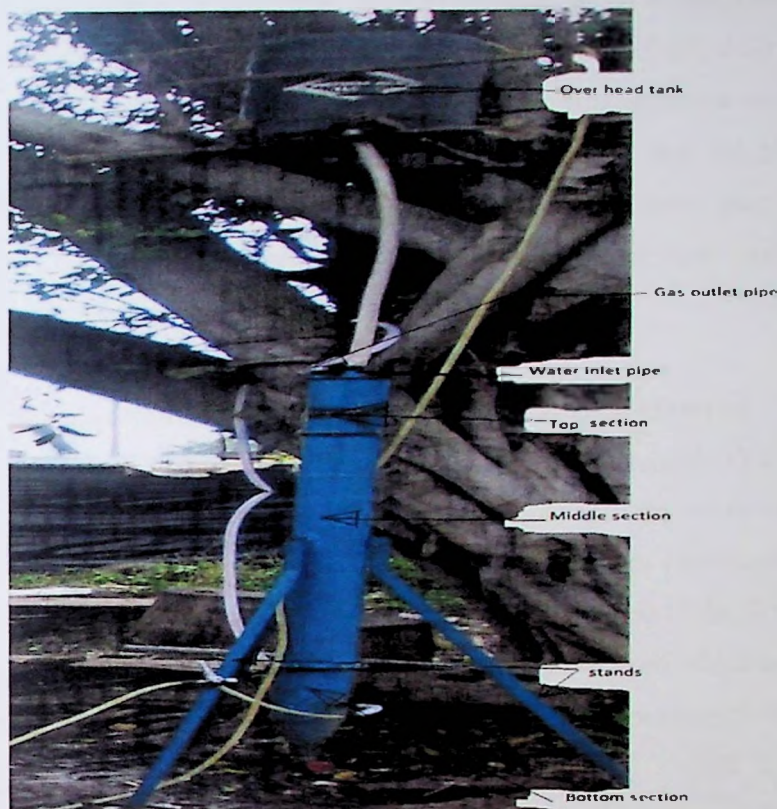
## **3.7 Testing of the New Water Scrubbing System**

The improved water scrubbing system was tested at water flow rates of 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0litres/minute and gas flow rates of 2, 4 and 6litres/minute. The tests were carried out in three stages namely, without packing material and with marble and steel wool as packing material.

### **3.7.1 Water Scrubbing Equipment without Incorporation of Packing Material.**

The water Scrubbing equipment was connected to the biogas delivery pipe using a hose pipe of 12.5mm diameter and the hose clips. Another hose pipe was connected to the processed gas outlet pipe and onto the hose was connected a tap for collecting processed gas into a biogas bag. Between the raw biogas delivery tube and scrubbing equipment was connected a gas flow meter

to measure the flow rate of the biogas. The scrubbing equipment was also connected to an overhead water tank filled with water using hose pipe of 25mm diameter and clips connected to the water inlet pipe to the Scrubbing column as shown in Figure 3.10.



**Figure 3.10: Installed water scrubbing system**

The raw biogas inlet valve to the scrubber column was fully opened and the gas flow meter first set at maximum flow rate (6litres/minute). The processed gas outlet tape was opened and the exhaust water valve closed. With gas flowing through the scrubbing system the water delivery valve was fully opened at a flow rate of 4litres/minute. The water level was maintained by continuously adding water in the overhead tank. The exhaust water valve was fully opened to avoid accumulation of water into the column. The experiment was left to run at water flow rate of 4litres/minute and biogas flow rate of 6litres/minute for 30 minutes. This was done in order to evacuate the system before processed gas was collected. At the start, the system is full of air therefore the biogas has to displace all the air for better results. Several samples of processed gas

were collected and tested using a biogas analyzer to determine the processed gas composition. This was done until consistent results were obtained. The number of samples required to obtain consistent results could vary per experiment carried out. The results of the tests were noted and recorded. The raw gas delivery valve, water delivery valve and the water exhaust together with processed gas valve were closed in that order to start another set of experiments. The above procedure was repeated for different water to gas ratios (0.25, 0.375, 0.67, 1.00 and 2.00). The raw biogas delivery valve was opened and gas flow rate set to 4litres/minute and 2litres/minute respectively while maintaining the water flow rate at 4litres/minute and the above procedure repeated. The methane enrichment and carbon dioxide reduction were then computed and recorded in the table. The experiment was repeated for varying water flow rates and fixed gas flow rates and the results were also recorded in the Table.

### **3.7.2 Water Scrubbing Equipment with Incorporation of Packing Material**

The top part of the column was opened and the column packed with marble to a height of 0.4m. The equipment was assembled back. Hose pipes from the biogas delivery valve to the inlet of the gas flow meter and to the raw biogas inlet pipe of the scrubbing system were connected. Another hose pipe was connected from the overhead tank to the water inlet pipe of the Scrubbing column and another hose pipe from the processed gas outlet pipe to a valve from which a biogas bag was connected to collect processed gas. The procedures in section 3.7.1 were repeated for different water to gas flow rate ratios (0.25, 0.375, 0.87, 1.00, 1.25, 1.50, 1.75 and 2.00). The above procedures were repeated for marble packed to a depth of 0.8m and steel wool packed to a depth of 0.4m and 0.8m.

### **3.8 Analysis and Presentation of Results**

The results were represented on charts and graphs for all the experiments carried out and a critical analysis done about the effect of water and gas flow rate, type and depth of packing material on the methane content in processed gas. For each of the experiments carried out, the water to gas flow rate ratios, and the resultant percentage CH<sub>4</sub> enrichment and CO<sub>2</sub> reduction were computed and recorded. The results were tabulated and graphs drawn to facilitate analysis of results. In the next chapter, the results obtained are presented and discussed.

**Table 4.1: Characteristics of raw biogas and water**

| Characteristics                                         | Biogas | Water |
|---------------------------------------------------------|--------|-------|
| Maximum flow rate of (litre/minute)                     | 6      | 4     |
| Maximum pressure (bar)                                  | 1.0589 | -     |
| Temperature (°C)                                        | 24     | 21.5  |
| Water pressure head at bottom of the tank (m)           | -      | 5.5   |
| Water pressure head at entry to the Scrubber column (m) | -      | 2.6   |
| Average P <sup>H</sup> of water                         | -      | 6.9   |
| <b>Composition of raw biogas</b>                        |        |       |
| CH <sub>4</sub> (%)                                     | 55.85  |       |
| CO <sub>2</sub> (%)                                     | 43.00  |       |
| H <sub>2</sub> S (ppm)                                  | 71.50  |       |
| O <sub>2</sub> (%)                                      | 0.58   |       |
| Balance (%)                                             | 0.72   |       |

The balance consists of carbon monoxide, ammonia, and hydrogen. H<sub>2</sub>S is measured in parts per million because in percentage form, it would be very small yet its products of combustion react with water to produce highly corrosive acids.

#### 4.3 Dimensions of the Old and New Water Scrubber

**Table 4.2: Dimensions of the Old and New equipment**

| Dimension                       | Old Scrubber | New Scrubber |
|---------------------------------|--------------|--------------|
| Diameter of scrubber(mm)        | 190.0        | 150.0        |
| Height of scrubber (mm)         | 1980.0       | 2600         |
| Gas inlet pipe(mm)              | 12.5         | 12.5         |
| Gas outlet pipe (mm)            | 12.5         | 12.5         |
| Water outlet pipe diameter (mm) | 30.0         | 50.0         |
| Height/diameter of the scrubber | 10.3         | 17           |
| Water inlet valve               | 30           | 25           |
| Water outlet valve              | 30           | 50           |

The dimensions of the old and new Scrubber (scrubber whose design was modified) are as shown in Table 4.2

## CHAPTER 4 : RESULTS AND DISCUSSION

### 4.1 Biogas Plant

A fixed dome biogas plant located in Uga Chick Poultry Breeder Ltd was used for experiments. The plant has a digester capacity of  $50\text{m}^3$  with a designed feed rate of 375kg of dung per day. The gas is used to cook food for employees of the company. Figure 4.1 show the fixed dome biogas plant installation.



Figure 4.1: Fixed dome digester installation

### 4.2 Characteristics of Biogas and Water

The characteristics of water and biogas were determined and these included: flow rate of water and biogas; pressure and temperature of water; relative pressure; and composition of the raw biogas. These results were as shown in Table 4.1. These values were determined at the beginning of each experimental day for 15 days. The averages were determined and are shown in Table 4.1

**Table 4.1: Characteristics of raw biogas and water**

| Characteristics                                         | Biogas | Water |
|---------------------------------------------------------|--------|-------|
| Maximum flow rate of (litre/minute)                     | 6      | 4     |
| Maximum pressure (bar)                                  | 1.0589 | -     |
| Temperature (°C)                                        | 24     | 21.5  |
| Water pressure head at bottom of the tank (m)           | -      | 5.5   |
| Water pressure head at entry to the Scrubber column (m) | -      | 2.6   |
| Average pH of water                                     | -      | 6.9   |
| <b>Composition of raw biogas</b>                        |        |       |
| CH <sub>4</sub> (%)                                     | 55.85  |       |
| CO <sub>2</sub> (%)                                     | 43.00  |       |
| H <sub>2</sub> S (ppm)                                  | 71.50  |       |
| O <sub>2</sub> (%)                                      | 0.58   |       |
| Balance (%)                                             | 0.72   |       |

The balance consists of carbon monoxide, ammonia, and hydrogen. H<sub>2</sub>S is measured in parts per million because in percentage form, it would be very small yet its products of combustion react with water to produce highly corrosive acids.

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| Gas outlet pipe (mm)            | 12.5         | 12.5         |
| Water outlet pipe diameter (mm) | 30.0         | 50.0         |
| Height/diameter of the scrubber | 10.3         | 17           |
| Water inlet valve               | 30           | 25           |
| Water outlet valve              | 30           | 50           |

The dimensions of the old and new Scrubber (scrubber whose design was modified) are as shown in Table 4.2

According to Dubey (2000), effective biogas scrubbing can be achieved with column height to diameter ratio of between 10 -133. The old water Scrubber had a height to diameter ratio of 10.3 which although within the specified range, is at a lower side for effective biogas scrubbing. Therefore, the old equipment was modified to a ratio of 17 since the higher the height to diameter ratio, the higher the efficiency of the scrubbing process. Additionally, in order to avoid scrubber column flooding as was the case in the old system, the new design incorporated a water exit valve that provided a higher maximum flow rate than the water inlet valve. With this modification, results showed that flooding was eliminated from the system. Further still, it was noted that in order to enhance CO<sub>2</sub> absorption in water, there was need to facilitate contact between water and biogas and also to increase the resident time of water in the column. Therefore, the old design was changed and a provision was made on the system to incorporate and change packing material depth and type.

To avoid leakage between welded joints, the equipment was sealed with polyester resin. The top, middle and bottom sections were joined together and between the parts were bolted rubber gaskets to prevent leakage of both gas and water.

## **4.4 Experimental Results**

### **4.4.1 Results without Packing Material**

The experiment was carried out for the unpacked Scrubber column at water to gas flow rate ratios of; 0.25, 0.375, 0.670, 1 and 2 with water at temperature of 23.8°C and biogas at an average relative pressure of 55 cm of H<sub>2</sub>O. The processed gas composition, CH<sub>4</sub> enrichment and CO<sub>2</sub> reduction were determined and the results are shown in Table 4.3.

Table 4.3: Results for unpacked column

| Water/gas flow rate ratio | Composition         |                     |                        |                    |             | Percentage CH <sub>4</sub> Enrichment | Percentage CO <sub>2</sub> Reduction |
|---------------------------|---------------------|---------------------|------------------------|--------------------|-------------|---------------------------------------|--------------------------------------|
|                           | CO <sub>2</sub> (%) | CH <sub>4</sub> (%) | H <sub>2</sub> S (ppm) | O <sub>2</sub> (%) | Balance (%) |                                       |                                      |
| 0.25                      | 36.0                | 60.7                | 0                      | 0.5                | 2.6         | 13.0                                  | 16.28                                |
| 0.25                      | 35.9                | 61.0                | 0                      | 0.9                | 2.2         | 9.22                                  | 16.51                                |
| 0.25                      | 35.8                | 60.8                | 0                      | 1.3                | 2.1         | 8.86                                  | 16.74                                |
| <b>Average</b>            | <b>35.9</b>         | <b>60.8</b>         | <b>0</b>               | <b>0.9</b>         | <b>2.3</b>  | <b>10.4</b>                           | <b>16.50</b>                         |
|                           |                     |                     |                        |                    |             |                                       |                                      |
| 0.375                     | 34.5                | 63.6                | 0                      | 1                  | 0.8         | 13.88                                 | 19.77                                |
| 0.375                     | 34.8                | 63.1                | 0                      | 1.3                | 0.7         | 12.98                                 | 19.07                                |
| 0.375                     | 33.9                | 63.9                | 0                      | 0.9                | 1.2         | 14.41                                 | 21.16                                |
| <b>Average</b>            | <b>34.4</b>         | <b>63.5</b>         | <b>0</b>               | <b>1.1</b>         | <b>0.9</b>  | <b>13.8</b>                           | <b>20.0</b>                          |
|                           |                     |                     |                        |                    |             |                                       |                                      |
| 0.67                      | 32.2                | 64.7                | 0                      | 1.1                | 1.8         | 15.85                                 | 25.12                                |
| 0.67                      | 33.5                | 64.9                | 0                      | 1.2                | 1.1         | 16.2                                  | 22.09                                |
| 0.67                      | 33.6                | 64.5                | 0                      | 1                  | 1           | 15.49                                 | 21.86                                |
| <b>Average</b>            | <b>33.1</b>         | <b>64.7</b>         | <b>0</b>               | <b>1.1</b>         | <b>1.3</b>  | <b>15.85</b>                          | <b>23.02</b>                         |
|                           |                     |                     |                        |                    |             |                                       |                                      |
| 1                         | 31.4                | 66.5                | 0                      | 1                  | 1.3         | 19.07                                 | 26.98                                |
| 1                         | 31.6                | 65.7                | 0                      | 1                  | 1.5         | 17.64                                 | 26.51                                |
| 1                         | 31.2                | 65.5                | 0                      | 1.4                | 2           | 17.28                                 | 27.44                                |
| <b>Average</b>            | <b>31.4</b>         | <b>65.9</b>         | <b>0</b>               | <b>1.1</b>         | <b>1.6</b>  | <b>17.99</b>                          | <b>26.98</b>                         |
|                           |                     |                     |                        |                    |             |                                       |                                      |
| 2                         | 20.7                | 73.7                | 0                      | 1.4                | 4.3         | 31.96                                 | 51.86                                |
| 2                         | 20.3                | 74.1                | 0                      | 1.5                | 4.2         | 32.68                                 | 52.79                                |
| 2                         | 20.3                | 73.3                | 0                      | 1.6                | 4.9         | 31.24                                 | 52.79                                |
| <b>Average</b>            | <b>20.4</b>         | <b>73.7</b>         | <b>0</b>               | <b>1.5</b>         | <b>4.5</b>  | <b>31.96</b>                          | <b>52.48</b>                         |

Figure 4.2 was generated from data in table 4.3 and shows the effect of varying water biogas flow rate ratio on percentage CH<sub>4</sub> enrichment for the unpacked column.

