PERFORMANCE AND EMISSION CHARACTERISTICS OF SPARK IGNITION ENGINE OPERATING WITH PURIFIED BIOGAS

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BY

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ABSTRACT

The Spark Ignition (SI) engine remains a global prime mover in the agricultural and transportation sectors as well as in electricity generation. However, its low thermal efficiency and consequential high emissions as related to the use of fossil fuels continue to be major concerns and necessitates the search for new fuels, such as purified biogas. Literature is sparse on the impact of purified biogas on the performance and emission characteristics of SI engines. This study was designed to evaluate the performance and emission characteristics of SI engine operating with purified biogas.

Cattle dung was obtained and tested for pH, total solids, carbon-nitrogen ratio and Biological Oxygen Demand (BOD) using standard procedures. A floating gas cap digester was designed and fabricated using standard principles. The cattle dung was fed into the digester and biogas was generated. The biogas was purified using single and double pass water scrubber to obtain Single-stage Water Scrubbed Biogas (SWSB) and Double-stage Water Scrubbed Biogas (DWSB), respectively. Both SWSB and DWSB were each compressed to 375.8 kPa. The methane content of Raw Biogas (RB), SWSB, DWSB were determined using Liquid Displacement Method (LDM), while the scrubber efficiencies were evaluated using established procedure. The Brake Power (BP), Brake Specific Fuel Consumption (BSFC), Brake Thermal Efficiency (BTE) and emissions (O_2, SO_2 and CO) from a 4.125 kW 4-stroke air cooled SI engine operating with Liquefied Petroleum Gas (LPG), RB, SWSB and DWSB were obtained and compared using established procedure. Data were analysed using ANOVA at $\alpha_{0.05}$.

The pH, total solids, carbon-nitrogen ratio and BOD of the substrate were 7.20, 17533.33 mg/L, 17.72 and 14956.66 mg/L, respectively. Methane content in RB, SWSB and DWSB were 73.47, 88.57 and 96.67% by volume, respectively. The capacity of the fabricated digester was 1.12 m^3. Scrubber efficiencies were 56.92 and 70.87% for SWSB and DWSB, respectively. Engine BP, BSFC and BTE for LPG at full load were 2.04±0.06 kW, 730.38±20.93 g/kWh and 10.70%, respectively and RB corresponding values were 1.03±0.03 kW, 672.37±25.72 g/kWh and 20.57%, respectively. BP, BSFC and BTE when SWSB was used were 1.26±0.09 kW, 551.53±40.20 g/kWh and 20.87%, respectively and corresponding DWSB values were 1.5±0.08 kW, 461.63±18.17 g/kWh and 22.78%, respectively. Engine O_2, SO_2 and CO emission characteristics for LPG at full load were 20.5±0.18, 51.8±24.42 and 4200 ±330 ppm, respectively and RB corresponding values were 20.88±0.04, 73.6±27.66 and 3100.00±265 ppm, respectively. Engine O_2, SO_2 and CO emission characteristics when operating with SWSB were 20.73±0.46, 71.33±18.9 and 2246.33±355.09 ppm, respectively and 20.6±0.12, 41.67±3.51 and 657.67±115.15 ppm, respectively when DWSB was used. Mean performance of engine run on SWSB and DWSB were better than RB. Mean performance of DWSB variables were significantly higher than corresponding means of SWSB indices.

Operating a spark ignition engine with double stage water scrubbed biogas gave better performance and lower emissions compared to liquefied petroleum gas and raw biogas. Thus, purified biogas is an alternative fuel for spark ignition engines.

Keywords: Water scrubbed biogas, Spark ignition engine, Cattle dung substrate, Floating gas cap digester

Word count: 483

CERTIFICATION

I certify that this work titled **"Performance and Emission Characteristics of a Spark Ignition Engine Operating with Purified Biogas"** was carried out under my supervision by Temilola T. Olugasa in the Department of Mechanical Engineering, University of Ibadan.

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DEDICATION

This work is dedicated to my parents, the Venerable Prof. O. O. & Mrs. Kehinde T. Olatunji and the Very Revd. J. O. & Mrs. Christiana O. Olugasa

My dear husband, the Revd. Canon Dr. Babasola Olugasa

and

My lovely children: Aanutomiwa, Ayokunnumi, Temitope and TOluwanimi

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List of Abbreviations

BDC	Bottom Dead Centre
BM	BioMethane
BP	Brake Power
BOD	Biological Oxygen Demand
BSFC	Brake Specific Fuel Consumption
CI	Compression Ignition
CNG	Compressed Natural Gas
C/N	Carbon-Nitrogen Ratio
CR	Compression Ratio
D_P	Daily production
DWSB	Double stage Water Scrubbed Biogas
FEP	Fuel Equivalent Power
$\boldsymbol{F_l}$	Molar flow rate of water
$\boldsymbol{F_g}$	Molar flow rate of gas
FP	Friction Power
G_C	Gas consumption
GC	Gas Chromatography
G_d	Specific gas production
Gs	Gas holder size
HC	HydroCarbon
ICE	Internal Combustion Engine
IP	Indicated Power
LDM	Liquid Displacement Method
LNG	Liquefied Natural Gas
LCFA	Long Chain Fatty Acids
MEB	Methane Enriched Biogas
ODM	Organic Dry Matter
OHV	Over-Head Valve
PVC	Poly Vinyl Chloride
RB	Raw Biogas

RT	Retention Time
SAE	Society of Automobile Engineers
SI	Spark Ignition
SWSB	Single stage Water Scrubbed Biogas
TS	Total Solids
V_D	Volume of Digester
VS	Volatile Solids
W	Wobbe index
WSB	Water Scrubbed Biogas

CHAPTER ONE

INTRODUCTION

1.1 Performance of Spark Ignition Engines

Spark Ignition (SI) engines have been used for centuries as major prime movers in several agricultural, industrial and power generation applications. However, the Thermal Efficiency (TE) of SI engines is generally on the low side, being in the range of 25 - 30 % (Cengel and Boles, 2011). Several researches have been conducted over the years with the aim of improving the performance of the SI engine. Efforts have been made to increase the performance by increasing the intake pressure of the engine through turbocharging or supercharging (Uguru-Okorie *et al*, 2017) as well as the re-design of the combustion chamber (Hill and Zhang, 1994). However, it has been observed that the performance of the SI engine is effectively improved by raising the compression ratio (CR) of the engine. The TE of SI engines depends on the CR of the engine as well as the specific ratio of the fuel (Gupta, 2006). The CR of SI engines are however limited to values between 8 and 12 (Cengel and Boles, 2011) in order to avoid knocking in engines. This occurs when the compression of the end gas to temperatures higher than the auto-ignition temperature of the fuel, causes an instantaneous ignition of the end gas before the flame front reaches it. Thus producing a knocking sound caused by the propagation of strong pressure waves in the combustion chamber.

The CR, power output and TE of an engine is limited by knocking phenomenon, which depends on the properties of the fuel used. The Octane Number (ON) of a fuel is an important property which indicates the measure of resistance of the fuel to knocking (anti-knock quality). The ON generally ranges from 0-100 and gasoline is rated 90 (Gupta, 2006). The higher the octane number the more resistant it is to knock. There is therefore, a search for new fuels because it has been observed that hydrocarbons, which are conventionally used in Internal Combustion Engines (ICEs), are disposed to knocking. The power output of the ICE is increased when fuels with ON greater than 100 is used as this allows for higher CRs.

Biogas has been found to be a renewable gaseous fuel which has a high methane number of 124-150 (Omid *et al.,* 2011). Its high Methane number gives it a high auto-ignition temperature, making it possible for it to operate at high compression ratios without knocks occurring. This property of biogas gives it the potential of being a fuel which can improve the performance of SI engines. Biogas not only has the potential of solving the problem of low thermal efficiency, it also has the potential of reducing the high emission of Hydrocarbons (HC), Carbon monoxide (CO), Sulphur dioxide (SO_2) and Nitrogen Oxides (NOx) which are common in ICEs operating with fossil fuels. Biogas can be used to fuel SI engines with the CR adjusted to higher values or it could be used in a Compression Ignition (CI) engine, which operates at CRs higher than SI engines and has a sturdier design to accommodate the high CR, though the CI engine will have to be converted to SI mode.

1.2 Background Information on Biogas Technology

Biogas is a mixture of carbon dioxide, (CO_2) and inflammable Methane (CH_4) gas, which is produced under anaerobic (oxygen-free) conditions by the action of bacteria on organic matter (Raven and Gregersen, 2005). The composition of biogas is influenced by the source of the biomass digested. Biogas has an organic origin and it is therefore a source of energy which can be replenished and has a calorific value which approximates to 0.5 Litres of diesel (6 kWh/m^3). As far back as the period of World War II, biogas has been used in internal combustion engines (ICEs) in form of sewage gas which powered thousands of vehicles in Europe. Biogas may be viewed as a suitable fuel for combustion in ICEs because the amount of CO_2 emitted during its combustion is the same as the amount of CO_2 absorbed from the atmosphere during photosynthesis in the natural CO_2 cycle (Chellini, 2007). The use of biogas in its raw form to operate ICEs has certain limitations. For instance, the presence of non-combustible gases such as carbon dioxide and hydrogen sulphide (H_2S) reduces its calorific value. The presence of hydrogen sulphide also causes the corrosion of the engine parts. There is therefore a need to upgrade biogas by removing the unwanted incombustible and corrosive gases, thereby increasing its energy content and compressibility.

Biogas technology is not new to Nigeria, but it is not as widespread and as beneficial to the country as should be expected. Nigeria is known globally for its biomass availability, thus, having abundance source materials for biogas production through biogas technology. Nigeria possesses adequate biomass to sustain biogas generation. The rain forest and savannah ecological belts support all-year-round production of cattle, sheep, goats as well as swine and poultry. Livestock production is naturally supported in large scales at graded distribution in the Federal Capital Territory as well as in all the 36 states in Nigeria, although the biomass-to-biogas technology scale varies from one State to another.

According to the National Planning Commission (NPC, 1997, Sambo, 2009) and the UNDP funded Nigeria Cow to Kilowatt Project (Adelegan *et al.,* 2006). Nigeria generates about 15.319 million tonnes of biomass from agricultural and municipal solid wastes across the country daily. Besides the characteristic environmental pollution and a minor use in crop farming as organic fertilizer, these wastes are the essential elements of biomass that can be more useful in providing fuel to power spark ignition engines for running agricultural, domestic, industrial, recreational and other activities in Nigeria. For several reasons, Nigeria has been limited to fossil fuel, especially petrol and diesel as the predominant source of energy for running internal combustion engines. Although Nigeria has the potential to generate some 12,522 MW of electricity from existing plants, yet it continues to operate under 5,000 MW of electricity supply for some three decades (NPA, 2018), which has suppressed Nigeria's industrialization and economic development (NPA, 2018). Biogas technology along with other natural sources of energy, including solar energy, can reverse Nigeria's chronic energy crisis.

Despite the abundant livestock farms and abattoir wastes across the country's land area of 923,768km^2 mainly used for agriculture, the International Renewable Energy Agency (IRENA) reported that Nigeria generated quite less than 0.1 MW of electric power from biogas technology each year over the last one decade. This is low compared to some other African countries like Cameroon, Kenya and South Africa with 2.5 MW in 2016 (Sampablo *et al.,* 2017), 25.7 MW in 2017, and 70 MW in 2016 (Laks, 2017), respectively. In several other countries globally, biogas technology capacity is far higher than exists in Africa. China had about 2060 MW in 2015, Germany had 4803 MW in 2015, India had 900MW in 2015, United States had 2550 MW in 2015 France had 320 MW in 2015, UK had 1448 MW in 2015 and Norway had 17 MW in 2015 (Scarlat *et al*., 2018).

Thus, a major question has continued to linger: “why has Nigeria’s biogas technology potential not been adequately explored to provide the benefits of biogas energy in Nigeria?” Several reasons have been adduced for the neglect of biogas technology for fuel production, distribution and utilization in Nigeria. High cost of installation of digesters, scrubbers and pressure storage facilities, as well as engine converter systems and maintenance of biogas system accessories are leading issues that adduced. Also, it is claimed that there are other major limitations of biogas technology domestication to drive higher energy outputs at much reduced cost, as well as dearth of companies producing biogas facilities and accessories in Nigeria.

1.3 Sustainability of Biogas Production in Nigeria

In a developing country like Nigeria, over 50 million metric tonnes of fuel wood is consumed annually as a result of over 60% rural dwellers relying on it for energy. The rate of consumption of fuel wood exceeds the rate at which it is being replenished through the afforestation programmes in the country (Sambo 2009). Nigeria produces an estimate of 15.319 million tonnes of agro waste and municipal solid waste which can be used for generating biogas (NPC, 1997; Sambo, 2009). However, solar photovoltaics, hydro power and wind power are the only renewable sources of energy being used for generating electricity in Nigeria (Sambo, 2009).

Resources are available in Nigeria locally for building biodigesters and the technology has been domesticated in Nigeria. At least 75% of the pilot biogas plants built in Nigeria, which are still in operation, are on cattle and poultry farms as well as on piggeries (Sambo, 2009) and some are located in abattoirs (Adelegan, 2006). The major application of biogas in Nigeria is for cooking. The design and construction of biogas digesters is now a trend in academic institutions in Nigeria, where they appreciate the need for an alternative source of power to tackle the challenge of insufficient power supply as well as the escalating prices of fossil fuels, which are the main alternative sources of power. Among such institutions are the University of Ibadan prototype (with a patent), Usman Danfodio University Biogas Plant, Obafemi Awolowo University plant (Akinbami et al., 2001), Non-Governmental Organisations (NGOs) and the private sector (Adelegan, 2006). All these show an increase in awareness and interest in renewable energy and consequently, biogas technology (Adelegan, 2006).

1.4 Statement of Research Problem

The use of fossil fuel in SI engines poses a limit to the performance spectrum of the engine because of the knocking tendency associated with increasing the compression ratio of the engine. This low performance, coupled with the potential adverse effect of its emissions on the environment, and the uncertainty of continuous availability of fossil fuel in the future has led to the discovery of biofuels. Biofuels are renewable and clean fuels in that they do not release smoke. Biogas is one of such renewable and clean fuels which have the potential of replacing fossil fuels after the removal of the incombustible gases which are naturally present in it.