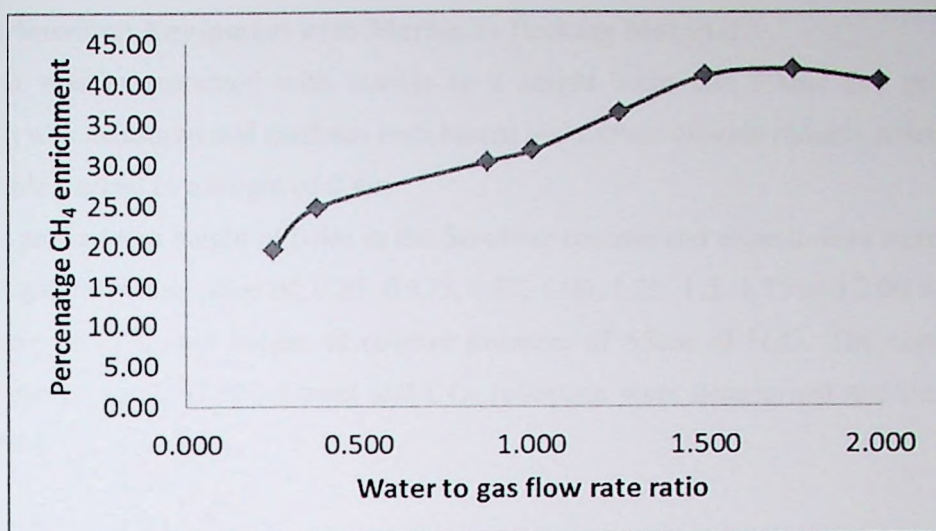


Figure 4.2: Percentage CH<sub>4</sub> enrichment for unpacked column

Figure 4.3 shows the effect of varying water gas flow rate ratio on percentage CO<sub>2</sub> reduction as generated from the data in Table 4.3.

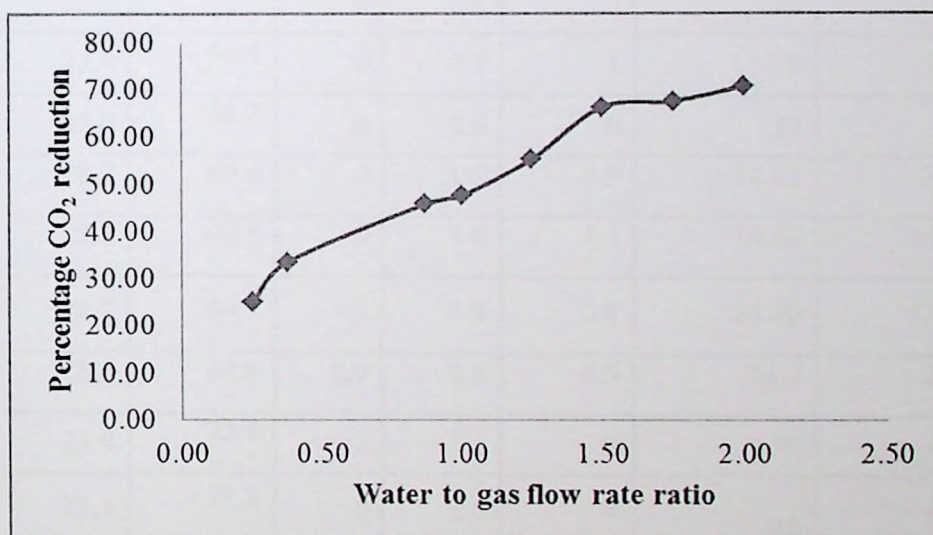


Figure 4.3: Percentage CO<sub>2</sub> reduction for unpacked column

#### 4.4.2 Experiment on Equipment with Marble as Packing Material

The column was incorporated with marble to a height 0.4m and 0.8m. The processed gas composition was measured and methane enrichment and carbon dioxide reduction determined.

##### a) Marble packed to a height of 0.4m

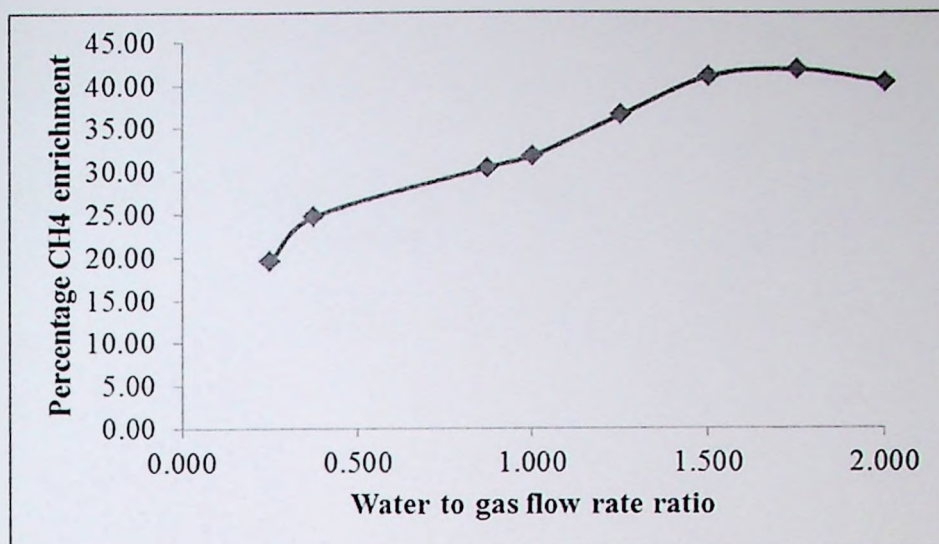
Marble was packed to a height of 0.4m in the Scrubber column and experiments were carried out for water to gas flow rate ratios of; 0.25, 0.375, 0.87, 1.00, 1.25, 1.5, 1.75 and 2.00 with water at a temperature of 21°C and biogas at relative pressure of 55cm of H<sub>2</sub>O. The composition of processed, percentage CH<sub>4</sub> enrichment and CO<sub>2</sub> reduction were determined and the results are shown in Table 4.4.

**Table 4.4: Results for marble packed to a depth of 0.4m**

| Water/<br>gas flow<br>rate<br>ratio | Composition         |                     |                           |                    |                | Percentage<br>CH <sub>4</sub><br>enrichment | Percentage<br>CO <sub>2</sub><br>Reduction |
|-------------------------------------|---------------------|---------------------|---------------------------|--------------------|----------------|---------------------------------------------|--------------------------------------------|
|                                     | CO <sub>2</sub> (%) | CH <sub>4</sub> (%) | H <sub>2</sub> S<br>(ppm) | O <sub>2</sub> (%) | Balance<br>(%) |                                             |                                            |
| 0.25                                | 32.4                | 66.9                | 0                         | 0.8                | 0              | 20                                          | 24.7                                       |
| 0.25                                | 32.2                | 66.9                | 0                         | 0.8                | 0              | 20                                          | 25.1                                       |
| 0.25                                | 32.3                | 66.4                | 0                         | 0.7                | 1              | 19                                          | 24.9                                       |
| <b>Average</b>                      | <b>32.0</b>         | <b>66.7</b>         | <b>0</b>                  | <b>0.8</b>         | <b>0</b>       | <b>19</b>                                   | <b>25</b>                                  |
| 0.375                               | 28.8                | 69.6                | 0                         | 1.0                | 0.9            | 24.62                                       | 33.02                                      |
| 0.375                               | 28.2                | 69.6                | 0                         | 1.0                | 1.1            | 24.62                                       | 34.42                                      |
| 0.375                               | 28.7                | 69.7                | 0                         | 0.8                | 0.8            | 24.80                                       | 33.26                                      |
| <b>Average</b>                      | <b>28.6</b>         | <b>69.6</b>         | <b>0.0</b>                | <b>0.9</b>         | <b>0.9</b>     | <b>24.7</b>                                 | <b>33.6</b>                                |
| 0.87                                | 23.9                | 72.8                | 0                         | 1.1                | 2              | 30                                          | 44.4                                       |
| 0.87                                | 22.1                | 72.8                | 0                         | 1.5                | 4              | 30                                          | 48.6                                       |
| 0.87                                | 23.9                | 72.8                | 0                         | 1.1                | 2              | 30                                          | 44.4                                       |
| <b>Average</b>                      | <b>23</b>           | <b>72.8</b>         | <b>0</b>                  | <b>1.2</b>         | <b>3</b>       | <b>30</b>                                   | <b>46</b>                                  |
| 1.00                                | 23.6                | 73.4                | 0                         | 1.5                | 2              | 31                                          | 45.1                                       |

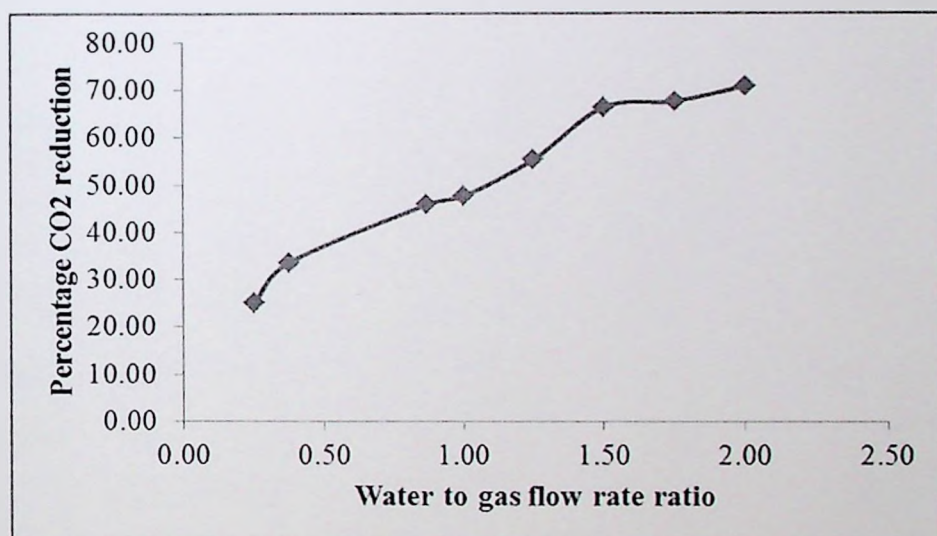
| Water/<br>gas flow<br>rate<br>ratio | Composition         |                     |                           |                    |                | Percentage<br>CH <sub>4</sub><br>enrichment | Percentage<br>CO <sub>2</sub><br>Reduction |
|-------------------------------------|---------------------|---------------------|---------------------------|--------------------|----------------|---------------------------------------------|--------------------------------------------|
|                                     | CO <sub>2</sub> (%) | CH <sub>4</sub> (%) | H <sub>2</sub> S<br>(ppm) | O <sub>2</sub> (%) | Balance<br>(%) |                                             |                                            |
| 1.00                                | 22.3                | 73.8                | 0                         | 1.3                | 3              | 32                                          | 48.1                                       |
| 1.00                                | 21.7                | 73.5                | 0                         | 1.5                | 3              | 32                                          | 49.5                                       |
| <b>Average</b>                      | <b>23</b>           | <b>73.6</b>         | <b>0</b>                  | <b>1.4</b>         | <b>3</b>       | <b>32</b>                                   | <b>48</b>                                  |
| 1.25                                | 18.6                | 76.3                | 0                         | 1.4                | 4              | 37                                          | 56.7                                       |
| 1.25                                | 18.8                | 76.3                | 0                         | 1.4                | 4              | 37                                          | 56.3                                       |
| 1.25                                | 20.2                | 76.0                | 0                         | 1.2                | 3              | 36                                          | 53                                         |
| <b>Average</b>                      | <b>19</b>           | <b>76.2</b>         | <b>0</b>                  | <b>1.3</b>         | <b>3</b>       | <b>36</b>                                   | <b>55</b>                                  |
| 1.50                                | 15                  | 78.7                | 0                         | 1.8                | 5              | 41                                          | 65.1                                       |
| 1.50                                | 14.8                | 78.7                | 0                         | 1.6                | 5              | 41                                          | 65.6                                       |
| 1.50                                | 13.6                | 78.8                | 0                         | 2                  | 7              | 41                                          | 68.4                                       |
| <b>Average</b>                      | <b>15</b>           | <b>78.7</b>         | <b>0</b>                  | <b>1.8</b>         | <b>6</b>       | <b>41</b>                                   | <b>66</b>                                  |
| 1.75                                | 13.3                | 79.1                | 0                         | 2                  | 6              | 42                                          | 69.1                                       |
| 1.75                                | 12.1                | 79.1                | 0                         | 3.1                | 6              | 42                                          | 71.9                                       |
| 1.75                                | 12.3                | 79.3                | 0                         | 2.1                | 6              | 42                                          | 71.4                                       |
| <b>Average</b>                      | <b>13</b>           | <b>79.2</b>         | <b>0</b>                  | <b>2.4</b>         | <b>6</b>       | <b>42</b>                                   | <b>71</b>                                  |
| 2.00                                | 13.6                | 78.1                | 0                         | 2                  | 6              | 40                                          | 68.4                                       |
| 2.00                                | 14                  | 78.5                | 0                         | 1.8                | 6              | 41                                          | 67.4                                       |
| 2.00                                | 14.2                | 78.4                | 0                         | 1.9                | 6              | 40                                          | 67                                         |
| <b>Average</b>                      | <b>14</b>           | <b>78.3</b>         |                           | <b>1.9</b>         | <b>6</b>       | <b>40</b>                                   | <b>68</b>                                  |

Figure 4.4 was generated from data in Table 4.4 and shows the effect of varying water to biogas flow rate ratio on percentage CH<sub>4</sub> enrichment for marble packed to a height of 0.4m.



**Figure 4.4: Percentage CH<sub>4</sub> enrichment for marble at 0.4m**

Figure 4.5 was generated from data in Table 4.4 and shows the effect of varying water to biogas flow rate ratio on percentage CO<sub>2</sub> reduction for the marble packed to a height of 0.4m.



**Figure 4.5: Percentage CO<sub>2</sub> reduction for marble at 0.4m**

b) Marble packed to a height of 0.8m

The column was packed with marble to a height of 0.8m and the experiment was run for water biogas flow rate ratios of; 0.25, 0.375, 0.75, 1 and 2 with water at a temperature of 20.5°C and

biogas at a relative pressure of 53cm of H<sub>2</sub>O. The composition, percentage CH<sub>4</sub> enrichment and CO<sub>2</sub> reduction were determined and results were as shown in Table 4.5.