There is however, paucity of research on the impact of biogas purification on the performance and emission characteristics of SI engines. Hence the need to investigate the performance of SI engine operating with purified biogas and also study the emission resulting from the combustion of such fuels in SI engines.

1.5 Research Aim

This study aims to purify biogas in two stages using water scrubbing technology with a view to investigate the effect of the different levels of purification on the performance characteristics and emission profile of the SI engine operating with the purified biogas.

1.6 Research Objectives

The objectives of this study are to:

1. Develop facilities for the generation, harvesting and purification of biogas.
2. Investigate the effect of single stage and double stage water scrubbing of biogas on the methane content and calorific value of the purified biogas.
3. Determine the thermodynamic conditions that would maximize the compression and storage of purified biogas for use in SI engines.
4. Study the impact of biogas purity on the performance of a SI engine operating with biogas of different methane contents.
5. Investigate the emission characteristics of a SI engine operating with purified biogas.

1.7 Research Justifications

Biogas has the potentials to replace other rural sources of energy like wood, plant residues, hard coal, kerosene and propane (Brown, 2006). Biogas has the capacity to reduce many adverse health and environmental impacts associated with traditional biomass energy. Apart from supplying energy and manure, the use of biogas helps in the mitigation of Green House Gas (GHG) emissions and the reduction of global warming. The Clean Development Mechanism (CDM), a body under the Kyoto Protocol on emissions reduction project in developing countries, singled out biogas as a potential renewable energy replacement for kerosene in the rural areas (UNECA, 2011). Biogas also has been shown to possess qualities that surpass that of other renewable energy sources (Sreenivas *et al*., 2009; Chae *et al*., 2002).

In this part of the world, much research has not been done on the use of biogas to power SI engines. This is due to instrumentation challenges as well as the laborious process of generating the gas. Most research work has involved the use of simulated biogas, which has its limitations.

It is therefore important to look into the use of biogas in SI engines as a means of generating power in a country like Nigeria with immense power deficiencies.

This study has therefore dealt with the generation, purification, compression and utilisation of biogas to power SI engines.

1.8 Scope of the Research

In this work, biogas was generated in a floating gas cap digester under anaerobic and mesophilic conditions. The generated gas was quantified by weight and purified. The contents were characterized using Liquid Displacement Method (LDM). Subsequently, the SI engine's performance characteristics were studied with emphasis on Brake Power (BP), Brake Specific Fuel Consumption (BSFC) and the Brake Thermal Efficiency (BTE). In addition, some specific emission characteristics were studied, namely, the Sulphur dioxide (SO_2), Oxygen and Carbon Monoxide (CO) outputs of a SI engine operating with purified biogas.

CHAPTER TWO
LITERATURE REVIEW

2.1 Internal Combustion Engines (ICEs)

Heat engines whose fuel is combusted within the cylinder of the engine are known as ICEs. They are used extensively in transportation, agricultural and power generation industries. Heat engines which are devices for transforming thermal energy to mechanical energy have been in use for over two and a half centuries (Heywood, 1988). They started as external combustion engines before evolving into ICEs in the 1860s. The first ICE to be used commercially was developed by a Frenchman, J.J.E. Lenoir in 1860 (Gupta, 2006) and by 1865 about 5000 engines had been built. The early ICEs achieved a maximum efficiency of about 5 percent and this intensified the quest for more research in this area. Nicolaus Otto and Eugen Lagen invented the Atmospheric engine in 1867, which though achieved an efficiency of 11% had the shortcomings of excessive weight. In order to surmount this challenge, Otto developed the four stroke spark ignition (SI) engine, which was operated for the first time in 1876. This was a breakthrough that brought about the establishment of the automobile industry (Pulbarek, 2004).

Further developments of ICEs followed the achievement of Otto. In the 1880s several engineers successfully developed the 2-stroke engine and in 1892, German Engineer Rudolf Diesel invented a type of ICE which starts its combustion process through the injection of fuel into hot compressed air. This type of ICE is known as the Diesel engine or a Compression Ignition (CI) engine. This was a development that brought about the doubling of the efficiency of ICEs (Heywood, 1988). Ever since then, there have been many engine developments, though not fundamental, but they have been very important. An example of a recent major development is the invention of the rotary engine in 1957 by Felix Wankel (Gupta, 2006).

The development of engines over the years has been influenced strongly by fuels. The foremost engines used for generating mechanical power burned gas, later in the 1800s it was gasoline and lighter forms of crude oil. With the challenge of unavailability of crude oil, scientist resorted to the use of thermally cracked crude oil which had high boiling points and the consequential challenge of cold weather starting. However, when electric heaters were introduced in 1912, this problem was resolved. Later kerosene was used on farms, though vapourisers had to be used with them. Recent advancements have permitted the use of fuels with better anti-knock properties, thus higher compression ratios can now be used and ultimately an increase in power and efficiency.

Since 1940, the use of ICEs has led to the onset of air pollution caused by automotive exhaust fumes. Diesel engines in particular have been a major source of hydrocarbons, smoke particles, and oxides of nitrogen (NOx). Several emission controls have been introduced which include the use of catalytic converters in SI engines, use of unleaded gasoline (gasoline without lead based anti-knock additives). All these requirements have influenced the design and operation of ICEs over the years. After over a century of development of ICEs, there are still improvements in power developed, engine efficiency, extent of emission control and introduction of novel materials which brings possibilities of reduced engine weight and cost. New fuels are also being introduced, especially renewable fuels (biofuels) which may bring about the development of an ICE which combines the characteristics of both SI and CI engines.

2.1.1 Classification of ICEs

According to Gupta (2006), ICEs can be classified based on the following:

(1) **Applications:** Stationary engines for power generation, marine engines for ship propulsion, automotive for land transportation, aero-engines for aircrafts and locomotive engines for railways.

(2) **Basic engine design:** There are two basic designs- Reciprocating and Rotary. Reciprocating design is divided by the number and arrangement of cylinders examples are single cylinder, in-line, V, radial, opposed. The second design is the rotary engine design which includes the Wankel and other geometries.

(3) **Working cycle:** The cycle employed may be either four strokes or two strokes.

Four strokes- In this cycle, the piston moves four times when the engine revolves twice for each cycle. Examples are naturally aspirated, supercharged and turbocharged

Two strokes- The cycle undergoes two piston movements over one revolution for each cycle. Examples are crankcase scavenged, supercharged and turbocharged (Pulkrabek, 2004).

(4) **Valve or Port design and location:** This refers to the arrangement of the valves or ports. For valves, it could be overhead valves (I-head) or under-head (L-head), rotary valves. For ports, it could be cross-scavenged, loop-scavenged, through- or uniflow-scavenged.

(5) Fuel: this could be gasoline (petrol), fuel oil (or diesel fuel), natural gas, liquefied petroleum gas, alcohols (methanol, ethanol), hydrogen, dual fuel.

(6) **Method of mixture preparation:** This could be through carburetion, which involves fuel being supplied into intake ports or manifold or it could be through injection in which the fuel is injected into the cylinder.

(7) **Method of Cooling:** The method of cooling employed could be either water cooling or air cooling. In water cooled engines, the walls of the cylinder are cooled by circulating water in the water jacket surrounding the cylinder by means of a radiator, water pump and fans. In air cooled engines on the other hand, atmospheric air blows over the hot surfaces which usually have cooling fins cast on them for effective cooling. Examples are motor cycles, scooters, electric generating sets, though there were some automobiles in the past which employed this type of cooling method (Gupta, 2006).

(8) **Method of Ignition:** There are two major methods of ignition. They are: Spark ignition (SI) and compression ignition (CI). In the SI process, the combustion process is started with the use of spark plug while for a CI engine; the combustion is started by self ignition of the air fuel mixture due to the high temperature of the mixture caused by compression of the mixture to high pressures (Pulkrabek, 2004).

2.1.2 Spark Ignition Engines

A SI engine is an ICE in which the combustion process is started by use of a spark plug (Pulbarek, 2004). In a four stroke SI engine, a 720^o crank angle is required to complete a cycle. The strokes are the induction/suction stroke, the compression stroke, the power stroke and the exhaust stroke.

Induction or suction stroke: This is the stroke that brings about the introduction of the mixture of the air and fuel into the cylinder. The inlet valve opens just before Top Dead Centre (TDC) allowing the inflow of the air /fuel mixture, while the exhaust valve remains closed. The inflow is as a result of a pressure difference which is as a result of a pressure drop to below atmospheric in the cylinder. The piston moves to Bottom Dead Centre (BDC).

Compression stroke: The inlet and exhaust valves are closed, then the piston changes position from BDC to TDC, thus compressing the charge in the cylinder. Just before the end of the compression stroke, a spark is introduced to the charge at a particular point which is usually at

25^o before TDC and the combustion process starts at almost constant volume and there large increase in temperature and volume.

Power or Expansion Stroke: The high pressure of the burnt gases pushes the piston down from TDC to BDC on its power stroke while the inlet and exhaust valves remain closed and power is obtained during this stroke. There is an expansion and consequently a temperature and pressure drop. At a point just before BDC, the exhaust valve opens.

Exhaust Stroke: The piston moves from BDC to TDC sweeping out all the burnt gases through the exhaust valve. The inlet valve remains closed and the pressure in the cylinder is slightly above atmospheric pressure. There are some burnt gases remaining in the clearance volume, known as residual gases.

In every cycle, the crankshaft revolves twice while there is one power stroke (Gupta, 2006).

Figure 2.1 shows a typical four-stroke single cylinder engine which is used as a prime mover for many agricultural machines such as irrigation pumps, threshers, grinders etc and also connected to electric generators for power generation. It was for this reason that an engine similar to this was used in this study to evaluate the performance and emission characteristics of an SI engine fuelled with purified biogas.

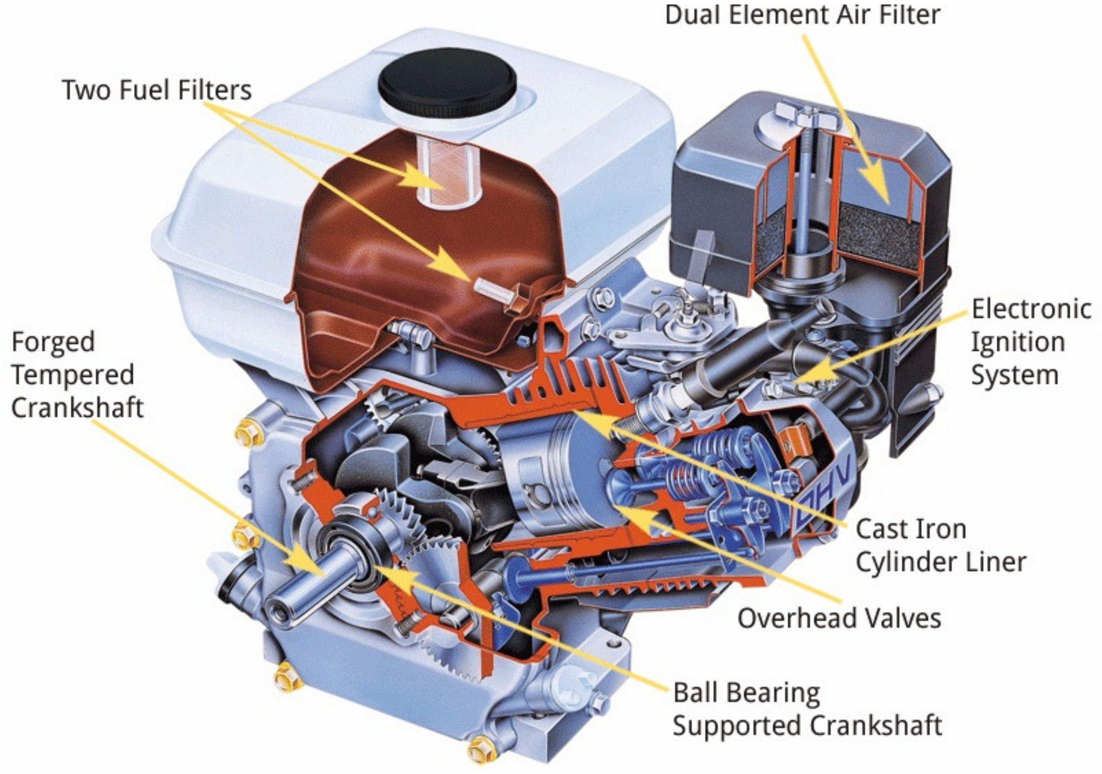

Figure 2.1: Typical small S.I Engine (GX-160)

Source: https://www.ebay.com/p/Honda-Gx160-Gasoline-Engine-

2.2 Fueling of Internal Combustion Engines with Biogas

The working principles of a gas engine are similar to that of CI and SI engines (Zareh 1998). Gas engines are usually modified SI or CI engines. SI gas engines usually have lower volumetric efficiencies than the equivalent petrol engines because the gas intake reduces the amount of air taken in. However gas engines make up for that with a higher compression ratio than that allowed for petrol engines (12 to 13:1). This is made possible as a result of the high methane number of gases, which increases its anti-knock properties. The modification necessary in gas engines includes: the feeding and ignition system. (Munoz *et al*., 2000).

SI engines can be converted to burn purified biogas by modifying carburetion to accommodate the lower volumetric heating value of the biogas (14.98–22.47 MJ/m^3) compared to natural gas (37.45 MJ/m^3) and by adjusting the timing on the spark to accommodate the slower flame velocity of biogas ignition systems (Chandra *et al*., 2011).

Gas treatment to prevent corrosion from H_2S is usually not necessary if care is taken with engine selection and proper maintenance procedures are followed. Typically, oil changes are recommended every 600 h for a natural gas engine. When operating on raw biogas, oil changes should be conducted every 300 h (Krich *et al.*, 2005).

Diesel engines can also be modified to operate on biogas in two ways namely: (1) by converting it to an SI engine by replacing the fuel injectors with spark plugs and replacing the fuel pump with a gas carburetor and (2) by using diesel fuel for ignition and adding a carburetor for the biogas as well as advancing the ignition timing. That is, operating it in a dual fuel mode (Ambarita, 2017). The high compression ratio of a diesel engine (16:1) lends itself to operation on biogas. SI engines generally operate at lower compression ratios in the range of 7:1 to 11:1, whereas biogas engines ideally operate in the 11:1–16:1 range (Krich *et al.*, 2005).