**Table 4.5: Results for marble packed to a depth 0.8m**

| water/gas<br>flow rate<br>ratio | Composition            |                        |                           |                       |                | Percentage<br>CH <sub>4</sub><br>enrichment | Percentage<br>CO <sub>2</sub> Reduction |
|---------------------------------|------------------------|------------------------|---------------------------|-----------------------|----------------|---------------------------------------------|-----------------------------------------|
|                                 | CO <sub>2</sub><br>(%) | CH <sub>4</sub><br>(%) | H <sub>2</sub> S<br>(ppm) | O <sub>2</sub><br>(%) | Balance<br>(%) |                                             |                                         |
| 0.250                           | 19.6                   | 71.5                   | 0                         | 3.0                   | 5.9            | 28.02                                       | 54.42                                   |
| 0.250                           | 19.9                   | 71.0                   | 0                         | 2.1                   | 5.3            | 27.13                                       | 53.72                                   |
| 0.250                           | 20.1                   | 71.3                   | 0                         | 2.5                   | 5.8            | 27.66                                       | 53.26                                   |
| <b>Average</b>                  | <b>19.9</b>            | <b>71.3</b>            | <b>0</b>                  | <b>2.5</b>            | <b>5.7</b>     | <b>27.6</b>                                 | <b>53.8</b>                             |
| 0.375                           | 19.5                   | 71.0                   | 0                         | 2.8                   | 6.5            | 27.13                                       | 54.65                                   |
| 0.375                           | 19.7                   | 72.4                   | 0                         | 2.2                   | 6.7            | 29.63                                       | 54.19                                   |
| 0.375                           | 18.0                   | 73.6                   | 0                         | 2.0                   | 6.2            | 31.78                                       | 58.14                                   |
| <b>Average</b>                  | <b>19.1</b>            | <b>72.3</b>            | <b>0</b>                  | <b>2.3</b>            | <b>6.5</b>     | <b>29.51</b>                                | <b>55.66</b>                            |
| 0.750                           | 17.0                   | 76.5                   | 0                         | 1.8                   | 4.7            | 36.97                                       | 60.47                                   |
| 0.750                           | 16.6                   | 76.5                   | 0                         | 1.8                   | 5.1            | 36.97                                       | 61.40                                   |
| 0.750                           | 17.0                   | 76.1                   | 0                         | 1.8                   | 5.4            | 36.26                                       | 60.47                                   |
| <b>Average</b>                  | <b>16.9</b>            | <b>76.4</b>            | <b>0</b>                  | <b>1.8</b>            | <b>5.1</b>     | <b>36.74</b>                                | <b>60.78</b>                            |
| 1.000                           | 15.5                   | 76.7                   | 0                         | 1.8                   | 6.0            | 37.33                                       | 63.95                                   |
| 1.000                           | 16.0                   | 76.5                   | 0                         | 1.8                   | 5.7            | 36.97                                       | 62.79                                   |
| 1.000                           | 15.8                   | 76.5                   | 0                         | 1.9                   | 5.9            | 36.97                                       | 63.26                                   |
| <b>Average</b>                  | <b>15.8</b>            | <b>76.6</b>            | <b>0</b>                  | <b>1.8</b>            | <b>5.9</b>     | <b>37.09</b>                                | <b>63.33</b>                            |
| 2.000                           | 14.9                   | 78.9                   | 0                         | 1.1                   | 5.1            | 41.27                                       | 65.35                                   |
| 2.000                           | 14.6                   | 79.4                   | 0                         | 1.6                   | 4.7            | 42.17                                       | 66.05                                   |
| 2.000                           | 14.7                   | 79.0                   | 0                         | 1.5                   | 4.9            | 41.45                                       | 65.81                                   |
| <b>Average</b>                  | <b>14.7</b>            | <b>79.1</b>            | <b>0</b>                  | <b>1.4</b>            | <b>4.9</b>     | <b>41.6</b>                                 | <b>65.7</b>                             |

Figure 4.6 was generated from the data in Table 4.5 and shows the the effect of varying water to gas flow rate ratio on  $\text{CH}_4$  enrichment for mable packed to 0.8m.

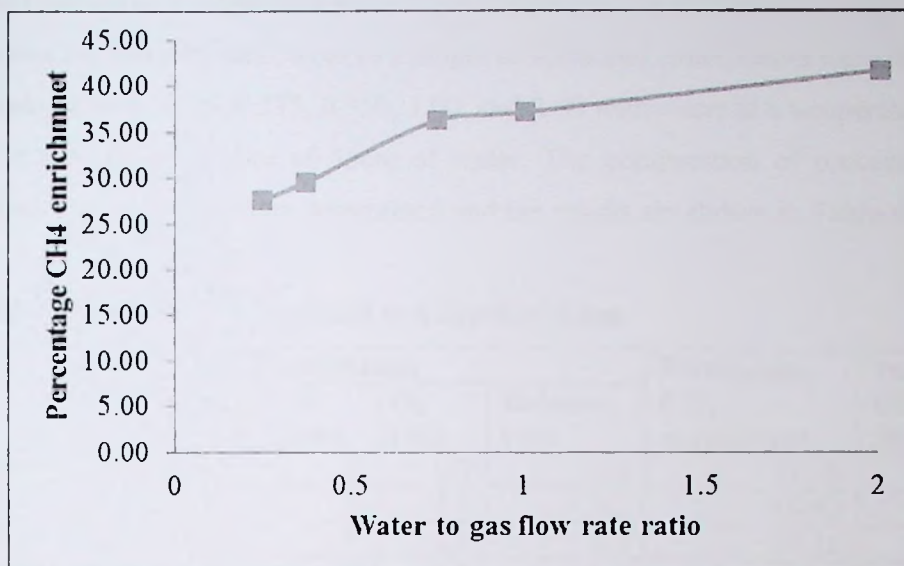


Figure 4.6: Percentage  $\text{CH}_4$  enrichment for marble at 0.8m

Figure 4.7 is generated from Table 4.5 and shows the effect of varying water gas to flow rate ratio on percentage  $\text{CO}_2$  reduction.

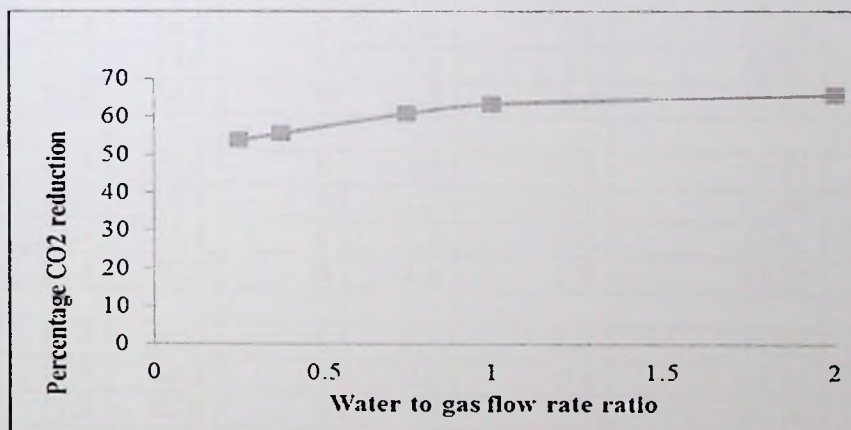


Figure 4.7: Percentage  $\text{CO}_2$  reduction for marble packed to 0.8m

#### 4.4.3 Experiment with Steel Wool as Packing Material

Experiments were performed with the column packed with steel wool to a height of 0.4m and 0.8m. The composition, CH<sub>4</sub> enrichment and CO<sub>2</sub> reduction were determined.

##### a) Steel wool packed to a height of 0.4m

The column was packed with steel wool to a height of 0.4m and experiments were run with water to gas flow rate ratios of 0.25, 0.375, 0.750, 1.00, and 2.00 with water at a temperature of 20.6°C and biogas at a relative pressure of 55cm of water. The composition of processed gas, CH<sub>4</sub> enrichment and CO<sub>2</sub> reduction were determined and the results are shown in Table 4.6.

Table 4.6: Results for steel wool packed to a depth of 0.4m

| water/gas<br>flow rate<br>ratio | Composition            |                        |                           |                       |                | Percentage<br>CH <sub>4</sub><br>enrichment | Percentage<br>CO <sub>2</sub><br>Reduction |
|---------------------------------|------------------------|------------------------|---------------------------|-----------------------|----------------|---------------------------------------------|--------------------------------------------|
|                                 | CO <sub>2</sub><br>(%) | CH <sub>4</sub><br>(%) | H <sub>2</sub> S<br>(ppm) | O <sub>2</sub><br>(%) | Balance<br>(%) |                                             |                                            |
| 0.250                           | 33.2                   | 65.5                   | 0                         | 0.9                   | 0.6            | 17.28                                       | 22.79                                      |
| 0.250                           | 33.3                   | 65.3                   | 0                         | 1.1                   | 0.2            | 16.92                                       | 22.56                                      |
| 0.250                           | 33.5                   | 65.5                   | 0                         | 0.8                   | 0.3            | 17.28                                       | 22.09                                      |
| <b>Average</b>                  | <b>33.3</b>            | <b>65.4</b>            | <b>0</b>                  | <b>0.9</b>            | <b>0.4</b>     | <b>17.16</b>                                | <b>22.48</b>                               |
| 0.375                           | 32.4                   | 66.4                   | 0                         | 0.9                   | 0.4            | 18.89                                       | 24.65                                      |
| 0.375                           | 32.3                   | 66.2                   | 0                         | 1.0                   | 0.1            | 18.53                                       | 24.88                                      |
| 0.375                           | 32.2                   | 66.6                   | 0                         | 1.0                   | 0.5            | 19.25                                       | 25.12                                      |
| <b>Average</b>                  | <b>32.3</b>            | <b>66.4</b>            | <b>0</b>                  | <b>1.0</b>            | <b>0.3</b>     | <b>18.89</b>                                | <b>24.88</b>                               |
| 0.750                           | 22.7                   | 74.1                   | 0                         | 1.3                   | 1.8            | 32.68                                       | 47.21                                      |
| 0.750                           | 22.8                   | 74.2                   | 0                         | 1.2                   | 1.8            | 32.86                                       | 46.98                                      |
| 0.750                           | 22.9                   | 73.9                   | 0                         | 1.8                   | 2.4            | 32.32                                       | 46.74                                      |
| <b>Average</b>                  | <b>22.8</b>            | <b>74.1</b>            | <b>0</b>                  | <b>1.4</b>            | <b>2.0</b>     | <b>32.62</b>                                | <b>46.98</b>                               |
| 1.000                           | 21.5                   | 74.8                   | 0                         | 1.3                   | 2.6            | 33.93                                       | 50.00                                      |
| 1.000                           | 21.2                   | 74.5                   | 0                         | 1.6                   | 2.6            | 33.39                                       | 50.70                                      |
| 1.000                           | 21.5                   | 74.8                   | 0                         | 1.2                   | 2.6            | 33.93                                       | 50.00                                      |
| <b>Average</b>                  | <b>21.4</b>            | <b>74.7</b>            | <b>0</b>                  | <b>1.4</b>            | <b>2.6</b>     | <b>33.75</b>                                | <b>50.23</b>                               |
| 2.000                           | 11.9                   | 80.4                   | 0                         | 2.1                   | 6.4            | 43.96                                       | 72.33                                      |
| 2.000                           | 11.7                   | 80.4                   | 0                         | 2.0                   | 5.6            | 43.96                                       | 72.79                                      |
| 2.000                           | 11.7                   | 80.5                   | 0                         | 1.9                   | 5.9            | 44.14                                       | 72.79                                      |
| <b>Average</b>                  | <b>11.8</b>            | <b>80.4</b>            | <b>0</b>                  | <b>2.0</b>            | <b>6.0</b>     | <b>44.02</b>                                | <b>72.64</b>                               |

Figure 4.8 was generated from data in Table 4.6 and shows the the effect of varying water gas flow rate ratio on the percentage CH<sub>4</sub> enrichment for steel wool packed to a height of 0.4m.

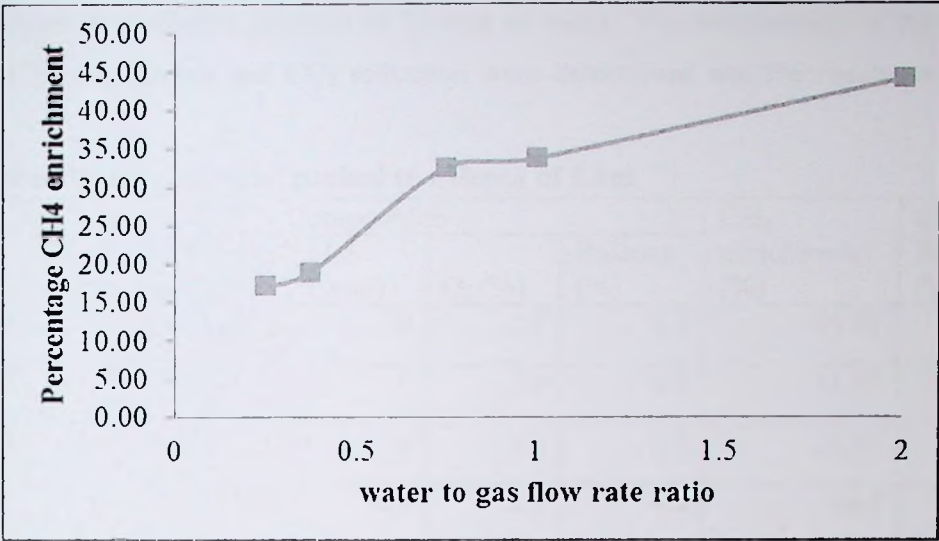


Figure 4.8: Percentage CH<sub>4</sub> enrichment for steel wool at 0.4m

Figure 4.9 was generated from data in Table 4.6 and shows the effect of varying water to gas flow rate ratio on percentage CO<sub>2</sub> reduction.

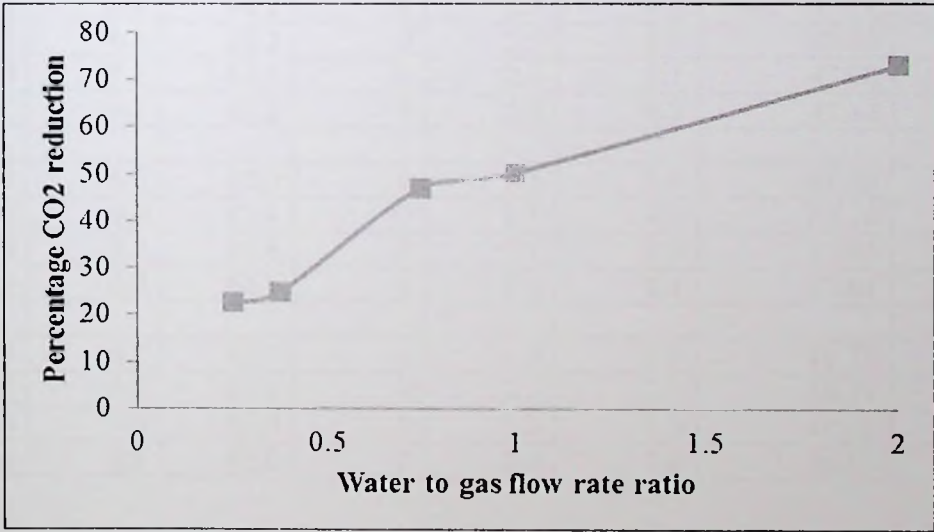


Figure 4.9: Percentage CO<sub>2</sub> reduction for steel wool at 0.4m

b) Steel wool packed to a height of 0.8m

The column was packed with steel wool to a height of 0.8m and experiments were carried out for water to gas flow rate ratios of; 0.25, 0.375, 0.750, 1.00 and 2.00 with water at a temperature of 20°C and biogas at a relative pressure of 53.6cm of water. The composition of processed gas, percentage CH<sub>4</sub> enrichment and CO<sub>2</sub> reduction were determined and the results are shown in Table 4.7.