As seen in Table 2.1 the flame-propagation speed of methane is very slow- 430 mm per second. Its spark timing therefore, has to be advanced to about 45^o according to Zhang *et al*., (2017) or 55^o according to Damrongsak and Tippayawong (2014), in order to give the slow biogas flame sufficient time to have a higher brake mean effective pressure. In Gomez-Montoya et al. (2013), incorporated high performance spark plugs, ignition coil, distributor, a biogas mixer, proportional valve and spark-timing regulator on a SI engine fuelled by simulated biogas to aid its smooth running.

The Wobbe index of biomethane is a very important factor to be considered in the use of biomethane as a vehicle fuel. The Wobbe index indicates the interchangeability of gases, that is, it shows to what degree gaseous fuels could be interchanged for a given pressure and valve setting and with similar energy output (Persson *et al*., 2006). The Wobbe index is given by:

$W = Q/\sqrt{d}$; where Q= Calorific value of the gas and d= density of the gas.

A variation of 5-10% of wobbe index is acceptable (Molino *et al*., 2013). It has been established that biomethane is interchangeable with petrol in conventional vehicles (Chandra *et al*., 2012).

The energy content of biogas is another important factor that is considered when biogas is being considered as a fuel in ICEs. It is recommended that fuels with only at least 34 MJ/Nm^3 can be used in Natural Gas Vehicles (Masebinu, 2015). This is shown in Table 2.2

Natural Gas (NG) has been found to be a better alternative to gasoline in terms of higher TE and lower emission of GHGs (Cho and He, 2007). NG which can be stored and distributed as Liquefied Natural gas (LNG) and Compressed Natural Gas (CNG) are both based on methane (Hagenow et al., 2007 and Pourkhesalian et al., 2010). CNG has about 90% methane (Rautre and Sodre, 2009) and its use in SI engines has been investigated extensively. According to Papacz (2011), the CH_4 content of biogas has to be upgraded to 95% vol. before it can be suitable for use in automobiles which have been converted for CNG use. For this reason, biogas must be purified for its subsequent use in ICEs.

The CH_4 component of biogas readily mixes with air, thus making it a suitable fuel for SI engines. The high methane number of biogas increases its anti-knock properties thereby making it possible to increase its compression ratio thus increasing its brake power and thermal efficiency (Von Mitzlaff, 1988). According to Crookes (2006), SI engines could be run on biogas if the CR of such engines were increased. This however led to the increase in NOx emissions as compared to when CNG or petrol was used as fuel. Rakopoulos and Michos (2009) observed that the addition of about 15% of hydrogen to biogas promotes the level of reversibility of the combustion process. Yamaski *et al*. (2013) developed a SI engine system which could run stably on a mixture of biogas and city supplied gas in any proportion after a control algorithm had been designed to adjust the fuel air ratio to attain higher efficiency and lower NOx emissions.

Table 2.1 Flame velocity of Various Gases (Constant & Naveau, 1989)

Combustible	Flame Velocity v, cm s^{-1}
Methane (CH_4)	43.4
Hydrogen sulphide (H_2S)	39.1
Propane C_3H_8	45.6
Butane (C_4H_{10})	44.8
Dihydrogen (H_2)	170
Ethanol (C_2H_5OH)	48.4
Methanol (CH_3OH)	48
Gasoline	40

Table 2.2: Energy content of some vehicle fuels

Source: Kukoyi *et al.*, 2016

Vehicle Fuel	Energy Content (MJ)
1 Nm^3 biomethane (97% CH_4)	34.8
1 Nm^3 of Natural gas	39.6
1 Litre of petrol	32.6
1 Litre of diesel	35.3

2.3 Properties of Biogas

Biogas is a mixture of both flammable and inflammable gases. It is generated from organic matter that has decomposed in the absence of air (anaerobically). Its composition is 50% to 70% of CH_4, 2% of H_2, 0.1% of H_2S, and up to 30% of CO_2. Table 2.3 shows the typical composition of biogas. The composition of biogas depends on the biomass digested and the process parameters such as the pH, temperature, ionic strength or salinity. If the biomass consists of mainly carbohydrates, the methane production will be low, whereas if the fat content is high, the methane production will be high. Biogas burns with an almost odourless blue flame with a calorific value of 21.5 MJ/m^3. CH_4 is the most important constituent of biogas because it is the only gas component (and the little hydrogen present) that are involved in the combustion process. The other gases on the other hand absorb the energy produced during combustion to increase their temperature/ heat contents. Biogas is lighter than air and has an ignition and flame temperature of approximately 700 °C and 870 °C, respectively (Sasse 1988).

Biogas can be upgraded by removing incombustible gases present, thus increasing the percentage of CH_4 while reducing the percentage of gases such as H_2S, CO_2 and water vapour. Purified biogas contains about 80% of CH_4 and has a calorific value of over 25 MJ (Mihic, 2004).

The thermodynamic properties of biogas are:

i. It possesses calorific value of about 20- 24 MJ/m^3 which is equivalent of 5.96 kWh/m^3.
ii. It has a density of 0.94 kg/m^3 which is about 20% lighter than air.
iii. It has a flame speed of 40 cm/s and a flame temperature of 870°C.
iv. It has an ignition temperature of about 700°C.
v. The volume of air required for combustion is 5.7 m^3/m^3.
vi. Biogas cannot be liquefied easily under pressure and at ambient temperature making it difficult to store.

The major constituent of biogas is CH_4 and its critical point 46 bar pressure and -82°C temperature; which implies that CH_4 will not liquefy above -82°C.

Table 2.3: Normal Biogas compositions

Component	Composition (vol. %)
CH_4	45 -75
CO_2	25 – 55
H_2S	10 – 30
N_2	0.01 – 5
O_2	0.01 – 2.0
CO	< 0.2
NH_3	0.01 – 2.5
Organics	Trace

Source: Omid *et al*., (2011)

2.4 Biomass for Biogas Generation

Biomass refers to the organic matter which has the potential to produce energy. For several years, people have combusted wood for cooking and heating homes, which makes biomass the oldest energy source. The energy possessed by biomass is derived from the sun through a process known as photosynthesis. During this process, the sunlight provides the plants with the energy necessary for the conversion of water, CO_2 and minerals into oxygen and water. Biomass is readily available and always being replenished, which makes it a renewable source of energy. Biomass is a feedstock for various fuels like biochar, biodiesels and biogas. Biomass can be distinguished from fossil fuels by considering the number of years needed in the replenishment of each of them. Biomass takes up carbon from the atmosphere as it grows, and it is replenished as it is burned. Biomass can be made sustainable so that it is periodically harvested from a crop which is always replenished as it is harvested (http://biofuelsassociation.com.au/biofuels/biomass/).

The fourth largest energy source in the world is from biomass and it contributes to nearly 14% of the world's raw energy demand (Mao *et al*., 2015). It meets most of the energy needs in the developing countries. For instance, it supplies about 85% of the energy needs in Nigeria, about 76% in Kenya, 75% in Coted'Ivoire, about 97% in Nepal and 86% in Bhutan (Demirbas *et al*., 2009). Despite the contributions of solar and wind power today, biomass is expected to play a major role in energy production in the future (Benato *et al*., 2017). Biomass comes in various forms and is classified based on its application, into fuel biomass, feed biomass, fibre biomass, organic fertilizer biomass and chemical biomass. Biomass should be used to meet the energy demands of a country by converting it into energy, adopting various techniques. Plant residues can be burnt and used to generate electricity, biofuels like ethanol can be obtained from the fermentation of plants, biomass can be burnt by pyrolysis to produce biodiesels and organic matter can be decomposed anaerobically to generate biogas. Most times biogas is generated from animal wastes such as poultry droppings, cow dung, swine dung, etc. These animal wastes, produce bad odours, pollutes the land and contaminates rivers thereby exposing the public to diseases and endangering the lives of water creatures. Generating biogas from animal wastes not only provides alternative and renewable energy, but helps manage waste and make the environment healthy.

A large mass of cow dung and other animal wastes are usually found in places where cows are confined such as in large farms or abattoirs. Large abattoirs are usually sited in the outskirts of every major town in Nigeria and would guarantee the availability of large deposits of cow dung. Cow dung is often used as a seeder in bio anaerobic digesters because it contains the necessary bacteria which can kick start biogas production (Chukwuma *et al*., 2013)

According to Mayer *et al*., (2014), substrates determine the maximum quantity of biogas produced. For instance, cattle dung generates 200 m^3 CH_4/t ODM (ODM – Organic Dry matter) and 20m^3 biogas/m^3 liquid; pig liquid manure generates 300 m^3 methane/t ODM and 30 m^3 biogas/m^3 liquid; sewage sludge generates 300 m^3 CH_4/t ODM and 5m^3 biogas/m^3 sewage sludge; biowaste generates 250 m^3 CH_4/t ODM and 100 m^3 biogas/m^3 t; old fat produces 720 m^3 CH_4/t ODM and 650 m^3 biogas/m^3 t old fat (www.energymanager.eu/getresource/10018/biogas.pdf).

The relationship between the substrate and the gas yield can be seen in the Buswell equation (Equation 2.1). To illustrate this important consideration, Buswell and Muller, (1952) produced a simplified overall picture of the anaerobic fermentation of a typical substrate ($C_nH_aO_b$) to carbon dioxide and methane. Their equation (although over simplified because the overall stoichiometry neglects cell formation) shows that:

$$C_nH_aO_b + H_2O \rightarrow \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right)CO_2 + \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CH_4 \qquad (2.1)$$

Biogas yield is higher when old fat is used as a substrate than when cattle manure, sewage sludge pig manure and bio-waste are used. Substrate digested and the temperature of the digester, influences the Retention Time (RT). At mesophilic temperature range of 20–40^{o}C, the RT of liquid cow manure is 20–30 days, animal manure mixed with plant material is 50–80 days liquid pig manure is 15–25 days and liquid chicken manure is 20–40 days (Kossmann *et al*., 1999).

Biogas yield is also improved by mixing together and co-digesting different classes of biomass. Chukwuma *et al.,* (2013) investigated the effect of co-digestion on biogas yield. He discovered that co-digested substrate of cow dung and poultry droppings in a mixing ratio of 25:75 produced a higher biogas yield than when cow dung was digested alone. Most energy crop biomasses need to be co-digested with livestock dung which usually has the needed micro-organism load.

Demirel and Scherer (2009) investigated the addition of Ammonium Chloride, NH_4Cl and Potassium hydrogen carbonate, $KHCO_3$ to the sugar beet silage to produce significant biogas yield.

The methane content of biogas is of utmost importance to researchers and biogas users. This is because the methane content of biogas is what determines its extent of usage. Biogas with a high methane content of about 95% vol. is used in ICEs while biogas with moderate methane content is used for applications such as lighting and cooking. Table 2.4 shows the percentage volume of methane typical in certain organic matter.

Table 2.4: Range of Methane yield obtained from different organic materials

Organic Matter	CH_4 Content [vol/vol%]
Cattle manure	65
Poultry Manure	60
Pig Manure	67
Farmyard Manure	55
Straw	59
Grass	70
Leaves	58
Kitchen waste	50
Algae	63
Water hyacinth	52
Sewage sludge	60-70
Organic- concentration waters	50-85
Organic fractions of municipal waste	55-65
Municipal waste in landfills	35-60
Sewage sludge	60-70

Sources: Kishore and Srinivas (2003), Sasse (1988)

2.5 Generation of Biogas

Anaerobic digestion is the breakdown of organic matter through a series of biological processes, in the absence of oxygen to produce methane and carbon dioxide gases and a nearly stable residue (Marchaim, 1992). These are the major constituents of biogas.

The process of biological digestion involves several steps like hydrolysis, acidogenesis, and methanogenesis reaction, as shown in Figure 2.2.

a) Hydrolysis – This involves the breaking down of long chain complex organic molecules of protein, carbohydrate and fat polymers into smaller molecules known as polymers by hydrolytic fermentative bacteria.

b) Acidogenesis – This is an intermediate stage where long – chain and short-chain fatty acids are formed. Fifty percent of monomers (glucose, xylose, amino acids) and long- chain fatty acids (LCFA) are broken down to acetic acid (CH_3COOH), hydrogen and carbon dioxide are formed from the 20% of the monomers, while remaining 30% is converted into short chain fatty acids (VFA) by the hydrogen producing and acetogenic organisms. (Jorgensen, 2009)

c) Methanogenesis – This is the final stage of CH_4 production by the methane-forming bacteria. The acetic acid breaks down to about 70% of methane while CO_2 and H_2 are produced from the remaining 30%. Figure 2.1 displays the processes involved in the formation of biogas.