**Table 4.7: Results for steel wool packed to a depth of 0.8m**

| water/gas<br>flow rate<br>ratio | Composition            |                        |                           |                    |                | CH <sub>4</sub><br>enrichment<br>(%) | CO <sub>2</sub><br>Reduction<br>(%) |
|---------------------------------|------------------------|------------------------|---------------------------|--------------------|----------------|--------------------------------------|-------------------------------------|
|                                 | CO <sub>2</sub><br>(%) | CH <sub>4</sub><br>(%) | H <sub>2</sub> S<br>(ppm) | O <sub>2</sub> (%) | Balance<br>(%) |                                      |                                     |
| 0.25                            | 18.0                   | 75.1                   | 0                         | 2.7                | 4.2            | 34.47                                | 58.14                               |
| 0.25                            | 17.8                   | 75.2                   | 0                         | 2.9                | 4.4            | 34.65                                | 58.60                               |
| 0.25                            | 17.9                   | 75.2                   | 0                         | 3.0                | 3.9            | 34.65                                | 58.37                               |
| <b>Average</b>                  | <b>17.9</b>            | <b>75.2</b>            | <b>0.0</b>                | <b>2.9</b>         | <b>4.2</b>     | <b>34.6</b>                          | <b>58.4</b>                         |
|                                 |                        |                        |                           |                    |                |                                      |                                     |
| 0.375                           | 16.9                   | 76.9                   | 0                         | 1.4                | 4.9            | 37.69                                | 60.70                               |
| 0.375                           | 17.5                   | 76.8                   | 0                         | 1.2                | 4.7            | 37.51                                | 59.30                               |
| 0.375                           | 15.3                   | 76.9                   | 0                         | 1.8                | 6.0            | 37.69                                | 64.42                               |
| <b>Average</b>                  | <b>16.6</b>            | <b>76.9</b>            | <b>0</b>                  | <b>1.5</b>         | <b>5.2</b>     | <b>37.63</b>                         | <b>61.47</b>                        |
|                                 |                        |                        |                           |                    |                |                                      |                                     |
| 0.750                           | 6.4                    | 82.2                   | 0                         | 2.7                | 8.8            | 47.18                                | 85.12                               |
| 0.750                           | 6.4                    | 82.2                   | 0                         | 2.5                | 8.9            | 47.18                                | 85.12                               |
| 0.750                           | 6.4                    | 82.1                   | 0                         | 2.6                | 9.1            | 47.00                                | 85.12                               |
| <b>Average</b>                  | <b>6.4</b>             | <b>82.2</b>            | <b>0</b>                  | <b>2.6</b>         | <b>8.9</b>     | <b>47.12</b>                         | <b>85.12</b>                        |
|                                 |                        |                        |                           |                    |                |                                      |                                     |
| 1.000                           | 6.2                    | 82.9                   | 0                         | 2.5                | 8.4            | 48.43                                | 85.58                               |
| 1.000                           | 6.0                    | 82.2                   | 0                         | 2.5                | 9.4            | 47.18                                | 86.05                               |
| 1.000                           | 5.8                    | 82.6                   | 0                         | 2.7                | 8.9            | 47.90                                | 86.51                               |
| <b>Average</b>                  | <b>6.0</b>             | <b>82.6</b>            | <b>0</b>                  | <b>2.6</b>         | <b>8.9</b>     | <b>47.84</b>                         | <b>86.05</b>                        |
|                                 |                        |                        |                           |                    |                |                                      |                                     |
| 2.000                           | 6.7                    | 83.1                   | 0                         | 2.3                | 7.9            | 48.79                                | 84.42                               |
| 2.000                           | 6.9                    | 83.1                   | 0                         | 2.3                | 7.7            | 48.79                                | 83.95                               |
| 2.000                           | 7.0                    | 82.9                   | 0                         | 2.3                | 7.9            | 48.43                                | 83.72                               |
| <b>Average</b>                  | <b>6.9</b>             | <b>83.0</b>            | <b>0</b>                  | <b>2.3</b>         | <b>7.8</b>     | <b>48.67</b>                         | <b>84.03</b>                        |

Figure 4.10 was generated from data in Table 4.7 and shows the effect of varying water to gas to flow rate ratio on percentage CH<sub>4</sub> enrichment for steel wool packed to a height of 0.8m.

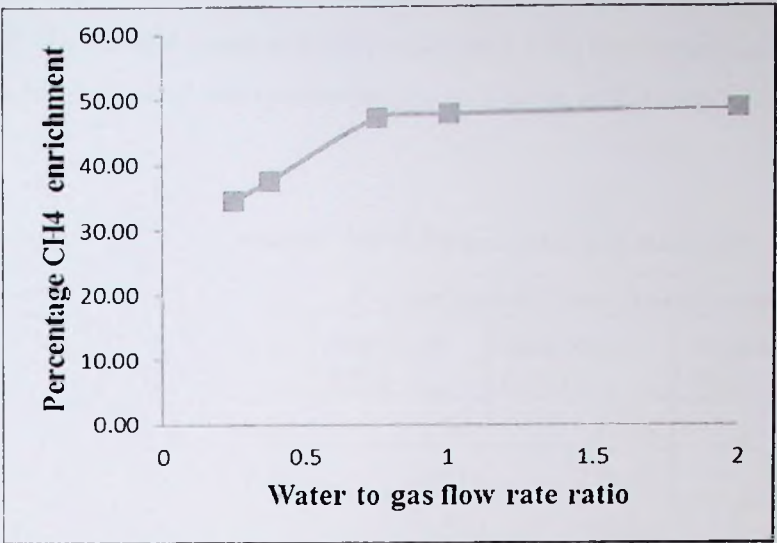


Figure 4.10: Percentage CH<sub>4</sub> enrichment for steel wool at 0.8m

Figure 4.11 was generated from data in Table 4.7 and shows the effect of varying water to gas to flow rate ratio on CO<sub>2</sub> reduction for steel wool packed to a height of 0.8m.

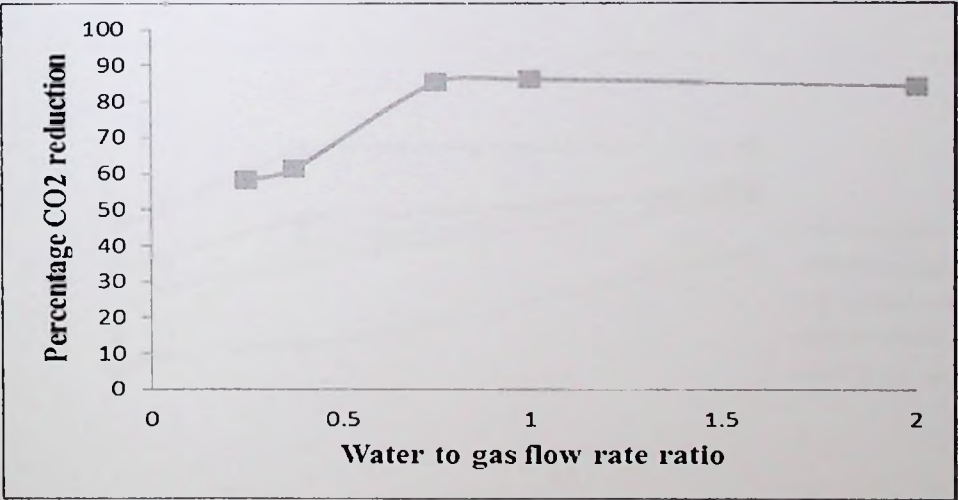


Figure 4.11: Percentage CO<sub>2</sub> reduction for steel wool at 0.8m

#### 4.4.4 Comparative Analysis

A comparative analysis was done between the different packing materials at similar water to gas flow rate ratios. The Table 4.8 below shows percentage CH<sub>4</sub> enrichment at similar water to gas flow rate ratios for steel wool and marble packed to a depth of 0.4 and 0.8m, and for unpacked column.

Table 4.8: Percentage CH<sub>4</sub> enrichment for different packing materials and depth

| water /gas flow rate ratio | Percentage methane enrichment |                |                    |                |                 |
|----------------------------|-------------------------------|----------------|--------------------|----------------|-----------------|
|                            | Steel wool at 0.8m            | Marble at 0.8m | Steel wool at 0.4m | Marble at 0.4m | Unpacked column |
| 0.250                      | 34.65                         | 27.6           | 17.16              | 19.5           | 11.10           |
| 0.375                      | 37.63                         | 29.51          | 18.89              | 24.7           | 13.80           |
| 0.750                      | 47.12                         | 36.26          | 32.62              | 28.47          | 16.37           |
| 1.000                      | 47.84                         | 37.09          | 33.75              | 31.7           | 17.99           |
| 2.000                      | 48.69                         | 41.6           | 44.02              | 40.3           | 31.96           |

Figure 4.12 shows a comparison of percentage CH<sub>4</sub> enrichment for steel wool and marble packed to a depth of 0.8m.

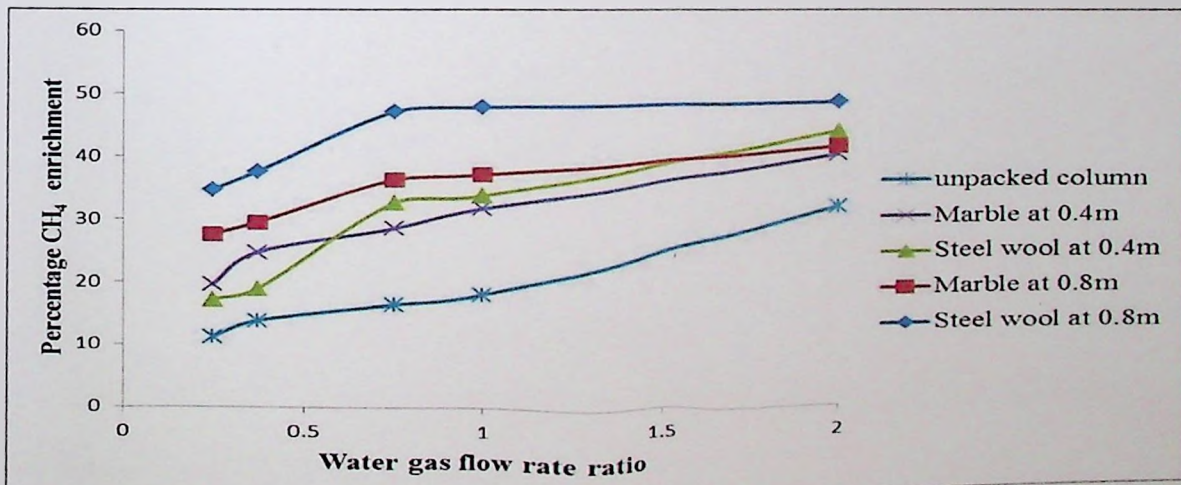


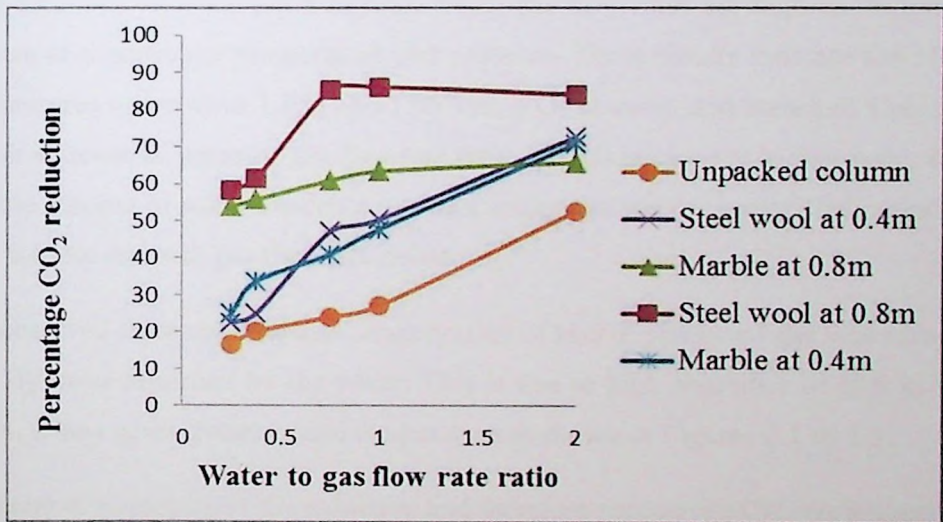
Figure 4.12: Percentage CH<sub>4</sub> enrichment for different packing materials and depth

Table 4.9 shows the percentage CO<sub>2</sub> reduction at similar water to gas flow rate ratios for steel wool and marble packed to a depth of 0.4 and 0.8m, and for unpacked column.

**Table 4.9: Percentage CO<sub>2</sub> reduction for different packing materials and depth**

| water gas flow rate ratio | Percentage CO <sub>2</sub> reduction |                |                    |                |                 |
|---------------------------|--------------------------------------|----------------|--------------------|----------------|-----------------|
|                           | Steel wool at 0.8m                   | Marble at 0.8m | Steel wool at 0.4m | Marble at 0.4m | Unpacked column |
| 0.250                     | 58.40                                | 53.80          | 22.48              | 25.0           | 16.50           |
| 0.375                     | 61.70                                | 55.66          | 24.88              | 33.6           | 20.00           |
| 0.750                     | 85.12                                | 60.78          | 40.91              | 45.8           | 23.98           |
| 1.000                     | 86.05                                | 63.33          | 50.23              | 47.6           | 26.98           |
| 2.000                     | 84.03                                | 65.70          | 72.64              | 70.8           | 52.48           |

Figure 4.13 shows the percentage CO<sub>2</sub> reduction at similar water gas flow rate ratios for steel wool and marble packed to a height of 0.8 and 0.4m.



**Figure 4.13: Percentage CO<sub>2</sub> reduction for different packing materials and depth**

#### 4.5 Discussion of Experimental Results

The results of the study indicate that water Scrubbing technology can be used to upgrade biogas to more than 80% CH<sub>4</sub> content without the use of external energy inputs in the form of electricity for biogas compression and water pumping. This disagrees with results obtained by Rasi et al

(2008) which showed that it is not possible to achieve CH<sub>4</sub> content of 80% and above without compressing the gas to at least 10 bars. This is probably because his experiments were carried out at low water to gas flow rate ratios of less than 0.25. The degree of CH<sub>4</sub> enrichment was found to be influenced by a number of factors. These include; the flow rate of water and biogas, type of packing material and depth of packing material. The effects of these on the effectiveness and efficiency of the biogas Scrubbing process are discussed in the sections that follow.

#### **4.5.1 Effect of Water and Biogas Flow Rate on the Effectiveness of the Process**

The results indicate that for any given gas flow rate, percentage CO<sub>2</sub> reduction and resulting percentage CH<sub>4</sub> enrichment increase with increase in water flow rate. This is in agreement with research results obtained by Vijay et al. (2006); and Wellinger & Lindberg (1999). Generally, the increase in CH<sub>4</sub> content in processed gas is due to dissolution of CO<sub>2</sub> in water leaving CH<sub>4</sub> in the gas phase. This is possible because at any temperature and pressure, CO<sub>2</sub> is more soluble in water than CH<sub>4</sub> as shown in Figure 2.1 and 2.2. Also at constant water flow rate, the percentage CH<sub>4</sub> enrichment and CO<sub>2</sub> reduction decrease with an increase in gas flow rate because more gas is in contact with less water hence the absorption of CO<sub>2</sub> in water is less effective. This is due to water being saturated with CO<sub>2</sub> at a fast rate when gas flow rates are high as compared to low gas flow rates at a particular temperature and pressure. These results indicate that, for the low operating pressures of between 1.052 and 1.057bar, CO<sub>2</sub> removal and therefore CH<sub>4</sub> enrichment increase with increase in water to gas flow rate ratio. This is because at higher water to gas flow rate ratios, the amount of water available to a unit amount of gas for a specified period of time is higher than for low water to gas flow rate ratios.