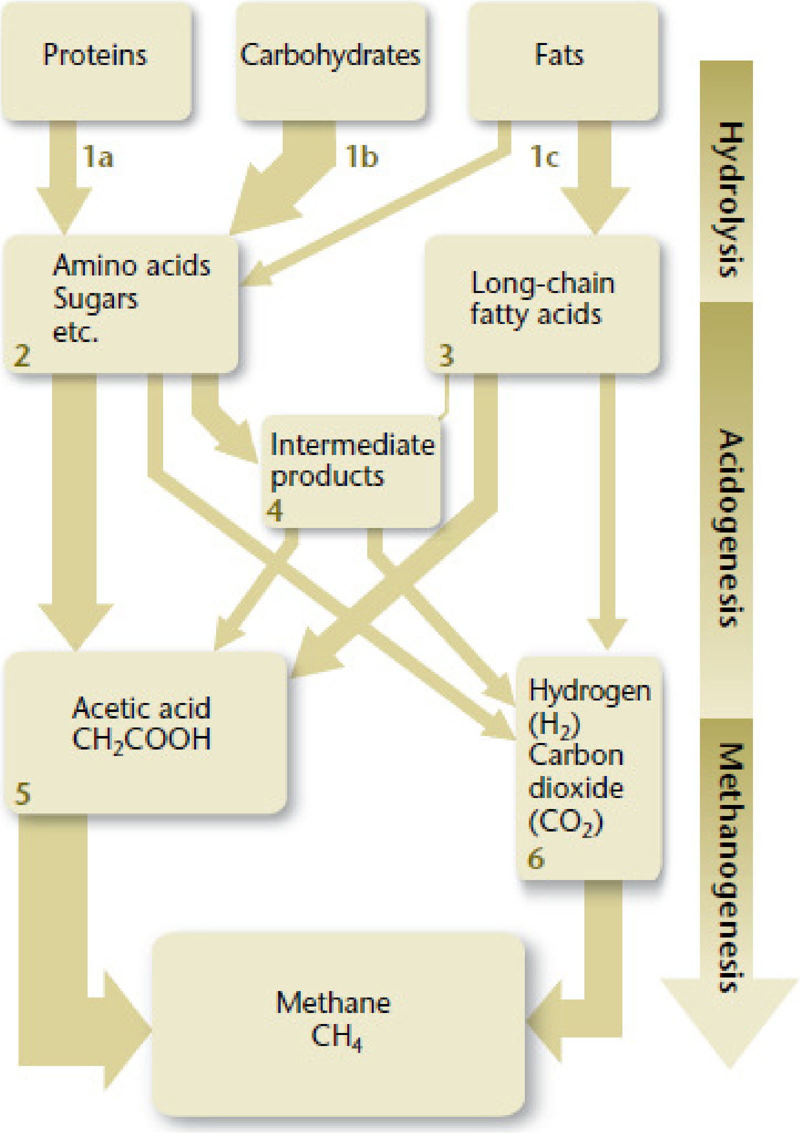

Figure 2.2: Biogas Production Process

Source: Jorgensen (2009)

2.5.1 Biogas Process Parameters

Several factors affect the performance of anaerobic digesters. This could be inhibitory or enhancement of the process. These include the characteristics of the feedstock, the reactor design and operational conditions (Babaee and Shayegan, 2011). Some of the parameters that need to be optimized for a favourable biogas yield are:

Temperature: The rate of biochemical processes generally increases with temperature. This is the same with rate of generation of biogas, which increases with the internal temperature of the digester. Anaerobic digestion can be classified based on the digester temperature as follows:
(i) Psychrophilic digestion which occurs between 10-20°C and RT of over 100 days.
(ii) Mesophilic digestion which occurs between 0-35 °C and has a RT of over 20 days.
(iii) Thermophilic digestion occurs between 50-60 °C and RT of over 8 days.
Thermophilic digestion is not used in simple plants because equipment has to be installed for heating the digesters and the digesters have to be lagged also. In practice, most biogas digesters operate in the mesophilic temperature range.

Acidity (pH)

Methanogens cannot thrive in an acidic environment, though their diet includes organic acids. The pH of the fermentation slurry is an indication of the right balance of the digestion process. The ideal pH should be about 7 which mean that the slurry should be neutral, that is, neither alkaline nor acid. A pH between 6.5 and 8 provides the conducive environment for biogas generation and preferred level is 7.2 (Jorgensen, 2009).

Substrate (Feedstock)

Biogas can in principle be obtained from any organic material. Cattle manure can be used as a "starter" for various substrates. However, substrates which contain lignin such as straw are usually indigestible and require some pre-treatment before digestion. This pre-treatment include pre-composting and chopping of the straw to smaller pieces to aid digestion. For instance, water hyacinth should undergo preliminary rotting for more than 10 days, though 20 days improves gas production substantially (Jorgensen, 2009).

Comminution

The finer the organic material, the larger the surface area and the more digestible it becomes because the bacteria is able to attack the material more easily. It is therefore necessary that the substrate be prepared in such a way as to produce a homogeneous suspension.

Dry Matter Content

It is recommended that the dry matter in a substrate should not be more than 50% to make digestion by the bacteria easy (Jorgensen, 2009).

Carbon/nitrogen (C/N) ratio

Nutrients are needed by the methanogens to multiply. Nitrogen is among the important macro nutrients, which is used by the bacteria to manufacture proteins. The C/N ratio provides information on the suitability of the nitrogen present. That is, whether or not the nitrogen present is sufficient for the bacteria. A high C/N could inhibit the process. The ideal C/N ratio should be less than 30/1.

Stirring

A digester must be agitated daily to prevent the formation of surface crusts which may be difficult to penetrate and may prevent the biogas generated from breaking through to the surface. Stirrers may be manually operated as is the case in simple biogas plants or it may be electrically operated as in large scale biogas plants.

Organic load

This is the rate of addition of biomass to the digester. It should be adequately controlled so that there is a balance, then, the rate at which organisms are added to the digester will be the same as the rate at which it is removed. Overloading can cause the organisms to be overfed and so they become inactive and the process becomes acidic. Refilling of the digester with substrate must be done gradually to afford the organisms the opportunity to adapt to the new environment. The normal organic loading rate is 1-6 kg COD/ m^3 reactor volume/day (Jorgensen, 2009).

2.6 Biogas digesters

The digester is the oxygen free tank or plastic bag in which the mixture of organic matter and water is placed for the generation of biogas. The organic matter, which is usually animal waste and water, is fed into the vessel and the gas produced is allowed to flow out through an outlet pipe which is located above the waste liquid levels in the tank. Similar mechanisms are achieved using plastic membranes. When plastic membranes are used for the digester, it is placed in a secure enclosure in the ground.

Digesters can be as simple as a mere plastic bag to a complex piece of engineered machinery. The main functions of a digester are:

- To hold the substrate, also known as the charge. It is a mixture of solids and water.
- To collect the biogas being generated for purification and storage.
- To provide a means of agitating the charge regularly for enhanced gas production.
- To receive new quantities of charge.
- To preserve the charge at optimum temperature.
- To provide a means of expelling the used up effluent. (Shannon, 1997)
- To make allowance for maintenance and repairs.

Anaerobic units often yield two products namely the biogas itself and a semi-solid by-product called sludge or effluent (Orakwe *et al*., 2011).

The three main types of simple biogas plants are:

1. Balloon plants
2. Fixed-dome plants, and
3. Floating-drum plants (Kossmann *et al*.,1999).

2.6.1 Balloon plants

The balloon plant is made up of an expansive bag usually made of PVC. The substrate is poured in through an inlet which is attached directly to the skin of the balloon. The gas fills up the upper section of the balloon while the inlet and outlet are situated in such a way that the digester has a plug flow. Weights are usually placed on the balloon to pressurise it for easy harvesting of the biogas generated.

2.6.2 Fixed-dome plants

The fixed-dome plant is composed of a digester with an immoveable gas holder, which sits on top of the digester, a mixing pit and an effluent tank/ pit which could also be called the compensation tank. The charge is introduced through an inlet from the mixing pit while the effluent is discharged in the effluent tank. As soon as gas production starts, some of the effluent flows into the effluent tank. The increased pressure required to harvest the gas is achieved by the an increase in gas produced and stored in the digester as well as the difference in the slurry height in the digester and the slurry height in the effluent tank.

2.6.3 Floating-drum plants

This consists of an underground digester and a moving gas-holder. The gas generated is collected in the gas holder which floats either on the substrate or in a water jacket, which rises or drops depending on the quantity of gas stored. Guides are often provided to prevent tilting of the gas drum which could cause gas leakage. If the drum floats in a water jacket, it cannot get stuck, even in substrate with high solid content.

2.7 Biogas upgrading processes

Biogas has a lot on-farm and off-farm applications. However, the presence of incombustible gases like CO_2 and hydrogen sulphide (H_2S) and water vapour gives RB a low energy density of only about 22.3 MJ/m^3. The presence of H_2S and water also makes it highly corrosive, difficult and uneconomical to compress (Kapdi *et al*., 2005), and consequently makes transportation for off-farm applications near impossible and this greatly reduces the potential for off-farm use (Krich *et al*., 2005). Biogas purification processes are the methods of removing unwanted gases from biogas to increase its calorific value and make it fit for use in ICEs, thus upgrading biogas to BM. The removal of CO_2 and H_2S increases the methane content of the biogas up to the level of methane in natural gas (Vijay *et al*., 2006). Enriched biogas therefore, possesses a calorific value of approximately 36.2 MJ/m^3 which gives it properties similar to that of NG which has domestic and industrial applications. It could therefore be injected into the natural gas pipeline, compressed and bottled to be sold for off-farm applications to industrial or commercial users and can be used fuel for vehicles. Enriched biogas is more versatile compared to RB and has more potential for commercialisation.

Purification of biogas is necessary for ICE applications. Studies have shown that the presence of impurities such as chlorine and sulphur inhibits catalytic activities and reduces the quality of the motor oil (Zamorska- Wojdyla *et al*.,2012). Siloxanes and their derivatives, which are also present in RB, are highly volatile and have the capacity to form deposits on the inner walls of gas motors, boilers, catalytic converters as well as deplete the lubricating properties of motor oils (Appels *et al*., 2008). Biogas must therefore be purified to the standard of Natural gas to be used as a fuel for ICEs. For instance, according to Zhou *et al*, (2011), the Wobbe index of biogas is upgraded to the standard of natural gas when the CO_2 in biogas is removed.

Table 2.5 shows the physical properties of natural gas and biogas, and it demonstrates the need for biogas purification. Many methods exist in the purification of the unwanted gases in biogas.

Table 2.5: Physical Properties of NG and Biogas

Key numbers	Unit	Natural gas	Biogas
CH_4 (Methane)	Vol %	91.0	55-70
CO_2 (Carbon)	Vol %	0.61	30-45
N_2 (Nitrogen)	Vol %	0.32	0.
H_2S (Hydrogen sulphide)	Ppm	~1	100 – 50,000
Net Calorific Value	MJ/m^3	39.2	23.3
Upper Wobbe Index	MJ/m^3	54.8	27.3
Lower Wobbe Index	MJ/m^3	49.6	25.1
Adiabatic Flame temperature	^0C	2040	1911

Source: Zhou *et al*., (2011)

2.7.1. Methods for scrubbing carbon dioxide

Many methods exist for removing carbon dioxide (CO_2) from biogas. Majority of these methods are those adopted for CO_2 removal from natural gas in petrochemical industries. These include physical or chemical absorption, adsorption on a solid surface, membrane separation, cryogenic separation and chemical conversion.

a) Physical or chemical absorption (water scrubbing)

The most commonly adopted method for biogas scrubbing is the Physical/chemical absorption method because it is uncomplicated and does not need many infrastructures, it does not need high level maintenance and the flow rates required for effective scrubbing are that which the biogas plants normally operate at. The pressurised water as an absorbent is the cheapest method used. Carbon dioxide removal through water scrubbing requires compression of biogas from 1.03 MPa to 2.07 MPa using two-stage compressor (Krich *et al.*, 2005). The gas is injected from the lower end of a tall vertical column and flows upward, while fresh water is passed counter-currently from the top of the column, downwards over a packed bed. The packed bed is usually composed of a plastic media with a high-surface-area that allows for more effective contact between the gas–water interface in a countercurrent absorption system. The biogas first passes through a pool of water which had accumulated at the bottom of the scrubber column in form of bubbles. The CO_2-absorbed water is steadily discharged from the bottom of the column and the purified gas exits from an upper vent.

Khapre (1989) designed a continuous counter-current scrubber type with 1.8 m^3/h gas flow rate and 48 kPa pressure with 0.465 m^3/h water inflow rate which continuously reduced CO_2 from 30% at inlet to 2% at outlet by volume. Dubey (2000) tested some three water scrubbers of diameters 150 mm, 100 mm and 75 mm, respectively and packed bed heights of 1.5 m, 10 m and 10 m, respectively to absorb/ remove 37–41% of CO_2 present in the raw biogas. He observed that CO_2 absorption was influenced by gas and water flow rates rather than variation in scrubber diameter. An Indian University, the G.B. Pant University of Agriculture and Technology, Pantnagar, developed a scrubber reported by Shyam (2002). The height of the scrubber was 6 m, with a length of 2.5 m packed with spherical plastic balls of 25 mm diameter. Raw biogas was injected into the tower at a pressure of 588 kPa and a flow rate of 2 m^3/h as water circulates through the tower. In this manner, an approximate 87.6% of CO_2 present was effectively removed from raw biogas.

In a single pass, about 95% methane purity can be readily achieved with marginal operator supervision. The water used for scrubbing can be regenerated by stripped it of CO_2 through air contact at atmospheric pressures especially in a packed bed column similar to the one used for absorption, or in a stagnant system such as a stock pond. A prototype packed bed scrubber was designed by Vijay *et al*., (2006) for steady removal of up to 95% of carbon dioxide from biogas. This achieves CO_2 reduction from 40 to 2% by volume in purified biogas. The dimension of the prototype scrubber was a diameter and packed bed height of 150 mm and 3500 mm, respectively. Ninety nine percent of CO_2 absorption was achieved at a gas and water flow rate of 1.5 m^3/h and at 1.8 m^3/h, respectively at a gas pressure of 1.0 MPa. The percentage of CO_2 absorption increased as the gas pressure increased for all gas flow rates tested.

In a bid to further improve on biogas purification, a scrubbing tower was considered needful and developed by Ilyas, (2006). The scrubber comprised of a unit for CO_2 uptake by water countercurrent scrubbing and the subsequent compression and storage of the purified biogas in standard gas cylinders. The scrubber dimension was approximately 150 mm diameter and 4500 mm height with a packed bed length of 3500 mm. This was aimed at purifying RB from 60% to 95% CH_4 by absorption of 40% of CO_2 available in the supplied gas to 5% in purified biogas product. Thus, the methane level is significantly increased. Another water scrubber developed by Bhattacharya *et al*. (1998) achieved 100% purity of methane which was influenced by dimensions of the scrubbing tower, gas pressure, composition of RB, water flow rates and purity of water used.

A water scrubbing system preceded by H_2S removal would be a practical, low-cost process for upgrading dairy biogas to BM. It is important that the H_2S be removed prior to the removal of the CO_2, as H_2S is highly corrosive and would result in decreased life and higher maintenance of the subsequent compressors required in the CO_2-removal step.

b) Chemical absorption

The chemical method of biogas purification follows the principle of CO_2 absorption, using suitable acid-base neutralization reaction in which chemical reagents in the categories of acid solution with corresponding base solution components within biogas. This process thereby absorbs and reduces the CO_2 content in biogas (Bajracharya, 2009). The use of NaOH, KOH and Ca $(OH)_2$ in chemical scrubbing of biogas was started by Savery and Cruzon (1972). The rate of absorption is proportionately increased along concentration gradient of the solutions. When NaOH is at 2.5–3.0 normality, the rate of absorption of CO_2 is most rapid (Kapdi *et al*., 2005). The absorption of CO_2 in alkaline solution is assisted by agitation.

c) Adsorption on a solid surface

In this scrubbing method, adsorption of CO_2 involves transfer of gas stream to the surface of a solid material, where they concentrate mainly as a result of physical or Vander wall forces. Viable adsorbents are commonly granular solids with a large surface area per square meter. It is usually accomplished at high temperature and pressure using silica, alumina, activated carbon or silicates. These solids are generally identified as molecular sieves, and are used as adsorbents. This method offers good moisture removal capacity. It is also simple in design and easy to operate. However, it is a relatively costly process with high heat requirement and high pressure drops (Kapdi *et al*., 2005).

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d) Membrane separation

Since some components of biogas could be transported through a thin membrane (<1 mm) while others are hindered, membrane separation method works on the principle of component separation. Pressure gradient is used along with a selective membrane, which allows preferential passage of one or more gases. The separation of the components is enhanced by the difference in partial pressure across the membrane. This in addition depends on the permeability of the membrane material (Kapdi *et al.*, 2005). Membrane permeability must be relatively high to achieve optimal methane purity. One commonly used membrane is the acetate–cellulose polymer. It separates methane from CO_2 and H_2S since it has 20 and 60 times permeability, respectively, above CH_4 (Hagen and Polman, 2001) even at a pressure of 2.5–4.0 MPa. One pilot plant for the removal of CO_2 from biogas was designed by Rautenbach *et al.,* (1987) using the membrane separation technique. He observed that acetate cellulose and Monsanto membranes were more permeable to CO_2, O_2 and H_2S than CH_4. The optimal temperature and pressure for best separation was considered to be 25^0C and 5.5 kPa, respectively. In addition, gas exchange across the membrane increases proportionally with the partial pressure difference. In this way, a higher pressure difference will require smaller membrane area.

e) Cryogenic separation

The undesirable gases, including CO_2, CH_4, and other contaminants liquefy at very different temperature and pressure levels. Based on this property, it is possible to separate pure CH_4 from biogas using cooling methods while compressing biogas to liquefy the $CO_{2,}$ thus separated from the remaining gas, which is predominantly CO_2. Krich *et al.*, (2005) reported that the extracted CO_2 in turn served as solvent for removing more impurities from biogas. Cryogenic separation therefore requires crude biogas is compressed to approximately 80 bar to use this method of purification. A dynamic multiple stage compression is made in which some inter-cooling mechanisms are integrated. The biogas is dried to avoid freezing of compressed gas during cooling process. Usually biogas cooling is done in chillers and heat exchangers to attain - 45^oC. As condensed CO_2 is removed in a separator, some authors recommend it could be further processed to recover dissolved methane, and recycled to the gas inlet. This process brings about purified methane in liquid form. The product is conveniently transported in this form, being about 97% purified methane (Kapdi *et al.,* 2005).

f) Chemical conversion method

Although chemical conversion method involves methanogenesis or methanation, in which CO_2 and H_2 are catalytically converted to methane and water after bulk removal of some impurities in the source gases, the process is considered extremely expensive and may not be afforded in most biogas ventures (Glub and Diaz, 1991). Yet, the CH_4 generated is extremely pure. The main disadvantage of the chemical conversion process is that the process requires a large amount of pure hydrogen (Kapdi *et al*., 2005).

Some authors, including Ofori-Boateng & Kwofie (2009) have assessed the capital, annual operational and maintenance costs of biogas water scrubbing technology, chemical absorption and biological method. They concluded that water scrubbing has the lowest operational and maintenance costs ($2995 and $595 respectively); whereas, chemical and biological scrubbing methods were $3719 and $3277, respectively. They reported that capital cost of water scrubbing technology is fairly expensive based on cost of fabrication of its towers, purchase of packed bed material and automation process. Nevertheless, it is considered relatively eco-friendly compared to the other methods.

2.7.2 Techniques for hydrogen sulphide removal

Hydrogen sulphide (H_2S) is a common component of biogas generated from animal manure. Its concentration is estimated to be in the range of 1000 to 2400 ppm (Krich *et al.*, 2005). The main determinant is the sulphate content of the local water source. The H_2S content of biogas has to be removed especially because it causes corrosion (Wellinger & Lindeberg, 1999) of the compressor, gas storage tanks and engines in general. In general, H_2S is a poisonous gas. It is corrosive thereby portends environmental hazards especially when converted to sulphur dioxide (SO_2) by combustion. The gas is highly undesirable in the upgrading process. Removal of H_2S is preferably done in the digester stage, but sometimes within subsequent upgrading process (Hagen and Polman, 2001).

A number of authors have provided details about H_2S removal methods, including Kapdi *et al.* (2005). The two main categories are:

(1) Dry oxidation process and
(2) Liquid phase oxidation process.

(1) Dry oxidation process

This involves the removal of H_2S from biogas by converting H_2S to sulphur or sulphur oxide. The method is usually adopted when though the concentration of H_2S is relatively low, yet a process is often used where gas sulphur content is comparatively low, yet high level of purity is required. Below are some types of dry oxidation processes.

(a) Injection of air/oxygen into the biogas system: This involves the use of an air pump to inject a small quantity of oxygen (2–6%) into the biogas system. This reduces the concentration of the H_2S present as a result of its oxidation into sulphur. This method does not need special equipment or chemicals, and is therefore simple and minimizes cost. The concentration of H_2S can be reduced by 95% to about 50 ppm depending on the temperature, the time allowed for the reaction to take place and the point of injection of the air. However, over dosing should be avoided, which could cause an explosion as biogas is explosive in air at 6 -12% concentration, depending on the methane content of the biogas (Wellinger and Lindeberg, 1999).

(b) Adsorption of H_2S using iron oxide: A stream of biogas passed through iron oxide pellets leads to a reaction between H_2S and the iron oxide with the formation of iron sulphide, thereby absorbing the H_2S present. The pellets over time become clogged with Sulphur and can be removed from the tube for regeneration. The process of regeneration, though simple is highly exothermic and could cause self-ignition if the temperature and air flow are not well managed (Cherosky, 2012). The other disadvantages of the regenerative process are that it is influenced by the water content of the biogas and the product of the reaction is toxic.

Baron *et al*. (2008) scrubbed hydrogen sulphide in biogas by passing the gas through a glass bottle filled with steel wool. It was a simple design which comprises of a glass bottle with a metal screw on top which had two holes for gas inlet and gas outlet. The inlet tube reached to the bottom of the glass bottle to ensure that the gas stream flowed over the whole length of the steel wool. A compressor was connected to the set up in such a way that the suction provided by the compressor forced the gas through the glass tube before it was stored in a gas cylinder.

Three adsorption columns filled with uncoated steel wool were used by Magomnang & Villanueva, (2015) to remove H_2S from biogas generated from swine manure. More than 95% of H_2S was eliminated. The steel wool was regenerated by exposing the steel wool to the atmosphere for 16 weeks. This brought about the conversion of the ferric sulphide formed during the scrubbing process to ferric oxide and sulphur. The regenerated steel wool was re-used and it still had 95% removal efficiency.

It has been observed that steel wool does not enhance the binding of sulphide on its surface due to its comparatively small surface area. Wood chips impregnated with iron oxide, has therefore been found to be a better alternative for reaction bed material. According to Krich *et al.* (2005), iron-oxide impregnated chips have a larger surface-to volume ratio and a lower surface-to-weight ratio than steel wool, due to the low density of wood. He estimated that about 20 g of hydrogen sulphide can be bound for every 100 g of iron-oxide impregnated chips. Apart from wood chips, iron oxide or iron hydroxide can also be bound on the surface of red mud made into pellets. Red mud, though denser than wood, possesses a higher surface to volume ratio than both steel wool and impregnated wood chips; though it is more expensive than wood chips. Red mud can be used to reduce high concentrations (1000-4000 ppm) of H_2S using red mud pellets and about 100g of pellets can bind 50 g of sulphide.

2) Liquid phase oxidation method

This method is mainly used for purifying gases which contain comparatively low H_2S concentration. This method adopts either the physical absorption process or a chemical absorption process.

In the physical absorption process, solvents are used to absorb the H_2S. Water is one of the solvents that are commonly used, however, only small quantities of H_2S are absorbed at high rate of water consumption. However, with the addition of some chemicals like sodium hydroxide, the absorption is improved. In spite of this improvement, majority choose to depend on the use of water alone for purification because of the problems associated with the disposal of the product of the process (sodium sulphide or sodium hydrosulphide) which cannot be regenerated. This process is therefore very expensive. Vijay *et al*. (2006) and Ilyas (2006) developed a water tower for the removal of CO_2 as well as traces of H_2S that may be present.

A transparent acrylic cylindrical water scrubber was designed by Lien *et al*. (2014) to eliminate H_2S from biogas containing 6000 ppm of H_2S. The designed scrubber was of 0.248 m diameter and 1.2 m height. At a biogas flow rate of 50 L/min, 78.3 % of H_2S was removed. It was observed that H_2S concentration in biogas reduced notably with the depth of water in the scrubber and increased with inlet biogas flow rate.

Olugasa and Oyesile (2015) explored the use of Iron wool as packing material in a water scrubber to increase the removal of H_2S alongside CO_2. Results show a drop in H_2S concentration from 1% vol to 0.4% vol and a CO_2 drop from 31% to 14% vol.

Iron salt solutions are also effective for the chemical absorption of H_2S. Iron chloride, $FeCl_3$ is useful for absorbing high concentrations of H_2S in gases thus forming insoluble precipitates. In this method the $FeCl_3$ can be put into the digester slurry. This process is most appropriate small sized biogas plants. The final concentration of H_2S after absorption is about 10 ppm. All other methods of H_2S removal are suitable and economically viable for large-scale digesters.
The requirement for Iron in grams/day can be determined by equation 2.2 (Ries, 1993)

$$Fe = \beta . \frac{M_{Fe}}{M_S} . \left(\frac{H_2S_{aq}}{f_{H2S}} . \dot{V}_{Substrat} + \frac{\Delta H_2\dot{S}_g}{1000} . \rho_{H2S} . \dot{V}_{Biogas} \right) \tag{2.2}$$

This method is effective for reducing high H_2S levels; however, it does not succeed at bringing the H_2S concentration down to the level desired in vehicles and direct grid injection. This method therefore has to be used in conjunction with other methods. This method could also be expensive as a result of the quantity of salt needed, which varies with the size of the digester. For instance Oechsner (2000) indicates that for the de-sulphurization from 2000-20 ppm a dosing of 120g to 160g per Nm^3 of biogas is required.

In the final analysis, pre-removal of H_2S (e.g., using iron sponge technology) is a more practical and environmentally friendly approach (Krich *et al.*, 2005). In this study, an iron sponge was first used to reduce the H_2S concentration then the biogas was water scrubbed in two stages to absorb CO_2, as well as absorb small quantities of H_2S that may be left after a pre-scrubbing had been done.

2.7.3. Removal of water vapour

Biogas from digesters is usually saturated with water vapour because it is normally collected over liquid or a moist substrate at the headspace. The temperature and pressure in the digester determines the quantity of saturated water vapour in the gas. Biogas characteristically contains

10% water vapour by volume at 43.33^0C, 5% by volume at 32.22 ^{0}C, and 1% by volume at 4.44 ^{0}C (Weast & Hodgeman, 1958).

The methods employed to eliminate water vapour include constructing moisture traps. This involves inserting a gas pipe of at least 20 cm in length into a container of water, which is placed outside the digester, in downward projection. This ensures that any moisture accumulated in the gas line flows downwards into the water container, instead of obstructing the gas line. However, the container must always be full of water so that the gas will not escape (Breslin *et al.,* 1980). The horizontal pipe is installed at a slope of 1:100 to remove the condensed water easily from the gas line. The water is usually drained from the line through a condensate drain or a drip tap or can located at points of low elevation along the pipeline. The limitation however lies in fact only water vapour that condenses in the piping will be removed and not water vapour in the digester (Krich *et al.,* 2005).

Vijay *et al.* (2006) adopted the method of using a set of three water filters (Pre-filter, Micro-filter and Sub-Micro filter) to eliminate water vapour. The three filters were arranged along the galvanised iron pipeline which was connected to an enriched biogas storage vessel and the three stage compressor. All the water vapour in the enriched biogas was dried as the gas was drawn through the filters by the suction force of the compressor and the dried gas was discharged into standard cylinders.

2.8 Biogas Evaluation and Analysis

It is important to analyse and evaluate the biogas to determine the component gases present and hence, its quality. The content of biogas goes a long way in determining the type of equipment that can handle the gas. There are Government regulations and standards that govern the use of biogas especially as vehicular fuel, because of the poisonous gases in biogas as well as some harmful products of biogas combustion. These standards differ from one country to another.

The methane content of biogas is the most significant trade parameter as well as its associated energy parameters which are the calorific value, the heat of combustion and the Wobbe index. The methane content of biogas can be determined by Gas Chromatography (GC) in line with

PN-EN ISO6974, 2006 (Zamorska- Wojdyla *et al*., 2012). GC helps in characterizing and analysing of multifarious constituents present in the form of gases or vapours in biogas in a fast and accurate manner. The constituents of biogas such as CH_4, CO_2, H_2S can be detected using GC- TCD (Thermo-Conductive Detectors) and GC with Mass Spectrometry. Portable biogas analysers can also be used to determine the constituent gases in biogas. They exist in various configurations based on the components of interest, from single valve/detector instruments to complex multi-channel analysers, depending on components of interest and demanded accuracy and the time of analysis. They could range from single valve/detector instruments to complex multi-channel analysers.

The energy parameters of biogas can be evaluated using the standards adopted by natural gas as quoted in PN-EN ISO 13686 from 2005 and PN-EN ISO 6976 from 2008 (Zamorska- Wojdyla *et al*. 2012).

2.9 Compression and storage of purified biogas

2.9.1 Compression of purified biogas

The compression of biogas reduces the storage capacity, concentrates the energy content and increases its pressure to enhance gas flow (Kapdi *et al*., 2005). It is easier to compress purified biogas than raw biogas. This is because all the incompressible impurities in raw biogas, such as water vapour, makes compression difficult. Biogas can be compressed by the conventional types of air compressors, because they all execute the same task of pressurizing the gas and reducing its volume. However, there are compressors that are actually built to compress biogas and such compressors come with additional qualities such as non – corrosive inner parts and oil free operation.