It was also observed from the data that concentration of H<sub>2</sub>S in processed gas was zero indicating that all the H<sub>2</sub>S was absorbed by the water. This is due to high solubility of H<sub>2</sub>S in water than CO<sub>2</sub> and CH<sub>4</sub> at any given pressure and temperature as shown in Figures 2.1 to 2.3.

Further, the rate of percentage CO<sub>2</sub> reduction and therefore percentage CH<sub>4</sub> enrichment increases up to a water to gas flow rate ratio of up to 0.75 for the packed column and then lowers for water to gas flow rate ratio of above 0.75 as shown in Tables 4.4, to 4.6 and Figures 4.4 to 4.10. This is an indication that for a fixed gas flow rate, the amount of CO<sub>2</sub> absorbed by a unit amount of

water for a given time is greater for lower water to gas flow rate ratios of up to 0.75 and reduces their after. For example, for steel wool packed to a depth 0.8m as shown in Figure 4.10, a raise in percentage CH<sub>4</sub> enrichment of 9% at water to gas flow rate ratio of below 0.75 would require 0.25m<sup>3</sup> of water for 1m<sup>3</sup> of biogas while for water to gas flow rate ratio of above 0.75, a raise in percentage CH<sub>4</sub> enrichment of 0.71% would require the same amount water. This implies that it may not be viable to go beyond water to gas flow rate ratios of 0.75 most especially if water is a costly resource. However if water is a free or very cheap resource, then it might be viable using water to gas flow rate ratios beyond 0.75.

#### **4.5.2 Effect of Type of Packing Material on the Effectiveness of the Process**

The results shown in Tables 4.3 to 4.6 and Figure 4.2 to 4.9 indicate that a packed column is more effective than an unpacked one. This is because a packed column provides a high-surface-area and allows for efficient contact between the water and gas phases in a countercurrent absorption process, promotes uniform liquid distribution on the packing surface and vapor gas flow across the column cross section. This explains why Chandra et al (2012), Rasi et al (2008) and Vijay et al. (2006) among others have designed water scrubbing systems with packed columns. A comparison between percentage CO<sub>2</sub> absorption and CH<sub>4</sub> enrichment results for similar water to gas ratios as shown in Figure 4.4 to 4.11 show that CO<sub>2</sub> absorption and therefore CH<sub>4</sub> enrichment is dependent on the type and nature of packing material. Steel wool therefore, performs better than marble because for steel wool all the gas is in contact with water thereby providing a larger surface area for absorption of CO<sub>2</sub>, steel wool has a structure as shown in Table 3.2 provide low resistance to flow of gas because it has an open structure hence low pressure drops. It can be concluded that steel wool performs better than marble.

#### **4.5.3 Effect of Packing Material Depth on the Effectiveness of the Process**

The results show that CH<sub>4</sub> content in processed gas increases with packing depth for the same type of packing material as observed in Figure 4.12 where the CH<sub>4</sub> enrichment for both marble and steel wool at 0.8m is higher than at 0.4m. This is due to; higher contact time between biogas and water provided by the packing material of higher depth and better distribution of water provided by higher depth packing. Thus, almost all the gas is in contact with water and larger

surface area for absorption of CO<sub>2</sub>. For example at a water to gas flow rate ratio of 0.25, the percentage CH<sub>4</sub> enrichment increased from 19% at 0.4m packing depth to 29% at 0.8m packing depth for marble as packing material. From this section, it can be concluded that higher packing depth of the column performs better than low packed column.

#### 4.5.4 Impact of Flow Rate Ratios on Water Cost and Annual Potential Power Revenue

Since the current research was limited to water scrubbing system that is not supported by an external energy source, the pressure of the gas was taken as that developed by the fixed dome digester. It was not altered through compression. Additionally, no water pump was used. Water pressure used was that developed in the overhead tank. Therefore, the biggest variable cost in the water scrubbing process under these circumstances was water. The potential electricity generation, water consumption, water cost and annual revenue were estimated based on the assumption that 15m<sup>3</sup> of biogas is generated daily; 65% of the gas is available after upgrading because un-upgraded biogas contains 71ppm of H<sub>2</sub>S and 43% of CO<sub>2</sub> of which are trapped in exhaust water during upgrading. Therefore, after upgrading most of CO<sub>2</sub> and almost all H<sub>2</sub>S is absorbed in the exhaust water. Marble and steel packed to a depth of 0.8m gave the best CH<sub>4</sub> enrichment therefore, the investigation was based on these two. The assumptions in table 4.10 were used to estimate the annual water cost and potential electricity revenue at different water to gas flow rates ratios.

Table 4.10: Assumptions for determining annual water cost and potential electricity revenue

| Parameter                                                                        | Value | Source                                                                                                       |
|----------------------------------------------------------------------------------|-------|--------------------------------------------------------------------------------------------------------------|
| Annual number of operating days                                                  | 365   |                                                                                                              |
| Generator efficiency (%)                                                         | 25    | Viquez (2009)                                                                                                |
| Potential electricity per 1m <sup>3</sup> of biogas at 65% CH <sub>4</sub> (kWh) | 6     | Elmar (2010)                                                                                                 |
| Cost of electricity per kWh (Ug. Shs)                                            | 600   | UMEME(an energy distribution company in Uganda)                                                              |
| Cost of water per m <sup>3</sup> (Ug. Shs)                                       | 2200  | National Water Sewerage Corporation (NWSC)-a body responsible for water treatment and distribution in Uganda |

The annual volume of biogas upgraded =  $365 \times 15 = 5475\text{m}^3$ . If all the gas is upgraded and used for electricity generation, then the volume of gas available after upgrading =  $0.65 \times 5475 = 3559\text{m}^3$ .

The annual water consumption was computed using equation 4.1.

$$\text{Water consumption} = \text{quantity of gas} \times \text{water to gas flow rate ratio} \quad 4.1$$

The annual power revenue was computed using equation 4.2.

$$\text{Potential annual power} = \frac{\text{CH}_4 \text{ content} \times 6 \times 3559}{65} \quad 4.2$$

The annual power revenue was computed using equation 4.3.

$$\text{Annual power revenue} = \text{potential power revenue} \times 600 \quad 4.3$$

The annual water cost was computed using equation 4.4.

$$\text{Water cost} = \text{water consumption} \times 2200 \quad 4.4$$

The potential power per unit water consumption was computed using equation 4.5.

$$\text{Potential annual power per unit water consumption} = \frac{\text{Potential annual power}}{\text{water consumption}} \quad 4.5$$

The annual power revenue per unit water consumption was computed using equation 4.6.

$$\text{Annual power revenue per unit water cost} = \frac{\text{Annual power revenue}}{\text{water cost}} \quad 4.6$$

The water consumption and cost; and potential power generated and revenue; potential annual power per unit water consumption and annual power revenue per unit water cost for marble at 0.8m were computed using equations 4.1 to 4.6 and recorded in Table 4.11.

**Table 4.11: Effect of water cost on annual power revenue for marble at 0.8m**

| Water/gas flow rate ratio | Water used (m <sup>3</sup> ) | Water cost (Ug. Shs) | CH <sub>4</sub> (%) | Potential annual power (kWh) | Annual power revenue (ugx) | Potential annual power per unit water used (kWh/m <sup>3</sup> ) | Annual power revenue per unite water cost |
|---------------------------|------------------------------|----------------------|---------------------|------------------------------|----------------------------|------------------------------------------------------------------|-------------------------------------------|
| 0.25                      | 1369                         | 3,010,700            | 71.3                | 5856                         | 3,513,554                  | 4.3                                                              | 1.17                                      |
| 0.375                     | 2053                         | 4,516,050            | 72.3                | 5938                         | 3,562,833                  | 2.9                                                              | 0.79                                      |
| 0.750                     | 4106                         | 9,032,100            | 76.4                | 6275                         | 3,764,874                  | 1.5                                                              | 0.42                                      |
| 1.000                     | 5474                         | 12,042,800           | 76.6                | 6291                         | 3,774,730                  | 1.1                                                              | 0.31                                      |
| 2.000                     | 10948                        | 24,085,600           | 79.1                | 6497                         | 3,897,926                  | 0.6                                                              | 0.16                                      |

The water consumption and cost; potential power generated and revenue; potential annual power per unit water consumption and annual power revenue per unit water cost for steel wool at 0.8m were computed using equations 4.1 to 4.6 and recorded in Table 4.12.

**Table 4.12: Effect of water cost on annual power revenue for steel wool at 0.8m**

| Water/gas flow rate ratio | Water used (m <sup>3</sup> ) | Water cost (ugx) | CH <sub>4</sub> (%) | Potential Annual power (kWh) | Annual power revenue (ugx) | Potential annual power per unit water used (kWh/m <sup>3</sup> ) | Annual power revenue per unite water cost |
|---------------------------|------------------------------|------------------|---------------------|------------------------------|----------------------------|------------------------------------------------------------------|-------------------------------------------|
| 0.25                      | 1369                         | 3,010,700        | 75.2                | 6176                         | 3,705,740                  | 4.5                                                              | 1.23                                      |
| 0.375                     | 2053                         | 4,516,050        | 76.9                | 6316                         | 3,789,514                  | 3.1                                                              | 0.84                                      |
| 0.750                     | 4106                         | 9,032,100        | 82.2                | 6751                         | 4,050,690                  | 1.6                                                              | 0.45                                      |
| 1.000                     | 5474                         | 12,042,800       | 82.6                | 6784                         | 4,070,401                  | 1.2                                                              | 0.34                                      |
| 2.000                     | 10948                        | 24,085,600       | 83.0                | 6817                         | 4,090,112                  | 0.6                                                              | 0.17                                      |

From Figure 4.11 and 4.12, it is observed that annual water cost and electricity revenue increases with water gas flow rate ratio. At a water to gas flow rate ratio of less than 0.25, the water consumption cost is less than electricity revenue while above 0.25 the water cost is higher than electricity revenue that could be generated. Therefore water gas flow rate ratio has to be kept as low as possible to optimize system performance. This is evident from the high potential annual power per unit water consumption and annual power revenue per unit water cost at water gas flow rate ratios of 0.25 as shown in Table 4.11 and 4.12.

The annual electricity revenue for cleaned gas was computed as shown below for comparison purposes with upgraded gas.

$$\text{Annual potential electricity} = \frac{5475 \times 0.25 \times 55.85 \times 6}{65} = 7056 \text{ kWh, where } 55.85\% \text{ CH}_4 \text{ in raw gas}$$

$$\text{Annual electricity revenue} = 7056 \times 600 = 4,233,600/ =$$

The 4,233,600/= obtained for cleaned biogas does not involve costs of water while for the upgraded biogas it involves water cost. Based on this, generation of electricity from upgraded biogas may not be viable when water is to be purchased at the price indicated in Table 4.10. However, if the water source is available and cheaper than the price in Table 4.10 or provision for regenerating the exhaust water, electricity generation from upgraded biogas could be viable.

Upgrading of biogas could be viable when it is to be utilized in generating a more modern form of energy such as electricity or for use in vehicles as fuel. It could be also possible in places such as schools and hospitals where direct lighting using biogas lamps is a safety hazard; in places where there is excess of biogas such that heating and lighting cannot fully utilize all the generated biogas; and places where biogas has to be packed and transported for ex-situ use.

## CHAPTER 5 : CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

The main objective of the research was to upgrade biogas using water scrubbing. With specific objectives; determining the characteristics for raw biogas, designing and constructing the water scrubbing system, and determining values of scrubber system operating parameters that would result in CH<sub>4</sub> content of in upgraded biogas of 80%.

Water scrubbing system that is free from leakage and flooding was designed and constructed. It was also designed in such a way that it is possible to incorporate and change packing material type and depth. This system was able to raise the CH<sub>4</sub> content to over 80% from 55.86%. This output signifies a CH<sub>4</sub> enrichment of 43.22%.

From the research, it can be concluded that percentage CO<sub>2</sub> reduction and therefore CH<sub>4</sub> enrichment increases with increase in water to gas flow rate ratio. It was also concluded that CO<sub>2</sub> reduction and therefore CH<sub>4</sub> enrichment is higher for packed columns than unpacked ones and is also dependent on type and characteristics of packing material. Steel wool performs better than all the other types of packing materials that were investigated during the experiments. It was also observed that CO<sub>2</sub> reduction and therefore CH<sub>4</sub> enrichment is dependent on depth of packing therefore it increases with packing depth.

Water to gas flow rate ratio has a great impact on water cost and revenue that can be generated from power. It can therefore be concluded that the revenue per unit water cost is higher at low water to gas flow rate ratios hence the water to gas flow rate ratio has to be kept as low as possible.

Based on the results, the water scrubbing system operating parameters for obtaining methane content of 80% was determined. The parameters for obtaining this percentage at 1.0589bar and water temperature of 21.5°C were steel wool packed to a depth of 0.4m and 0.8m at water to gas flow rate ratio of 1.9 and 0.7 respectively. While for marble packed to a depth of 0.4m and 0.8m

this percentage could be achieved at water to gas flow rate ratio of greater than 2. It can also be concluded that under pressures of between 1.059 and 1.046bar of water built within the fixed dome digester, it is possible to raise the methane content from 55.85% to over 80%.

## 5.2 Recommendations

The following recommendations can be drawn for use of water scrubbing system

1. The use of water scrubbing technology for biogas upgrading such that biogas can be used for decentralized electricity generation rather than relying on hydroelectricity and fossil fuels.
2. Upgrading of biogas at water to gas flow rate ratios of 0.75 and below since a higher CH<sub>4</sub> enrichment is realized at water to gas flow rate ratio of 0.75 and below than above.
3. Upgrading of biogas at very low water to gas flow rate ratios since they give a higher potential annual power to water consumption and therefore a higher annual power revenue per unit water cost.

The following are the recommendations for further research

1. In order to avoid pressure fluctuations during experiments, it is recommended that further research on water scrubbing equipment with the use floating cover digester instead of a fixed dome digester without using a compressor and a pump.
2. The upgrading process could be investigated using a multi-stage biogas upgrading at low water flow rates rather than single stage at higher water flow since the increase was observed to be low

## 5.3 Limitations

During this research, the following problems were faced;

- Access or permission to carryout experiments for longer period of time during the research. Even when permission was granted to carryout experiments, it was not possible to request users to completely abandon its use for the entire three month that were spent on site. This limited maximum gas pressure to 1.0589bar.

- Because the researcher was using a fixed dome digester, it was not possible to control digester pressure. The pressure decreases with use of biogas and it would change from 1.0589 to 1.046bar.
- It was also not possible to achieve water to gas flow rate ratios of less than 0.25 since the maximum gas flow rate that could be achieved was 6litre/minute and least flow rate of water was 1.5litre/minute.