Positive displacement compressors are the most common type of compressors that operate on the principle of allowing gas into a space and then reducing the volume of that space. They are the most common compressors used and include the reciprocating, rotary screw and rotary vane compressors. Reciprocating compressors are the most commonly available compressors in the market and they range from fractional to very high horsepower. Rotary compressors (Screw and Vane) and the centrifugal compressors are rarely used for biogas operations because they operate at high flow rates and power and are therefore more appropriate for industrial use. They are also very expensive. Multi-stage gas compressors pressurize the gas in two or more stages. The gas is allowed to pass through an intercooler between the stages in order to reduce the temperature raised during compression which reduces the compressor efficiency. They are suitable for compressing biogas for industrial applications and have the capacity to compress to pressures up to 200 psi.

In biogas compression, at least two compressors are employed. One is normally used for delivering RB to the purification unit at medium pressures, to enhance CO_2 absorption by water, while the other is used for compressing purified biogas to very high pressures into storage cylinders. Vijay *et al*., 2006 used two compressors for purifying biogas and storing the purified gas. The first one was a 1.1 kW capacity compressor while the second one was a multi stage reciprocating compressor used for high pressure compression of BM into cylinders to a pressure of 20 MPa. Shel *et al* (2016) compressed two biogas samples that had been upgraded to BM of 95.11% vol methane and 94.69% vol methane, to a pressure of 150 psi using an electric hermetic compressor. The compressed biogas was stored in gas cylinders.

2.9.2 Storage of biogas

The storage of biogas is very important because it is usually generated on farms where there is access to biomass (farm and animal waste). Biogas is usually generated on these farms at a rate that exceeds the use on –site. It is therefore necessary to store the gas for future use on-site and /or for use outside the farm (off-site applications). Methane is highly flammable and the risk associated with its storage increases with the storage pressure. Biogas has to therefore be stored in vessels best suited to the storage pressure of the gas. Table 2.4 shows the common storage vessel used for biogas based on the storage pressure.

Low pressure storage of biogas

Biogas plants usually operate at low pressures less than 13.79 kPa. The Floating gas holders on the digester can therefore be used for storing the gas generated at low pressures. The gas holders are normally made from steel, fibre glass, PVC or an expansible material (Krich *et al*., 2005). The use of a PVC gas bag is the cheapest and easiest to maintain storage vessel because the H_2S gas doesn't corrode PVC.

Table 2.6: Storage options for biogas.

Source: Kapdi *et al*. (2005)

Pressure	**Storage device**	**Material**
Low (0.18 - 0.44 bar)	Water sealed gas holder	Steel
Low	Gas bag	Rubber plastic vinyl
Medium (1.05-1.97 bar)	Propane or butane tanks	Steel
High (200 bar)	Commercial gas cylinders	Alloy

Medium-pressure storage of purified biogas

At medium pressures in the range of 13.79 and 1378.96 kPa biogas can be stored in standard gas tanks. It is however important to purify the gas by removing H_2S in order to avoid the corrosion of the gas cylinder (Ross *et al,* 1996). Typical propane gas tanks have the capacity to store gas at pressures up to 1723.7 KPa. The power needed to achieve this is about 5 kWh per 1000 ft^3 (Wellinger and Lindeberg, 1999) and this usually takes up about 10% of the energy content of the bottled biogas (Ross *et al.,* 1996).

High-pressure storage of purified biogas

Purification of biogas makes compression and storage easier. Purified biogas is often called Biomethane and when compressed to high pressures it is known as Compressed BioMethane (CBM). CBM is often stored at very high pressures in steel cylinders which are equipped with safety devices such as pressure relief valves and rupture disk. Gas scrubbing is even more important at high pressures because impurities such as H_2S and water are very likely to condense and cause corrosion.

The gas is stored in steel cylinders such as those typically used for storage of other commercial gases. Storage facilities must be adequately fitted with safety devices such as rupture disks and pressure relief valves. The cost of compressing gas to high pressures between 13.79 MPa and 34.47 MPa is much greater than the cost of compressing gas for medium-pressure storage.

Compression to 13.79 MPa requires nearly 14 kWh per 1000 ft of BM (Ross *et al*, 1996). If the biogas is upgraded to 97% methane and the assumed heat rate is 12,000 Btu/kWh, the energy needed for compression amounts to 17% of the energy content of the gas.

Vijay *et al.* (2006) used a low suction capacity and high pressure three stage compressor to compress the enriched biogas to a pressure of 20 MPa. The compressed biogas was stored in high pressure steel cylinders that are readily available in the market for CNG storage. The biogas was tested on a vehicle (Maruti-800 car). The test results on performance were observed as good as on CNG operated Maruti-800 car in terms of easy and quick starting and smooth running after engine tuning and restriction in air intake.

Ilyas, (2006) also used a three-stage compressor to compress purified gas up to 20-103 kPa pressure and it was stored in 0.0215 m^3 water capacities CNG cylinders. Biogas could also be compressed using a reciprocating piston compressor that is manually operated. Baron et al. (2008) developed one which was made up of three cylinders which were held in place vertically by an A-frame. Attached to the A- frame is a long lever which is used to manually compress the purified biogas compressor for compressing purified biogas. The compressor achieved a pressure of approximately 241.3 kPa in a 7 gallon air tank which was fitted with a blow-off valve for preserving the pressure of the tank at 965.25 kPa.

2.10 Engine Performance Parameters and Measurement

The engine performance depends on the relationship between the power output of the engine, the engine speed and specific fuel consumption at each operating condition within the useful speed and load range (Reddy *et al.,* 2016). It is an indication of how successful the engine converts chemical energy to useful work. The degree of success is compared on the following basis:

(i) Brake power
(ii) Indicated power
(iii) Brake thermal efficiency
(iv) Indicated thermal efficiency
(v) Volumetric efficiency
(vi) Mechanical efficiency
(vii) Specific fuel consumption
(viii) Mean effective pressure

2.10.1 Brake Power (BP)

The brake power is the power developed at the output shaft of an engine. It is given by

$$BP = 2\pi NT \qquad (2.3)$$

Where N= speed in revolutions per second.
T= Torque

The torque and speed are measured using a dynamometer and a Tachometer, respectively. There are two types of dynamometer: Absorption thermometers and Transmission type dynamometers. The absorption type dynamometer converts the work done on the engine by the dynamometer into heat while the transmission type measures the torque directly and does not absorb part of the engine's work output (Gupta, 2006). The absorption dynamometers are most commonly used.

2.10.1.1 Types of Absorption Dynamometers

Prony Brake Dynamometers

It absorbs energy in a mechanical friction brake known as the Prony brake. It is the simplest dynamometer (Pulkrabek, 2004). It consists of a frame with brake shoes which are held firmly on the rotating drum rim by means of blocks of wood, bolts and nuts as seen in Figure 2.3. A load bar extends from the top of the brake and a weight is hanged to the other end of the load bar. The load W is adjusted so that the arm is horizontal and the shortest distance between the centre line of the weight and the line passing through the pulley is r. The torque is given by ωr. Knowing the speed of the wheel, brake power can be calculated thus:

$$BP = \frac{2\pi NT}{60} = \frac{2\pi N\omega r}{60} \qquad (2.4)$$

The dynamometer is allowed to cool by running water through the rim.

Rope Brake

A rope brake dynamometer is directly coupled to the output shaft of the engine as seen in Figure 2.4. Two or more ropes, evenly spaced by means of wooden blocks, are allowed to rest on the rim of the pulley. Weights are attached to the ends of these ropes to create a tight pull while the total pull on the slack ends of these ropes are displayed on a spring balance. The power absorbed is due to friction between the rope and the drum and this friction torque on the pulley may be increased by adding weights. It is also not very accurate (Gupta, 2006).

Hydraulic Dynamometers

A section of Heenan-Froude hydraulic dynamometer is shown in Figure 2.5. It is made up of a shaft carrying a rotor which revolves in a water tight casing. The rotor vanes and stator vanes are arranged facing opposite directions. The centrifugal force created as a result of the change in momentum and this highly turbulent process repeats itself over and over again thus creating eddies in the water which absorbs the engine power. This absorption increases the engine temperature of the circulating water is cooled by arranging a continuous flow of water through the dynamometer. The load can be varied by inserting or withdrawing some plates in between the rotors by turning a wheel.

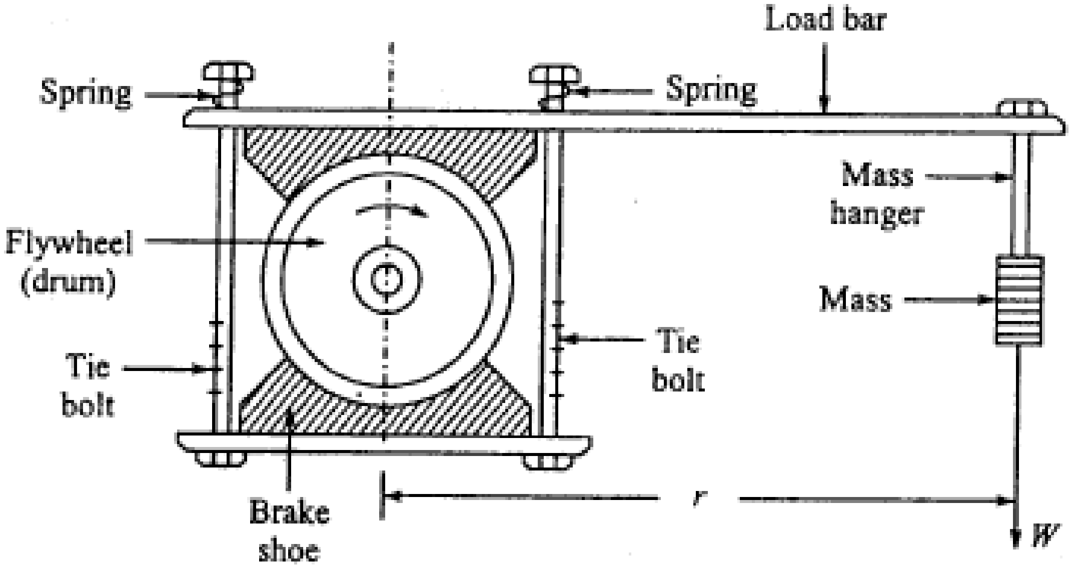


Figure 2.3: Prony Brake

Source: Pulkrabek (2006)

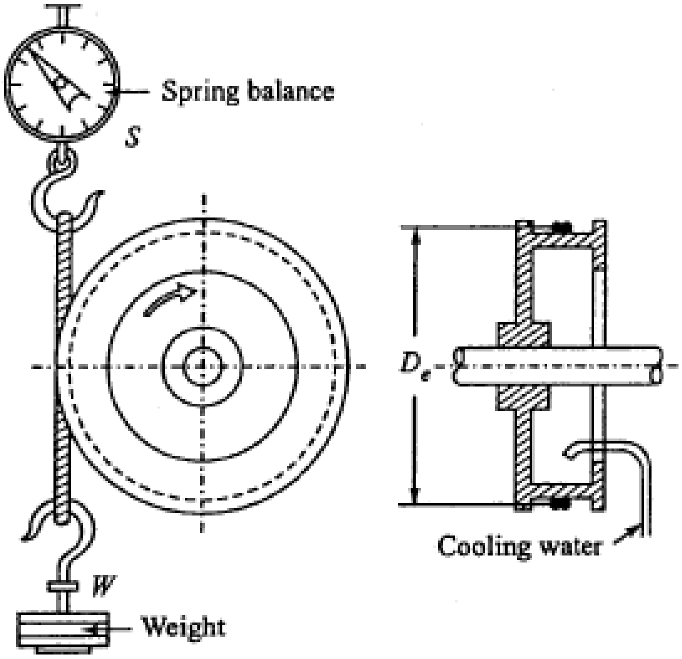


Figure 2.4: Rope brake absorption Dynamometer

Source: Pulkrabek (2006)

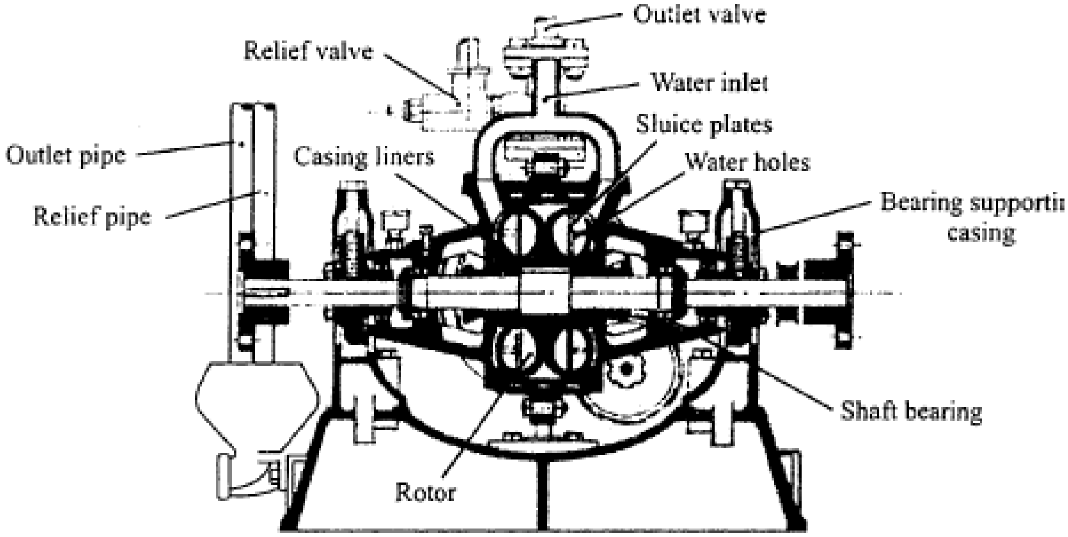


Figure 2.5: A section of Heenan-Froude hydraulic dynamometer

Source: Pulkrabek (2006)

Eddy Current Dynamometer

It consists of a rotor which is mounted on a shaft running in bearings which rotate in a casing. Two field coils are in the casing and a magnetic field is created when direct current is fed into the coils. The turning of the rotors in the magnetic fields generates eddy currents. The rotational torque can then be measured by a spring balance attached to the arm. A pressurized water cooling system is used to prevent overheating of the dynamometer (Pulkrabek, 2006)

Swinging Field DC Dynamometer

The electric or swinging field dynamometer is the most accurate dynamometer which measures torque over a wide range of speed and power. It is a DC shunt motor which runs either as a generator or a motor. The torque of the engine is balanced by a torque arm and the torque is absorbed by generating electrical energy in the armature circuit (Pulkrabek, 2006).