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## APPENDICES

### Appendix 1: Composition of processed Gas Raw Data without Packing Material

| Temperature of water (°C) | Water flow rate (l/min) | Biogas flow rate (l/min) | P (cm H <sub>2</sub> O) | Composition         |                     |                    |             |
|---------------------------|-------------------------|--------------------------|-------------------------|---------------------|---------------------|--------------------|-------------|
|                           |                         |                          |                         | CO <sub>2</sub> (%) | CH <sub>4</sub> (%) | O <sub>2</sub> (%) | Balance (%) |
| 23.9                      | 4                       | 6                        | 60                      | 20.2                | 35.1                | 8.9                | 36.0        |
|                           | 4                       | 6                        |                         | 23.1                | 42.0                | 6.9                | 28          |
|                           | 4                       | 6                        |                         | 23.8                | 45                  | 6.3                | 24          |
|                           | 4                       | 6                        |                         | 24.4                | 51                  | 5.2                | 20          |
|                           | 4                       | 6                        |                         | 29.3                | 57                  | 2.9                | 11          |
|                           | 4                       | 6                        |                         | 29.2                | 59.0                | 2.9                | 9.1         |
|                           | 4                       | 6                        |                         | 29.7                | 62                  | 2.1                | 6.4         |
|                           | 4                       | 6                        |                         | 27.6                | 61                  | 2.6                | 9.1         |
|                           | 4                       | 6                        |                         | 25.2                | 64                  | 2.8                | 9.0         |
|                           | 4                       | 6                        |                         | 26.5                | 67                  | 1.8                | 4.9         |
|                           | 4                       | 6                        |                         | 28.7                | 66                  | 1.4                | 3.7         |
|                           | 4                       | 6                        |                         | 31.0                | 66.0                | 1.1                | 2.1         |
|                           | 4                       | 6                        |                         | 31.9                | 65                  | 1.1                | 2.5         |
|                           | 4                       | 6                        |                         | 32.9                | 65                  | 1.1                | 1.5         |
|                           | 4                       | 6                        |                         | 33.5                | 64                  | 0.8                | 1.5         |
|                           | 4                       | 6                        |                         | 30.3                | 63                  | 2.3                | 4.9         |
|                           | 4                       | 6                        |                         | 32.2                | 65                  | 1.1                | 1.8         |
|                           | 4                       | 6                        |                         | 33.5                | 65                  | 1.2                | 1.1         |
|                           | 4                       | 6                        |                         | 33.6                | 65                  | 1.0                | 1.0         |
|                           | 4                       | 6                        |                         | 33.3                | 63                  | 1.2                | 2.2         |
|                           | 4                       | 4                        |                         | 31.4                | 62.0                | 1.8                | 5.0         |
|                           | 4                       | 4                        |                         | 31.6                | 64.0                | 1.3                | 3.0         |
|                           | 4                       | 4                        |                         | 31.2                | 65.4                | 1.1                | 2.4         |
|                           | 4                       | 4                        |                         | 30.5                | 66.1                | 1.5                | 2.1         |
|                           | 4                       | 4                        |                         | 31.4                | 66.5                | 1.0                | 1.3         |
|                           | 4                       | 4                        |                         | 30.4                | 64.9                | 1.5                | 3.2         |
|                           | 4                       | 4                        |                         | 30.8                | 64.7                | 1.4                | 3.1         |
|                           | 4                       | 4                        |                         | 31.6                | 65.7                | 1.0                | 1.5         |
|                           | 4                       | 4                        |                         | 31.2                | 65.5                | 1.4                | 2.0         |
|                           | 4                       | 4                        |                         | 31.2                | 63.0                | 1.3                | 4.5         |
|                           | 4                       | 2                        |                         | 30.7                | 64.8                | 1.2                | 3.5         |
|                           | 4                       | 2                        |                         | 25.4                | 68.3                | 1.7                | 4.8         |
|                           | 4                       | 2                        |                         | 24.8                | 69.1                | 1.5                | 4.9         |

| Temperature of water (°C) | Water flow rate (l/min) | Biogas flow rate (l/min) | P (cm H <sub>2</sub> O) | Composition         |                     |                    |             |
|---------------------------|-------------------------|--------------------------|-------------------------|---------------------|---------------------|--------------------|-------------|
|                           |                         |                          |                         | CO <sub>2</sub> (%) | CH <sub>4</sub> (%) | O <sub>2</sub> (%) | Balance (%) |
|                           | 4                       | 2                        |                         | 23.2                | 69.0                | 1.7                | 6.1         |
|                           | 4                       | 2                        |                         | 22.4                | 70.6                | 1.7                | 5.3         |
|                           | 4                       | 2                        |                         | 22.2                | 72.0                | 1.9                | 4.3         |
|                           | 4                       | 2                        |                         | 21.7                | 72.2                | 1.4                | 4.5         |
|                           | 4                       | 2                        |                         | 21.2                | 73.1                | 1.5                | 4.3         |
|                           | 4                       | 2                        |                         | 21.2                | 73.9                | 1.2                | 3.8         |
|                           | 4                       | 2                        |                         | 20.5                | 72.5                | 1.6                | 5.4         |
|                           | 4                       | 2                        |                         | 20.3                | 74.1                | 1.5                | 4.2         |
|                           | 4                       | 2                        |                         | 20.3                | 73.3                | 1.6                | 4.9         |
|                           | 4                       | 2                        |                         | 21.0                | 73.9                | 1.3                | 3.8         |
|                           | 4                       | 2                        |                         | 20.7                | 73.7                | 1.4                | 4.3         |
|                           | 4                       | 2                        |                         | 21.1                | 73.5                | 1.1                | 4.3         |
|                           | 1.5                     | 6                        |                         | 34.0                | 59.0                | 2.1                | 5.3         |
|                           | 1.5                     | 6                        |                         | 34.4                | 59.7                | 2.0                | 3.9         |
|                           | 1.5                     | 6                        |                         | 35.1                | 60.0                | 1.9                | 2.4         |
|                           | 1.5                     | 6                        |                         | 35.0                | 61.9                | 1.5                | 1.5         |
|                           | 1.5                     | 6                        |                         | 36.0                | 60.7                | 0.5                | 2.6         |
|                           | 1.5                     | 6                        |                         | 35.9                | 61.0                | 0.9                | 2.2         |
|                           | 1.5                     | 6                        |                         | 35.8                | 60.8                | 1.3                | 2.1         |
|                           | 1.5                     | 6                        |                         | 35.9                | 60.8                | 0.9                | 2.3         |
|                           | 1.5                     | 6                        |                         | 35.5                | 60.5                | 1.1                | 2.9         |
|                           | 1.5                     | 4                        |                         | 35.4                | 61.8                | 1.1                | 2.7         |
|                           | 1.5                     | 4                        |                         | 35.0                | 62.8                | 0.9                | 1.3         |
|                           | 1.5                     | 4                        |                         | 34.9                | 63.0                | 1.1                | 1.2         |
|                           | 1.5                     | 4                        |                         | 34.5                | 63.6                | 1.0                | 0.8         |
|                           | 1.5                     | 4                        |                         | 34.8                | 63.1                | 1.3                | 0.7         |
|                           | 1.5                     | 4                        |                         | 33.9                | 63.9                | 0.9                | 1.2         |

Appendix 2: Composition of Processed Gas Raw Data for Mable at 0.4m

| Temperature of water (°C) | Water flow rate (l/minute) | Biogas flow rate (l/minute) | P (cm H <sub>2</sub> O) | Composition         |                     |                        |                    |             |
|---------------------------|----------------------------|-----------------------------|-------------------------|---------------------|---------------------|------------------------|--------------------|-------------|
|                           |                            |                             |                         | CO <sub>2</sub> (%) | CH <sub>4</sub> (%) | H <sub>2</sub> S (ppm) | O <sub>2</sub> (%) | Balance (%) |
| 21                        | 4.0                        | 4                           | 55                      | 21.2                | 74.2                | 0                      | 1.60               | 2.8         |
|                           | 4.0                        | 4                           |                         | 19.8                | 75.8                | 0                      | 1.30               | 3.1         |
|                           | 4.0                        | 4                           |                         | 18.6                | 76.1                | 0                      | 1.50               | 3.8         |
|                           | 4.0                        | 4                           |                         | 18.5                | 75.9                | 0                      | 1.50               | 4.2         |
|                           | 4.0                        | 4                           |                         | 18.2                | 76.3                | 0                      | 1.70               | 3.7         |
|                           | 4.0                        | 4                           |                         | 18.1                | 75.6                | 0                      | 1.50               | 4.8         |
|                           | 4.0                        | 4                           |                         | 17.6                | 76.6                | 0                      | 1.70               | 4.1         |
|                           | 4.0                        | 4                           |                         | 17.3                | 75.8                | 0                      | 1.90               | 5.1         |
|                           | 4.0                        | 4                           |                         | 17.9                | 76.6                | 0                      | 1.50               | 4.0         |
|                           | 4.0                        | 2                           |                         | 16.7                | 76.0                | 0                      | 2.00               | 5.3         |
|                           | 4.0                        | 2                           |                         | 13.1                | 76.6                | 0                      | 2.50               | 8.0         |
|                           | 4.0                        | 2                           |                         | 13.6                | 78.1                | 0                      | 2.00               | 6.3         |
|                           | 4.0                        | 2                           |                         | 14.0                | 78.5                | 0                      | 1.80               | 5.6         |
|                           | 4.0                        | 2                           |                         | 14.2                | 77.5                | 0                      | 1.90               | 6.1         |
|                           | 4.0                        | 2                           |                         | 14.2                | 78.4                | 0                      | 1.90               | 5.5         |
|                           | 4.0                        | 2                           |                         | 13.9                | 77.8                | 0                      | 2.20               | 7.1         |
|                           | 3.5                        | 4                           |                         | 13.8                | 78.7                | 0                      | 2.10               | 5.4         |
|                           | 3.5                        | 4                           |                         | 16.3                | 77.5                | 0                      | 1.80               | 4.4         |
|                           | 3.5                        | 4                           |                         | 18.3                | 76.1                | 0                      | 1.60               | 4.0         |
|                           | 3.5                        | 4                           |                         | 20.0                | 74.1                | 0                      | 1.70               | 4.2         |
|                           | 3.5                        | 4                           |                         | 21.4                | 74.3                | 0                      | 1.40               | 2.8         |
|                           | 3.5                        | 4                           |                         | 22.1                | 72.8                | 0                      | 1.50               | 3.6         |
|                           | 3.5                        | 4                           |                         | 23.0                | 73.7                | 0                      | 1.30               | 2.1         |
|                           | 3.5                        | 4                           |                         | 23.3                | 72.8                | 0                      | 1.30               | 2.7         |
|                           | 3.5                        | 4                           |                         | 23.8                | 71.9                | 0                      | 1.30               | 3.3         |
|                           | 3.5                        | 4                           |                         | 23.9                | 72.8                | 0                      | 1.10               | 2.3         |
|                           | 3.5                        | 4                           |                         | 23.7                | 73.0                | 0                      | 1.20               | 2.1         |
|                           | 3.5                        | 4                           |                         | 23.5                | 73.2                | 0                      | 1.20               | 2.2         |

| Temperature of water (°C) | Water flow rate (l/minute) | Biogas flow rate (l/minute) | P (cm H <sub>2</sub> O) | Composition         |                     |                        |                    |             |
|---------------------------|----------------------------|-----------------------------|-------------------------|---------------------|---------------------|------------------------|--------------------|-------------|
|                           |                            |                             |                         | CO <sub>2</sub> (%) | CH <sub>4</sub> (%) | H <sub>2</sub> S (ppm) | O <sub>2</sub> (%) | Balance (%) |
|                           | 3.5                        | 4                           |                         | 23.3                | 73.3                | 0                      | 1.30               | 2.0         |
|                           | 3.5                        | 4                           |                         | 23.5                | 73.1                | 0                      | 1.40               | 2.1         |
|                           | 3.5                        | 2                           |                         | 13.7                | 76.9                | 0                      | 2.20               | 7.2         |
|                           | 3.5                        | 2                           |                         | 13.2                | 78.4                | 0                      | 2.20               | 6.3         |
|                           | 3.5                        | 2                           |                         | 13.2                | 78.9                | 0                      | 2.00               | 5.6         |
|                           | 3.5                        | 2                           |                         | 13.3                | 79.1                | 0                      | 2.00               | 5.7         |
|                           | 3.5                        | 2                           |                         | 12.7                | 78.6                | 0                      | 2.20               | 6.5         |
|                           | 3.5                        | 2                           |                         | 12.3                | 78.8                | 0                      | 2.30               | 6.8         |
|                           | 3.5                        | 2                           |                         | 12.1                | 79.1                | 0                      | 3.10               | 5.7         |
|                           | 3.5                        | 2                           |                         | 12.3                | 79.3                | 0                      | 2.10               | 6.3         |
|                           | 3.0                        | 2                           |                         | 18.6                | 76.3                | 0                      | 1.40               | 3.9         |
|                           | 3.0                        | 2                           |                         | 16.4                | 75.5                | 0                      | 1.90               | 6.3         |
|                           | 3.0                        | 2                           |                         | 15.8                | 76.4                | 0                      | 1.90               | 6.0         |
|                           | 3.0                        | 2                           |                         | 15.0                | 78.2                | 0                      | 1.90               | 4.9         |
|                           | 3.0                        | 2                           |                         | 15.0                | 78.7                | 0                      | 1.80               | 4.5         |
|                           | 3.0                        | 2                           |                         | 14.8                | 78.7                | 0                      | 1.60               | 5.2         |
|                           | 3.0                        | 2                           |                         | 14.5                | 78.4                | 0                      | 1.90               | 4.9         |
|                           | 3.0                        | 2                           |                         | 13.6                | 78.8                | 0                      | 2.00               | 6.9         |
|                           | 3.0                        | 2                           |                         | 13.9                | 78.4                | 0                      | 2.00               | 5.8         |
|                           | 2.5                        | 2                           |                         | 18.7                | 75.8                | 0                      | 1.50               | 4.0         |
|                           | 2.5                        | 2                           |                         | 18.7                | 76.6                | 0                      | 1.40               | 3.3         |
|                           | 2.5                        | 2                           |                         | 21.2                | 73.5                | 0                      | 1.70               | 4.0         |
|                           | 2.5                        | 2                           |                         | 20.4                | 76.0                | 0                      | 1.20               | 2.4         |
|                           | 2.5                        | 2                           |                         | 20.2                | 76.0                | 0                      | 1.20               | 2.8         |
|                           | 2.5                        | 2                           |                         | 19.7                | 75.1                | 0                      | 1.40               | 3.8         |
|                           | 2.5                        | 2                           |                         | 21.6                | 74.9                | 0                      | 1.20               | 2.3         |
|                           | 2.5                        | 2                           |                         | 17.7                | 75.2                | 0                      | 1.80               | 5.4         |
|                           | 2.5                        | 2                           |                         | 18.5                | 75.6                | 0                      | 1.60               | 4.3         |
|                           | 2.5                        | 2                           |                         | 18.6                | 76.3                | 0                      | 1.40               | 3.9         |
|                           | 2.0                        | 2                           |                         | 27.3                | 70.5                | 0                      | 1.00               | 1.1         |