2.10.2 Indicated Power is the total power developed by combusting the fuel. It forms the basis for evaluating combustion efficiency. It is higher than brake power. I.P = BP + Frictional power. It is measured by using mechanical or electrical indicators.

The friction power is measured using the Willan's line method, the Morse test and the motoring test.

2.10.3 Mechanical Efficiency: This is the ratio of the Brake power and the indicated power.

2.10.4 Fuel Consumption

This is the rate at which fuel is used up by the engine. There are two basic types of fuel measuring devices; they are the volumetric and the gravimetric. The gravimetric uses a weighing balance to measure the mass of gas consumed while the volumetric device measures the volumetric consumption of fuel. Rotameters and electric flow meters can be used.

2.11 Performance of Internal Combustion engines run on Biogas

It has been observed that SI engines are readily available in the market and at relatively low costs, while biogas engines are not yet readily available in the market. It is therefore important to study the performance of the readily available SI engines when run on biogas.

Biogas has been found to perform better in dedicated systems than in petrol engines. Studies have revealed that there are similarities in the performance indices (brake power, thermal efficiency, fuel economy) of constant speed engines run on natural gas and those fuelled with enriched biogas (Kukoyi & Muzenda, 2014). The use of biogas in SI engine is usually employed in a bi-fuel mode, where both biogas and petrol are used interchangeably. Such an engine has the advantage of lower fuel costs and anti-knock properties of a high octane gaseous fuel. However, in dedicated systems, the efficiency is greatly improved as the positive qualities of biogas are factored into the design to yield higher power outputs and efficiencies. The compression ratio is usually increased to about 15:1 to improve combustion (Kukoyi et al., 2016). Rossetto *et al.*, (2013) compared the performance of a SI engine operating with Petrol, RB and CNG and he observed that the RB had the lowest performance compared to the other fuels but its performance improved remarkably when the CR was increased to 12.5:1 and the spark timing was advanced to 45^{o}. However, Nindhia *et al.* (2013) reported some success running a single cylinder 4-stroke SI engine with compressed purified biogas by adjusting the CR from 8.5:1 to 9.0:1 and achieving a maximum speed of 3600 rpm.

A number of researches have been done in the area of power generation from biogas. In some cases synthetic biogas has been used to simulate the performance of biogas from various sources. Ehsan and Naznin (2005) used synthetic biogas with methane contents of 55%, 60%, 65% and 70% to fuel a modified Kubota Spark ignition engine generator. The air flow rate, fuel flow rate, air fuel ratio, BSFC and the overall TE were the main parameters studied. There was a linear increase in the air flow rate and load. The fuel flow rate for both petrol and the biogas increased with load. Higher fuel flow rate was needed in biogas with low methane content. It was concluded that a small scale SI engine generator could be run on biogas with simple modifications and it seems to have reduced emissions and more complete combustion when compared to SI engines run on petrol. It is however necessary that the biogas must have a methane content of at least 60% by volume. In the current study, for easy ignition, the engine was first started with petrol after which biogas was gradually introduced. The gas flow rate was also gradually adjusted to the fixed speed engine to support the change in loading of the engine.

A number of researches have been conducted regarding simulated biogas application in internal combustion engines. Huanga and Crookesb (1998) studied the performance of a Ricardo E6 single cylinder engine fuelled with simulated biogas with 40% methane content. Experimental results indicated lower cylinder pressure, thermal efficiency and 20% reduction in power. The authors were of the opinion that had the CR had been increased, the performance would have improved. Jawurek et al. (1987) also investigated the performance of a biogas-petrol dual fuel system. It was perceived that as the methane content in the biogas decreased, there was an increase in power loss. There was about 37% drop in rated power as the CO_2 content reached 50%. It was concluded that the simultaneous use of small quantities of petrol with biogas of low methane content would improve its performance generally.

Surata *et al*. (2014) developed a simple method for converting a small 4-stroke air-cooled single cylinder SI engine to a biogas fuelled SI engine. The CR of the engine was 8.5:1and the engine was used to run an electric generator. The biogas used was desulphurised using annealed iron and dried with a dehumidifier. A mixer was developed using a vacuum valve to control the biogas flow. Mixture of biogas and LPG in ratio 80, 85 and 90% were investigated and it was discovered that the maximum speed attainable using 100% biogas was 1500 rpm while maximum speed using 80%biogas and 20% LPG was 3600 rpm, thus showing that the addition of LPG increases the speed and consequently the performance of SI engines.

Chandra *et al*. (2015) converted a 5.9 kW CI engine to SI mode and experimented with Compressed Natural gas (CNG), RB (generated from Jatropha and pongama oil seed cakes) and water scrubbed biogas. The engine was run varying the ignition advances at 30^o, 35^o, and 40^o before TDC. It was noted that the BP developed by the engine when running on the three selected fuels increased with load at the three ignition advances. Maximum BP of 3.914, 3.8 and 2.661 kW were recorded when the engine was run on CNG, methane enriched biogas and RB, respectively. It was detected that there was a power reduction of the CI engine as a result of its conversion to a SI engine. The power output of the engine run on methane enriched biogas (MEB) was 1.43 times the power output of the engine run with RB. The engine speed and BP of the engine when run with CNG was similar to values obtained when run with MEB, which is because CNG has a composition with methane content similar to that contained in MEB. The brake thermal efficiencies, of the raw biogas (23.3%), methane enriched biogas (26.2%) were higher than that of CNG (22%).

Pandya *et al*. (2016) compared the performance of a 7.5 hp CI engine converted to SI when operating with petrol and enriched biogas. It was observed that the BP of the engine increased with speed when operating with both petrol and enriched biogas, though the BP developed when the engine was running on enriched biogas was higher than that of petrol. The engine was also more fuel efficient when running with petrol than when running with enriched biogas. The minimum fuel consumption associated with the use of petrol was 0.87 kg/kWh and 1.18 kg/kWh for enriched biogas. The mechanical efficiency of the enriched biogas (42.93%) was however higher than that of petrol (30.9%).

Reddy *et al.* (2016) investigated the performance of a 1.4 kVA constant speed generator running on LPG and biogas separately using different flow rates and also observed the exhaust gases. It was discovered that there was a 32% drop in power when RB was used, compared to LPG. There was however an increase in maximum power and BTE from 812 W to 1.154 kW and 19.50% to 22.55 % when the gas was pressurized. This further confirms the observation made in Muharam *et al., (*2015). There was however, no significant difference in the NOx emissions of the engine run with LPG and when it was run with biogas.

Ayade and Lattey (2016) compared the performance of a 50 kW four-cylinder SI engine using various petrol-biogas blends. It was observed that the engine performance improved with the increase in biogas percentage substitution. The BSFC dropped with a rise in biogas concentration and the BTE increased with biogas substitution. However, the CO and HC emissions increased with biogas substitution. A petrol-biogas of ratio 80:20 was found to give the best results as regards of the TE of the engine as well as lowest CO and HC emissions.

2.12 Emissions from Biogas Combustion in ICEs

The exhaust emissions normally contain three major constituent which contribute to air pollution and global warming: HC, CO and NOx. The emission of hydrocarbon depends on the design of the induction system, combustion chamber and on the operating conditions such as the air fuel ratio, speed and load (Ray *et al.,* 2013). CO is produced as a result of incomplete combustion, and it occurs only in the engine exhaust. With biogas, the CO emissions are lower than that of gasoline. Reddy et al. (2016) compared the emissions of biogas and LPG and noted that though the NO emissions were slightly higher in biogas, due to the presence of Nitrogen, the CO and Hydrocarbon emissions in biogas were very low compared to LPG. This demonstrates that biogas is indeed and eco-friendly fuel.

The exhaust composition is usually affected by the exhaust temperature. As the exhaust temperature increases so does the NOx emissions (Muharam et al., 2015). The NOx emissions in an engine operating with biogas is not significantly different from that of an engine running with LPG (Reddy *et al*., 2016)

Zhang *et al*. (2017) tested the emission characteristics of an SI engine fuelled with biogas obtained from Two- Phase Anaerobic Digestion (T-PAD) process and varied the composition of hydrogen and CH_4 in the biogas. It was observed that with an increase in methane content there was a decrease in the value of unburnt hydrocarbons and CO. However with an increase in hydrogen, there was an increase in the peak cylinder temperature, increase in thermal efficiency but there was also an increase in NOx emissions.

Reddy *et al.* (2016) performed a comparative study on the emission characteristics of a single cylinder SI engine fuelled with biogas and that fuelled with LPG. It was observed that there was a decrease in CO % with load for both LPG and raw biogas. However the CO% emissions for biogas (0.07%), was lower than that of LPG (7.41%). The hydrocarbon levels of LPG were also higher than that of biogas. This was attributed to the higher order of hydrocarbons (Propane and butane) found in LPG compared to only methane in biogas. The NOx emissions were observed to increase with load for both fuels, but there was no significant difference between that of LPG and that of raw biogas.

Chen *et al.,* (2017) investigated the effect of adding hydrogen to methane and diluting methane with CO_2. Different hydrogen substitution ratios (HSR) and different Fuel Dilution Ratios (FDR) were used and it was observed that the NOx emissions reduced with increase in FDR and the CO emissions increased with FDR. It was also noted that the maximum CO emission recorded was when the equivalence ratio was less than the stoichiometric ratio.

2.13 Climatic and Economic Benefits of Biogas Utilization in Nigeria

Biogas production from biomass generated in livestock production units goes a long way in aiding environmental management and production of clean energy, which are highly beneficial to the community. It is a clean source of energy because its production does not bring about environmental pollution or degradation which is normally associated with the production of fossil fuels. The use of fossil fuels in ICEs has the consequence of the depleting the ozone layer which causes climate change and then earth surface (life) discomfort.

Clean energy from biogas is renewable in that it is generated from biomass which can be easily replenished through agriculture. Generation of biogas has great potentials for the Nigerian economy. It brings about reduction in cost of resources going into solid waste management; it brings about the provision of relatively cheap energy sources which can be utilized for driving the domestic and industrial cores of the country. Biogas can be generated at different scales of production. Households could tap into it by generating biogas to meet their local energy demands as well as helping to promote ecosystem health. The nation could also invest in biogas technology as a major alternative source of power especially in the rural areas in Nigeria which are not connected to the national electricity grid. Nigeria has the capacity to sustain the biomass needed for biogas production. According to Sambo (2009), Nigeria daily generates 4.075 million tonnes of municipal waste, 11.244 million tonnes of agro-waste, which is equivalent to 147,700 MJ of energy, 1.8 million tonnes of saw dust with an energy value of 31,433 MJ. These biomasses can sustain large biogas plants. The waste generated from biogas production can also be used as fertilisers on farms. Thus, reducing the high cost and the adverse effects associated with the use of chemical fertilisers.

ICEs run on biogas will have lower running costs, as biogas is cheaper than petrol and readily available. Since biogas is a clean fuel, it is expected that running a SI engine on biogas will reduce maintenance cost. That is the engine oil and spark plugs will be changed less often. Environmental benefits are reduction in CO and NOx emissions.

2.14 Environmental Health Impact of Biogas Utilization

The quantity of organic waste generated in Nigeria from households, farms, markets and industries are enormous and the facilities put in place to dispose these wastes are inadequate. Nigerians therefore resort to disposing them in heaps on farms, market places and at the road side. Such heaps are leading causes of disease outbreaks like cholera, malaria and air pollution. When we consider wastes generated on farms in Nigeria, it has been discovered that about 227,500 tons of animal waste is generated daily (Akinbami *et al*., 2001). Liquid manure if undigested emits ammonia, composted organic materials also emit ammonia, nitrous oxide etc. Digestion of these organic materials goes a long way in reducing the emission of greenhouse gases. If all the animal wastes can be dumped into digesters and used for generating biogas, then biogas production would be a profitable means of reducing the menace of urban wastes (Adelegan, 2006).

2.15 Electricity Generation from Biogas

There are two major options available in the utilization of biogas in generating electricity:

1. Using Upgraded biogas as fuel for an ICE. It may be used for Spark ignition engine or Compression ignition engines after some modifications. The ICE may then be used to power generators.
2. Using upgraded biogas as fuel for the combustor of a micro-turbine. Micro gas turbines are the latest gas turbines used for stationary power generation (Yehia et al, 2008). They work on the same principle as large turbines only that its components are miniaturized. A turbine cannot be used because it will require a large volume of biogas to drive it and this amount is not usually generated in farms. Olugasa and Jimoh, (2018) designed a 10 kW micro-turbine for generating electricity using biogas. The combustor was evaluated to operate at a fuel flow rate of 0.0037 kg/s and air flow rate of 0.14 kg/s. The reference area of the combustor was 0.00365 m^2 and it had a total length of 30.25 mm.

2.16 General Observation and Direction of this Work

Literature has shown that there is a need to purify biogas to optimize its use, especially in ICEs. Various researches have been conducted on biogas purification, however much has not been done on biogas purification using water scrubbing. In Vijay *et al*., (2006) and Ilyas (2006) the developed water scrubber achieved 95% CO_2 absorption, meaning the percentage of methane in the biogas could still be increased by absorbing more CO_2. This study introduced the use of a second water scrubbing tower in the purification process so that the second stage scrubber acts on the first stage purification and gives a purer biogas. The effect of a second stage scrubbing was therefore investigated in this study. The methane content of the product and the impact of the double stage scrubbing on the engine performance were observed.

Most research work involving the use of biogas and upgraded biogas for running ICEs, either SI or CI has employed the use of raw biogas (Gomez-Montoya *et al*., 2013; Rossetto *et al*.,2013; Reddy *et al*., 2016; Damrongsak and Tippayawong, 2014), some employed the use of raw biogas blended with LPG, petrol or diesel dual fuel mode (Surata *et al.,* 2014; Ayade and Latey, 2016; Chandra *et al*., 2011) while others used simulated biogas to model purified biogas and not the actual purified biogas (Shah *et al*., 2016; Chen *et al.,* 2017; Pandya *et al.,* 2016, Chandra *et al*., 2011). Only few researches have made use of the actual biogas in experimental work (Vijay *et al.,* 2006). This study has experimented with biogas generated from cow dung, embarked on its purification, its compression and bottling in a most practical way and its consequent use in running SI engines.