| Temperature of water (°C) | Water flow rate (l/minute) | Biogas flow rate (l/minute) | P (cm H <sub>2</sub> O) | Composition         |                     |                        |                    |             |
|---------------------------|----------------------------|-----------------------------|-------------------------|---------------------|---------------------|------------------------|--------------------|-------------|
|                           |                            |                             |                         | CO <sub>2</sub> (%) | CH <sub>4</sub> (%) | H <sub>2</sub> S (ppm) | O <sub>2</sub> (%) | Balance (%) |
|                           | 2.0                        | 2                           |                         | 25.2                | 71.9                | 0                      | 1.30               | 1.6         |
|                           | 2.0                        | 2                           |                         | 23.6                | 73.4                | 0                      | 1.50               | 1.5         |
|                           | 2.0                        | 2                           |                         | 22.3                | 73.8                | 0                      | 1.30               | 2.7         |
|                           | 2.0                        | 2                           |                         | 21.7                | 73.5                | 0                      | 1.50               | 3.3         |
|                           | 2.0                        | 2                           |                         | 21.3                | 73.0                | 0                      | 1.50               | 4.5         |
|                           | 1.5                        | 6                           |                         | 19.8                | 59.7                | 0                      | 4.10               | 16.6        |
|                           | 1.5                        | 6                           |                         | 23.9                | 58.3                | 0                      | 4.00               | 16.2        |
|                           | 1.5                        | 6                           |                         | 27.7                | 60.4                | 0                      | 2.90               | 9.1         |
|                           | 1.5                        | 6                           |                         | 29.9                | 61.7                | 0                      | 2.30               | 6.2         |
|                           | 1.5                        | 6                           |                         | 32.2                | 64.0                | 0                      | 1.30               | 2.5         |
|                           | 1.5                        | 6                           |                         | 32.1                | 64.9                | 0                      | 1.30               | 1.7         |
|                           | 1.5                        | 6                           |                         | 32.0                | 65.3                | 0                      | 1.20               | 1.5         |
|                           | 1.5                        | 6                           |                         | 31.5                | 64.2                | 0                      | 1.20               | 3.1         |
|                           | 1.5                        | 6                           |                         | 32.4                | 66.3                | 0                      | 0.90               | 0.5         |
|                           | 1.5                        | 6                           |                         | 32.2                | 65.9                | 0                      | 0.90               | 1.0         |
|                           | 1.5                        | 6                           |                         | 32.4                | 66.9                | 0                      | 0.80               | 0.0         |
|                           | 1.5                        | 6                           |                         | 32.3                | 66.4                | 0                      | 0.70               | 0.6         |
|                           | 1.5                        | 6                           |                         | 31.7                | 66.2                | 0                      | 1.00               | 1.3         |
|                           | 1.5                        | 6                           |                         | 31.8                | 66.3                | 0                      | 0.80               | 1.1         |
|                           | 1.5                        | 6                           |                         | 32.2                | 66.9                | 0                      | 0.80               | 0.1         |
|                           | 1.5                        | 4                           |                         | 28.9                | 63.2                | 0                      | 3.00               | 6.4         |
|                           | 1.5                        | 4                           |                         | 29.4                | 67.6                | 0                      | 0.90               | 2.2         |
|                           | 1.5                        | 4                           |                         | 28.9                | 69.2                | 0                      | 0.90               | 1.2         |
|                           | 1.5                        | 4                           |                         | 28.8                | 69.6                | 0                      | 1.00               | 0.9         |
|                           | 1.5                        | 4                           |                         | 28.2                | 69.6                | 0                      | 1.00               | 1.1         |
|                           | 1.5                        | 4                           |                         | 27.8                | 68.0                | 0                      | 1.20               | 3.1         |
|                           | 1.5                        | 4                           |                         | 28.7                | 69.7                | 0                      | 0.80               | 0.8         |

### Appendix 3: Composition of Processed Gas Raw Data for Marble at 0.8m

| Water flow rate<br>(l/minute) | Biogas flow rate<br>(l/minute) | P (cm<br>H <sub>2</sub> O) | Composition         |                     |                        |                    |             |
|-------------------------------|--------------------------------|----------------------------|---------------------|---------------------|------------------------|--------------------|-------------|
|                               |                                |                            | CO <sub>2</sub> (%) | CH <sub>4</sub> (%) | H <sub>2</sub> S (ppm) | O <sub>2</sub> (%) | Balance (%) |
| 4.0                           | 4                              | 53.6                       | 11.7                | 76.5                | 0                      | 2.7                | 9.1         |
| 4.0                           | 4                              |                            | 14.2                | 76.2                | 0                      | 2.0                | 7.5         |
| 4.0                           | 4                              |                            | 15.5                | 76.7                | 0                      | 1.8                | 6.0         |
| 4.0                           | 4                              |                            | 16.0                | 76.5                | 0                      | 1.8                | 5.7         |
| 4.0                           | 4                              |                            | 15.8                | 76.5                | 0                      | 1.9                | 5.9         |
| 1.5                           | 4                              |                            | 18.9                | 64.5                | 0                      | 3.5                | 13.0        |
| 1.5                           | 4                              |                            | 19.8                | 68.7                | 0                      | 2.6                | 9.0         |
| 1.5                           | 4                              |                            | 19.5                | 71.0                | 0                      | 2.8                | 6.5         |
| 1.5                           | 4                              |                            | 19.7                | 72.4                | 0                      | 2.2                | 6.7         |
| 1.5                           | 4                              |                            | 18.0                | 73.6                | 0                      | 2.0                | 6.2         |
| 1.5                           | 2                              |                            | 17.5                | 76.0                | 0                      | 1.7                | 4.8         |
| 1.5                           | 2                              |                            | 17.0                | 76.5                | 0                      | 1.8                | 4.7         |
| 1.5                           | 2                              |                            | 16.6                | 76.5                | 0                      | 1.8                | 5.1         |
| 1.5                           | 2                              |                            | 17.0                | 76.1                | 0                      | 1.8                | 5.4         |
| 1.5                           | 6                              |                            | 20.7                | 70.9                | 0                      | 2.7                | 5.7         |
| 1.5                           | 6                              |                            | 20.1                | 71.3                | 0                      | 2.5                | 5.8         |
| 1.5                           | 6                              |                            | 20.5                | 70.8                | 0                      | 2.9                | 5.6         |
| 1.5                           | 6                              |                            | 19.6                | 71.5                | 0                      | 3.0                | 5.9         |
| 1.5                           | 6                              |                            | 20.8                | 70.9                | 0                      | 2.8                | 5.1         |
| 1.5                           | 6                              |                            | 19.9                | 71.0                | 0                      | 2.8                | 5.9         |
| 4.0                           | 2                              |                            | 14.6                | 78.5                | 0                      | 1.7                | 5.4         |
| 4.0                           | 2                              |                            | 15.7                | 77.9                | 0                      | 1.8                | 4.6         |
| 4.0                           | 2                              |                            | 15.8                | 77.8                | 0                      | 1.9                | 4.9         |
| 4.0                           | 2                              |                            | 15.3                | 78.0                | 0                      | 1.6                | 5.8         |
| 4.0                           | 2                              |                            | 15.2                | 78.2                | 0                      | 1.2                | 5.0         |
| 4.0                           | 2                              |                            | 15.0                | 78.4                | 0                      | 1.2                | 5.3         |
| 4.0                           | 2                              |                            | 15.9                | 77.9                | 0                      | 1.0                | 5.3         |
| 4.0                           | 2                              |                            | 14.9                | 78.9                | 0                      | 1.1                | 5.1         |
| 4.0                           | 2                              |                            | 14.8                | 78.8                | 0                      | 1.4                | 5.6         |
| 4.0                           | 2                              |                            | 14.6                | 79.4                | 0                      | 1.6                | 4.7         |
| 4.0                           | 2                              |                            | 14.7                | 79.0                | 0                      | 1.5                | 4.9         |

#### Appendix 4: Packing of the Water Scrubbing Equipment



# Appendix 5: Composition of Processed Gas Raw Data for steel wool at 0.4m

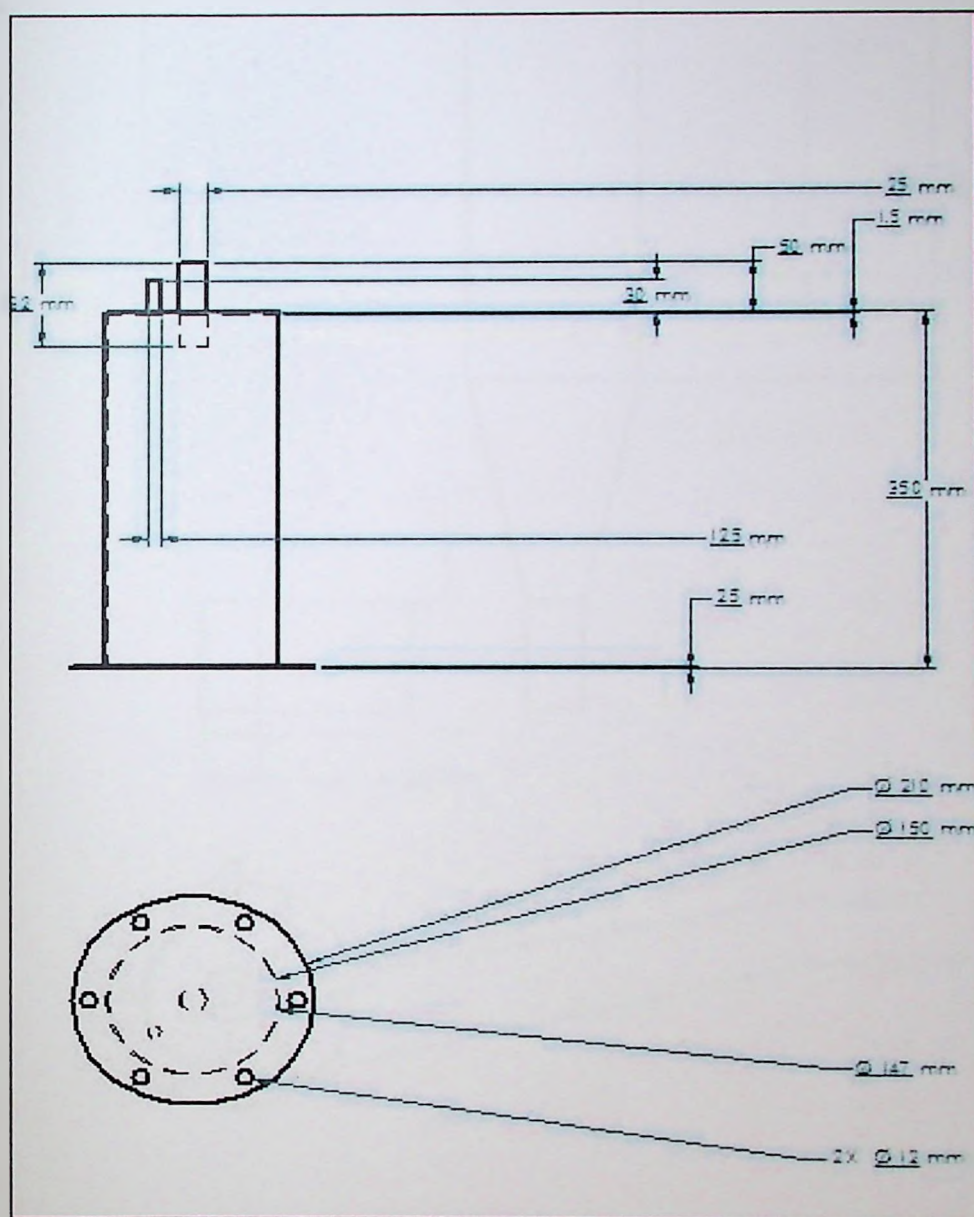
| Temperature of water (°C) | Water flow rate (l/minute) | Biogas flow rate (l/minute) | P (cm H <sub>2</sub> O) | Composition         |                     |                        |                    |             |
|---------------------------|----------------------------|-----------------------------|-------------------------|---------------------|---------------------|------------------------|--------------------|-------------|
|                           |                            |                             |                         | CO <sub>2</sub> (%) | CH <sub>4</sub> (%) | H <sub>2</sub> S (ppm) | O <sub>2</sub> (%) | Balance (%) |
| 20.6                      | 4.0                        | 4                           | 55                      | 23.1                | 73.4                | 0                      | 1.2                | 2.1         |
|                           | 4.0                        | 4                           |                         | 20.7                | 74.5                | 0                      | 1.8                | 3.2         |
|                           | 4.0                        | 4                           |                         | 21.5                | 74.8                | 0                      | 1.3                | 2.6         |
|                           | 4.0                        | 4                           |                         | 21.2                | 74.5                | 0                      | 1.6                | 2.6         |
|                           | 4.0                        | 4                           |                         | 21.5                | 74.8                | 0                      | 1.2                | 2.6         |
|                           | 4.0                        | 2                           |                         | 20.2                | 75.6                | 0                      | 1.4                | 3.0         |
|                           | 4.0                        | 2                           |                         | 17.8                | 76.9                | 0                      | 1.7                | 3.0         |
|                           | 4.0                        | 2                           |                         | 11.7                | 76.8                | 0                      | 2.6                | 3.6         |
|                           | 4.0                        | 2                           |                         | 11.8                | 77.5                | 0                      | 2.5                | 8.9         |
|                           | 4.0                        | 2                           |                         | 11.8                | 78.1                | 0                      | 2.4                | 8.5         |
|                           | 4.0                        | 2                           |                         | 12.3                | 78.4                | 0                      | 2.0                | 7.8         |
|                           | 4.0                        | 2                           |                         | 12.2                | 79.1                | 0                      | 2.2                | 7.2         |
|                           | 4.0                        | 2                           |                         | 11.8                | 79.1                | 0                      | 1.9                | 6.5         |
|                           | 4.0                        | 2                           |                         | 12.1                | 79.5                | 0                      | 2.0                | 7.2         |
|                           | 4.0                        | 2                           |                         | 11.7                | 79.8                | 0                      | 2.1                | 6.4         |
|                           | 4.0                        | 2                           |                         | 11.9                | 80.4                | 0                      | 2.1                | 6.4         |
|                           | 4.0                        | 2                           |                         | 11.7                | 80.4                | 0                      | 2.0                | 5.6         |
|                           | 4.0                        | 2                           |                         | 12.1                | 80.5                | 0                      | 2.0                | 5.5         |
|                           | 4.0                        | 2                           |                         | 11.7                | 80.5                | 0                      | 1.9                | 5.9         |
|                           | 1.5                        | 6                           |                         | 31.7                | 60.7                | 0                      | 1.8                | 5.8         |
|                           | 1.5                        | 6                           |                         | 31.8                | 62.8                | 0                      | 1.5                | 3.6         |
|                           | 1.5                        | 6                           |                         | 31.7                | 63.5                | 0                      | 1.6                | 3.2         |
|                           | 1.5                        | 6                           |                         | 32.4                | 65.5                | 0                      | 2.0                | 1.6         |
|                           | 1.5                        | 6                           |                         | 32.3                | 64.4                | 0                      | 1.6                | 1.8         |
|                           | 1.5                        | 6                           |                         | 33.2                | 65.5                | 0                      | 0.9                | 0.6         |
|                           | 1.5                        | 6                           |                         | 33.3                | 65.3                | 0                      | 1.1                | 0.2         |
|                           | 1.5                        | 6                           |                         | 33.5                | 65.5                | 0                      | 0.8                | 0.3         |
|                           | 1.5                        | 4                           |                         | 32.4                | 66.0                | 0                      | 1.3                | 0.0         |
|                           | 1.5                        | 4                           |                         | 31.8                | 65.7                | 0                      | 1.5                | 1.2         |
|                           | 1.5                        | 4                           |                         | 32.6                | 66.2                | 0                      | 1.0                | 0.4         |
|                           | 1.5                        | 4                           |                         | 32.4                | 66.4                | 0                      | 0.9                | 0.4         |
|                           | 1.5                        | 4                           |                         | 32.3                | 66.2                | 0                      | 1.0                | 0.1         |
|                           | 1.5                        | 4                           |                         | 32.2                | 66.6                | 0                      | 1.0                | 0.5         |
|                           | 1.5                        | 2                           |                         | 30.2                | 68.3                | 0                      | 1.1                | 0.1         |
|                           | 1.5                        | 2                           |                         | 28.5                | 69.4                | 0                      | 1.1                | 0.8         |
|                           | 1.5                        | 2                           |                         | 27.1                | 70.8                | 0                      | 1.1                | 0.8         |
|                           | 1.5                        | 2                           |                         | 25.7                | 71.4                | 0                      | 1.1                | 0.8         |

| Temperature of water (°C) | Water flow rate (l/minute) | Biogas flow rate (l/minute) | P (cm H <sub>2</sub> O) | Composition         |                     |                        |                    |             |
|---------------------------|----------------------------|-----------------------------|-------------------------|---------------------|---------------------|------------------------|--------------------|-------------|
|                           |                            |                             |                         | CO <sub>2</sub> (%) | CH <sub>4</sub> (%) | H <sub>2</sub> S (ppm) | O <sub>2</sub> (%) | Balance (%) |
|                           | 1.5                        | 2                           |                         | 24.0                | 72.6                | 0                      | 1.2                | 2.1         |
|                           | 1.5                        | 2                           |                         | 23.3                | 73.1                | 0                      | 1.5                | 2.0         |
|                           | 1.5                        | 2                           |                         | 23.1                | 73.9                | 0                      | 1.1                | 1.9         |
|                           | 1.5                        | 2                           |                         | 22.7                | 74.1                | 0                      | 1.3                | 1.8         |
|                           | 1.5                        | 2                           |                         | 22.8                | 74.2                | 0                      | 1.2                | 1.8         |
|                           | 1.5                        | 2                           |                         | 22.9                | 73.9                | 0                      | 1.8                | 2.4         |

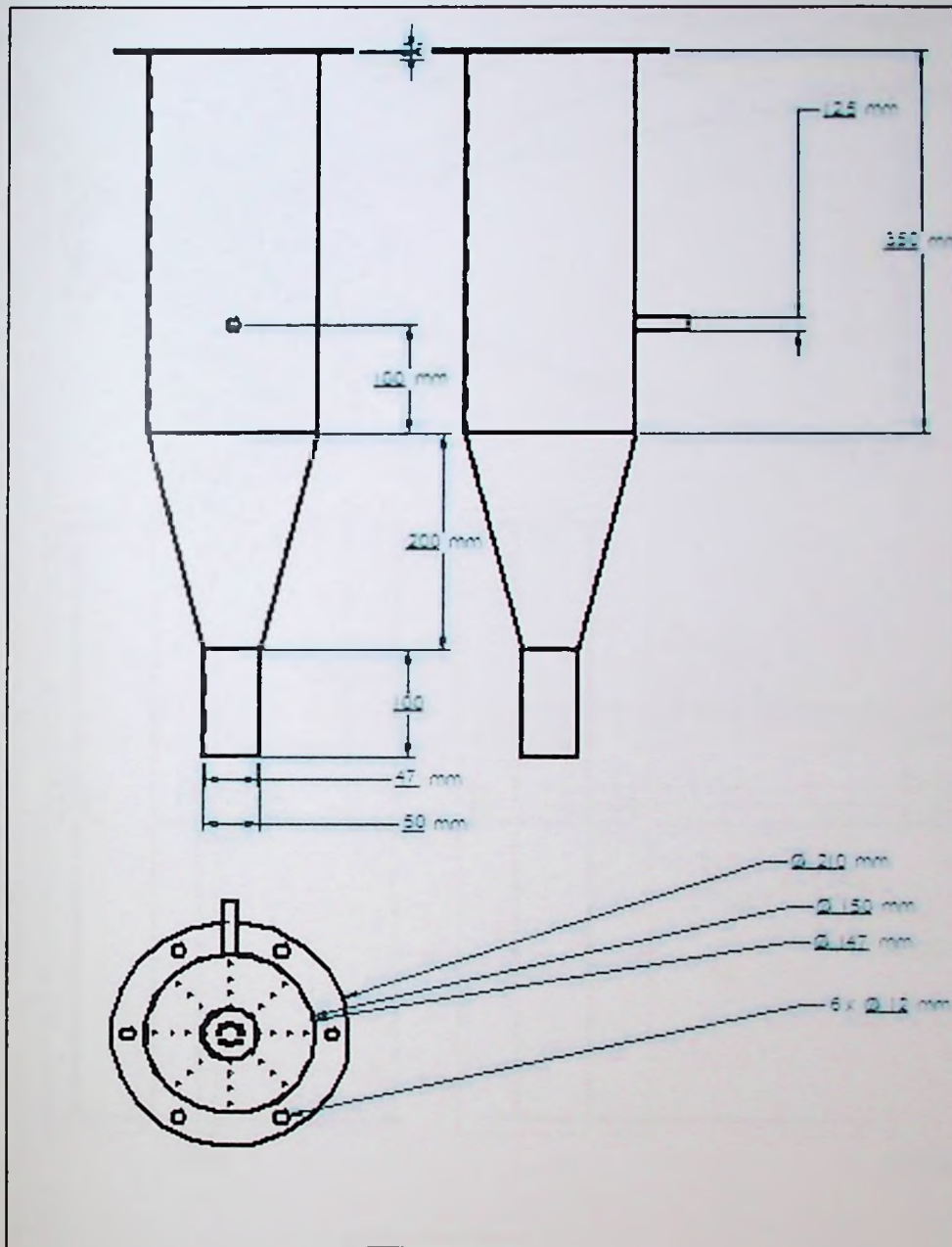
# Appendix 6: Composition of Processed Gas Raw Data for Steel Wool at 0.8m

| Temperature of water (°C) | Water flow rate (liter/minute) | Biogas flow rate (liter/minute) | P (cm H <sub>2</sub> O) | Composition         |                     |                        |                    |             |
|---------------------------|--------------------------------|---------------------------------|-------------------------|---------------------|---------------------|------------------------|--------------------|-------------|
|                           |                                |                                 |                         | CO <sub>2</sub> (%) | CH <sub>4</sub> (%) | H <sub>2</sub> S (ppm) | O <sub>2</sub> (%) | Balance (%) |
| 20                        | 4.0                            | 4                               | 53.6                    | 16.9                | 77.4                | 0                      | 1.4                | 4.3         |
|                           | 4.0                            | 4                               |                         | 9.6                 | 79.3                | 0                      | 2.5                | 8.7         |
|                           | 4.0                            | 4                               |                         | 7.7                 | 82.0                | 0                      | 2.4                | 8.1         |
|                           | 4.0                            | 4                               |                         | 6.5                 | 80.9                | 0                      | 2.7                | 9.9         |
|                           | 4.0                            | 4                               |                         | 6.2                 | 82.9                | 0                      | 2.5                | 8.4         |
|                           | 4.0                            | 4                               |                         | 6.0                 | 82.2                | 0                      | 2.5                | 9.4         |
|                           | 4.0                            | 2                               |                         | 5.8                 | 82.6                | 0                      | 2.7                | 8.9         |
|                           | 4.0                            | 2                               |                         | 5.5                 | 81.8                | 0                      | 2.8                | 9.9         |
|                           | 4.0                            | 2                               |                         | 5.3                 | 81.4                | 0                      | 2.8                | 9.8         |
|                           | 4.0                            | 2                               |                         | 5.5                 | 81.9                | 0                      | 2.7                | 9.9         |
|                           | 4.0                            | 2                               |                         | 6.2                 | 82.3                | 0                      | 2.8                | 9.6         |
|                           | 4.0                            | 2                               |                         | 6.7                 | 83.1                | 0                      | 2.3                | 7.9         |
|                           | 4.0                            | 2                               |                         | 6.9                 | 83.1                | 0                      | 2.3                | 7.7         |
|                           | 4.0                            | 2                               |                         | 7.0                 | 82.9                | 0                      | 2.3                | 7.9         |
|                           | 1.5                            | 4                               |                         | 7.6                 | 66.1                | 0                      | 4.9                | 21.3        |
|                           | 1.5                            | 4                               |                         | 9.2                 | 71.5                | 0                      | 3.8                | 15.2        |
|                           | 1.5                            | 4                               |                         | 11.1                | 74.0                | 0                      | 3.0                | 11.9        |
|                           | 1.5                            | 4                               |                         | 12.5                | 74.5                | 0                      | 2.7                | 10.3        |
|                           | 1.5                            | 4                               |                         | 14.3                | 76.3                | 0                      | 2.1                | 7.4         |
|                           | 1.5                            | 4                               |                         | 15.3                | 76.9                | 0                      | 1.8                | 6.0         |
|                           | 1.5                            | 4                               |                         | 15.4                | 77.0                | 0                      | 1.8                | 5.9         |
|                           | 1.5                            | 4                               |                         | 16.1                | 75.7                | 0                      | 1.6                | 6.8         |
|                           | 1.5                            | 4                               |                         | 16.9                | 76.9                | 0                      | 1.4                | 4.9         |
|                           | 1.5                            | 4                               |                         | 17.5                | 76.8                | 0                      | 1.2                | 4.7         |
|                           | 1.5                            | 2                               |                         | 4.9                 | 74.7                | 0                      | 4.1                | 16.2        |
|                           | 1.5                            | 2                               |                         | 5.6                 | 78.8                | 0                      | 3.3                | 12.3        |
|                           | 1.5                            | 2                               |                         | 5.9                 | 78.2                | 0                      | 3.3                | 12.6        |
|                           | 1.5                            | 2                               |                         | 6.1                 | 79.0                | 0                      | 3.5                | 11.6        |
|                           | 1.5                            | 2                               |                         | 6.2                 | 79.6                | 0                      | 3.0                | 11.3        |
|                           | 1.5                            | 2                               |                         | 6.4                 | 81.8                | 0                      | 2.8                | 9.1         |
|                           | 1.5                            | 2                               |                         | 6.4                 | 82.2                | 0                      | 2.7                | 8.8         |
|                           | 1.5                            | 2                               |                         | 6.4                 | 82.2                | 0                      | 2.5                | 8.9         |
|                           | 1.5                            | 2                               |                         | 6.4                 | 82.1                | 0                      | 2.6                | 9.1         |
|                           | 1.5                            | 6                               |                         | 17.1                | 75.9                | 0                      | 2.7                | 4.2         |
|                           | 1.5                            | 6                               |                         | 17.5                | 75.3                | 0                      | 3.0                | 4.3         |
|                           | 1.5                            | 6                               |                         | 18.0                | 75.1                | 0                      | 2.7                | 4.2         |
|                           | 1.5                            | 6                               |                         | 17.8                | 75.2                | 0                      | 2.9                | 4.4         |
|                           | 1.5                            | 6                               |                         | 17.9                | 75.2                | 0                      | 3.0                | 3.9         |
|                           | 1.5                            | 6                               |                         | 18.3                | 75.0                | 0                      | 3.4                | 3.2         |

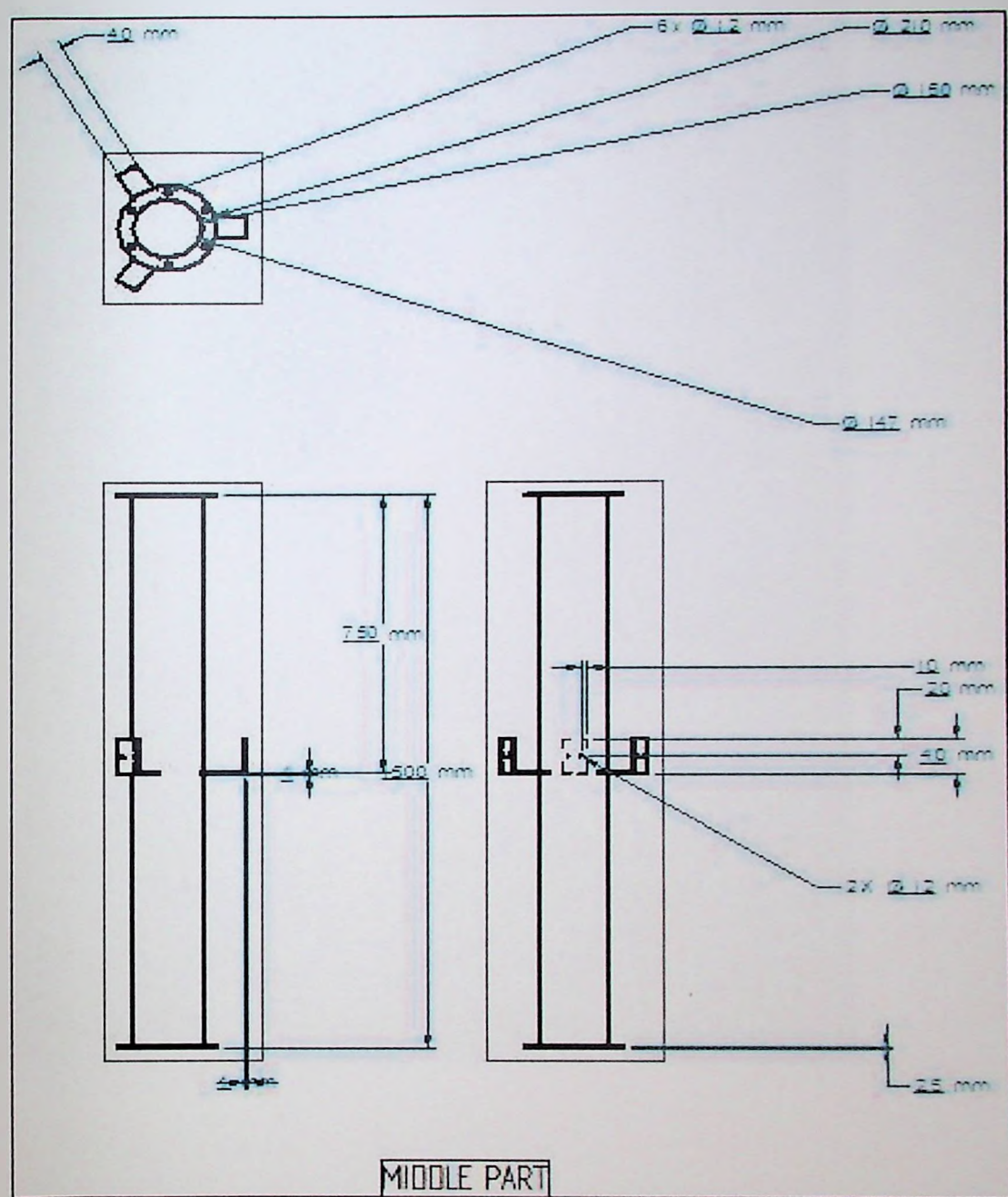
# Appendix 7: Working Drawing for the Top part of Scrubber Column



Appendix 8: Working Drawing for the Bottom part of the Scrubber Column



# Appendix 9: Working Drawing of the Middle Section



## Appendix 10: Assembly Model of the Scrubbing System