The performance and emission characteristic of a readily available commercial SI engine, which was modified for biogas use by installing a commercial CNG conversion kit distributed by Simbatek, Nigeria, was used in this work. The 4.125 kW 4-stroke air cooled SI engine used is one readily available in the market and which is used for many applications.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Design of the Digester

3.1.1 Design Considerations

(i) The digester was designed to be a continuous loading type to ensure steady supply of biogas.

(ii) The quantity of waste required to generate a specific volume of gas was determined using the relationship used by Itodo *et al*, (1992)

1 kg of cow dung = 0.045 m^3 of biogas

(iii) It was estimated that about 5m^3 of biogas was sufficient to carry out the study. However since the gas cannot be used up at once it can be generated in batches of 2 $m^{3.}$ According to Okoroigwe and Agbo (2007), gas yield is improved with the frequency of biogas evacuation from the digester.

From Itodo *et al*. (1992) 1 kg of cow dung produces 0.045 m^3 of biogas. To generate 2m^3 of biogas, $\frac{2\,m^3}{0.045m^3/kg}$ = 44.44 kg

Assumed quantity to be loaded daily= 6.89 kg/day

(iv) A floating gas cap type of digester was designed for ease in estimating volume of biogas produced through liquid displacement.

3.1.2 Determination of digester volume

In determining the size of a biogas plant, certain parameters were considered:

(i) Daily fermentation slurry arisings S_d (l/day)

(ii) Retention time, RT

(iii) Specific gas production, G_d which depends on the feed material and the retention time (Sasse, 1988).

The biogas plant size depends on the average daily feed stock and the expected RT of the materials in the biogas system. The volume of the digester was estimated using equation (3.1):

$Volume\ of\ Digester$ (litres)=$S_d(l/day) \times RT(days)$ (3.1) (Sasse, 1988)

S_d= Quantity of slurry (biomass + water)

RT= Retention time in days

Quantity of cow dung loaded will be $96.5\,kg \approx 97kg$ and the substrate was prepared using a 1:1 biomass to water mixing ratio, then 97 kg of water will also be used, which will give 194 litres of slurry.

Estimated slurry per day = $13.857\ l/day$ (litres/day)

The retention time is the period a feed material spends in a digester. It is usually shorter than the time taken for the material to be completely digested. The retention time usually used for digesters operated in the tropics is 60 – 80 days. 80 days was chosen for the purpose of the study.

Thus, $Volume\ of\ digester = 13.857 \times 80 = 1108.56\ litres \approx 1.12\ m^3$

3.1.3 Determination of Gas holder size

The size of the gas holder depends on gas production and the volume of gas drawn off. It is determined primarily by the quantity of gas drawn off and when it is drawn off. This is a very important parameter during the planning stage because if the gas holder capacity is insufficient some gas will be lost and if it is too large, the construction cost will be unnecessarily high. The gasholder capacity was evaluated using equation (3.2):

For floating-drum plants

$G_s = (D_p - G_c) \times safety\ margin$ (3.2) (Sasse, 1988)

Where Gs= Gas holder size

Dp= Daily production

Gc = Gas consumption

Safety margin = 25%

Since the quantity to be loaded daily is 6.89 kg/day, then daily production, Dp was estimated to be 500 litres/day and Gc was estimated to be 250 L/day

$G_s = (500 - 250) \times 1.25 = 312.5\ litres$

3.1.4 Determination of Gas holder capacity (Gcp)

Gas holder capacity is the ratio of the gas holder size (or volume) to the daily production as expressed in equation (3.3)

$$G_{cp} = \frac{G_C}{D_p} \qquad (3.3) \qquad \text{(Sasse, 1988)}$$

$$G_{cp} = \frac{250}{500} = 0.5 = 50\%$$

3.1.5 Determination of the Form of the digester

The form of the digester was determined by the digester/gas holder ratio as shown in equation (3.4).

$$D/G = \frac{V_D}{G_S} \qquad (3.4)$$

Where V_D = Volume of the digester

G_S = Gas holder size

Therefore,

$$\frac{D}{G} = \frac{V_D}{G_S} = \frac{1.12}{0.5} = 2.24:1$$

For low ratios- 1:1 to 3:1 a cylindrical shape is recommended

For high ratios: 4:1 to 6:1 a spherical dome shape is recommended (Sasse, 1988)

For low ratios, a cylindrical shape is best. A cylindrical shape was therefore chosen for the design.

3.1.6 Material Selection

Two cylindrical tanks made of PolyVinyl Chloride (PVC) were selected for constructing the digester because of the anti-corrosion properties of PVC. The presence of hydrogen sulphide in biogas and the presence of water in the substrate have the tendency to cause corrosion. The use of PVC will elongate the life span of the digester.

3.1.7 Auxilliary Parts

Clamps and belt

Two U-clamps made from twisted mild steel were erected at both sides of the digester and a belt was passed through them, over the digester gas holder in order to keep it in place and prevent toppling when the gas holder as risen due to gas yield.

Slurry Influent and Effluent pipes

According to Kuria and Maringa (2008), standard PVC pipes should be used for the influent and effluent pipes since they do not corrode in the alkaline and moisture conditions in the digester. Influent pipe of diameter 11.5 cm was selected because it is wide enough to prevent clogging of the substrate when being loaded into the digester. PVC pipe of 10.5 cm was selected for effluent pipe. Its diameter is a bit smaller than that of the influent pipe since the effluent contains materials that have been broken down already by the methanogens.

Brass Ball valve

A brass ball valve to which a gas nipple was attached was used at the gas outlet. The brass ball valve is corrosion resistant and the gas nipple allows for easy connection of the digester to flexible gas hoses.

A PVC ball valve

This was used at the bottom of the tank at the sampling point.

3.1.8 Cost Analysis for the Development of the Digester

The cost analysis was done based on the market prices of the materials. The Total Capital Investment (TCI) was estimated to include the cost of purchasing the digester including the direct and indirect costs associated with the fabrication and installation of the digester.

TCI = PEC + DC +IC

Where:

PEC= Purchased equipment costs

DC = Direct installation costs

IC = Indirect installation costs

3.2 Generation of biogas

Biogas is generated from the anaerobic digestion of organic material. The organic material selected for the generation of biogas for this study was cow dung. Cow dung was selected because high number of research findings indicated the superiority of cow dung in generating high quality biogas (Odeyemi, 1987, Fulford 1998, Ofoefule *et al.*, 2010 and Eze, 2011). The cow dung used for this study was collected from the Cattle unit of the University of Ibadan Teaching and Research Farm from July, 2016 to December, 2017. The Teaching and Research

Farm of the University of Ibadan have 39 cows and the estimated amount of waste generated daily was about 237.2 kg of cattle manure. Fresh cattle dung was collected using shovels, sacks and buckets. The estimated amount of cattle dung collected each time was 97 kg and this was collected about twelve times during the study (Plate 3.1).

3.2.1 Substrate Preparation

Cattle dung was first scooped into a bucket using a trowel and the mass of the cattle dung was estimated using a spring weighing scale. An equivalent mass of water was used to mix the cattle dung in the ratio 1:1. It was stirred manually to produce a substrate of even texture (Plate 3.1). The substrate was then fed into the digester through the 100mm diameter inlet pipe and the substrate was agitated in the digester by means of a manual stirrer attached to the gas cap.

3.2.2 Analysis of the Substrate

The substrate prepared from the cow dung was analysed in the laboratory to determine the pH, total solids, Carbon/Nitrogen ratio (C/N) and Biological Oxygen Demand (BOD). All analyses were conducted in accordance with the 19th edition of the Standard Methods for Examination of Water and Wastewater (AWWA, 1995).

3.2.3 Harvesting and Storage of Biogas

It was observed that after about 21 days the gas cap began to rise, signifying the onset of biogas generation. The volume of the gas was estimated by taking account of the displacement height of the gas cap and the pressure of the gas generated was determined using a manometer which was attached to the gas outlet pipe (Plate 3.1).

The biogas generated was first pre-scrubbed using a dry scrubber which contains 50 g activated charcoal for the drying of the gas and steel wool for the removal of hydrogen sulphide. The inlet of the dry scrubber was attached to the gas outlet pipe of the digester while the outlet hose was connected to the suction port of a compressor. The discharge port of the compressor was then connected to a 37 kg cylinder by means of a gas hose and held in place by hose clips (Plate 3.1). The 37 kg cylinder was first evacuated using a vacuum pump to a pressure of -206.84 kPa. Raw biogas from the digester was delivered into the 37 kg cylinder at a pressure of 68.95 kPa at the rate of 1.3 L/s by means of a 1.5 hp compressor.

A: Weighing of the cattle dung **B: Preparation of substrate**

C: Gas pressure measurement **D: Harvesting of biogas into a cylinder**

Plate 3.1: Biogas Generation and Harvesting

3.3 Storage of Biogas

Storage vessels are used for the purpose of collecting biogas and also as transport media. The choice of storage vessels depends on the pressure of the gas to be stored. For this study the storage vessels used were tyre tubes and gas cylinders of various sizes (6 kg, 12.5 kg and 37 kg) based on the pressure of the gas to be stored. Based on the different stages of the study, different storage vessels were used.

1. Gas cylinders were used for harvesting of the gas into cylinder via a compressor.
2. Gas cylinders were used to supply the gas into the first stage scrubber.
3. Tyre tubes were used for the collection of the scrubbed gas from both the first stage and second stage scrubbers.
4. Cylinders were used to store the compressed purified biogas.
5. Cylinders were used to transport the raw and purified biogas for engine testing.

3.4 Design of Biogas Water Scrubbers

The scrubbers were designed to remove carbon dioxide from biogas so as to increase the percentage content of Methane in biogas. The operation of water scrubbing systems is highly dependent on the solubility of carbon dioxide at particular temperature and pressure in water to form dilute carbonic acid as seen in equation (3.5):

$$CO_2 + H_2O \rightarrow H_2CO_3 \qquad (3.5)$$

As stated in Olugasa *et al.*, (2014) the percentage of methane achieved after water scrubbing could be improved by carrying out double staged scrubbing. For this reason, two scrubbers were designed for this study-

A first stage scrubber which will purify the gas from 60 percent methane by volume to 90% methane by volume and a second stage water scrubber which will act on the biogas upgraded by the first stage scrubber and achieve biogas with a methane content of 99% by volume.

The design of a packed bed water scrubber involves the following steps as stated in Vijay *et al.*, (2006):

i. Assumptions of basic data.
ii. Solubility data generation.
iii. Material balance and determination of water flow rate.

iv. Selection of packing material.
v. Determination of column diameter.
vi. Determination of the height of the packed bed column.
vii. Selection of packing support and water distributor.

3.4.1 Design of the First stage Water Scrubber

3.4.1.1 Assumptions of Basic Data

The basic data assumed during the design of the scrubber were:

Composition of Raw Biogas: 60% Methane
40% Carbon dioxide

Composition of Biogas after scrubbing: 90% Methane
10% Carbon dioxide

Operating pressure of scrubber = 150 kPa; This is based on the fact that packed bed scrubbers are usually operated at pressures greater than atmospheric pressure (approx 100kPa) and temperatures near ambient (25^0C) (Peters *et al*, 2004)

Scrubber is desired to achieve a percentage drop of 35 to 10% CO_2 in biogas.

Volume of Biogas to be scrubbed= 1.0 m^3

3.4.1.2 Determination of solubility data

Henry's Law as given by equation (3.6) was used to determine the concentration of CO_2 in water. Solubility of CO_2 in water at 1 bar and 298 K is given as 2857 Pa.m^3/mol (Carroll *et al.* 1991)

$$p_i = K_H C_{max} \qquad [3.6]$$

C_{max}=Saturation concentration of CO_2 in mol/m^3

K_H= Henry's coefficient [Pa.m^3/mol]= 2857Pa.m^3/mol (Carroll *et al*, 1991)

p_i= Partial pressure of CO_2 component in biogas [Pa]

= 40% of biogas at 1.5 bar= $0.40 \times 150\ kPa = 60\ kPa$

$C_{max} = \frac{60,000}{2857}$ = 21.001 mol/m^3

Equation (3.6) was used to determine the Henry's law constant of CO_2; which indicates the solubility of CO_2 in water. It also reflects the relationship between the Henry's law constant and the concentration of CO_2 in water which is an inverse relationship. The Henry's law constant of CH_4 is very high due to the insolubility of CH_4, compared to that of CO_2 and H_2S which are both soluble in water. The high Henry's coefficient indicates that the gas phase is more dominant than the liquid phase (Levenspiel, 1999).

According to Carroll *et al.* (1992), equation (3.7) can be used to determine the solubility of CO_2 in water.

$$K_{Hcc} = \frac{C_{aq}}{C_G} = 0.8 \qquad (3.7)$$

Where C_{aq} = Concentration of water for absorption

C_G = Concentration of the gas to be absorbed

That is, $0.8\, X\, 10^{-4}\, m^3$ of CO_2 will dissolve in $1.0\, X\, 10^{-4}\, m^3$ of water. Since 1.0 m^3 of biogas is to be scrubbed and this contains $0.4m^3$ of CO_2 (40% of 1.0 m^3 biogas)

Volume of water needed to absorb $0.40m^3$ of $CO_2 = \frac{1 \times 10^{-4}}{0.8 \times 10^{-4}} \text{ x } 0.40$

$= 0.5m^3$ of water

500 Litres of water is needed to scrub 1 m^3 of biogas.

To estimate the concentration of the water (C_{aq}) in moles, the mass was obtained using equation (3.8)

$$\rho = \frac{mass}{volume} \qquad (3.8)$$

Where $e\ of\ water = \ 1000kg/m^3$, therefore mass

$mass = 1000 \times 0.5 = 500\ kg$ The number of moles can then be estimated using equation (3.9)

$$m = NM \qquad (3.9)$$

Where N= Number of Moles and M= Molar mass= 18kmol/kg

$N = \frac{500}{18} = 27.78$ mol

3.4.1.3 Determination of the Flow rate of CO_2 and Water

Solubility of CO_2 in clean water at normal temperature is

$$(0.87\ \times Partial\ pressure\ of\ CO_2 in\ atm) litres/\ litre\ of\ water$$

$$(0.87\ \times 0.4\ \times 1.5\ atm) litres/\ litre\ of\ water$$

$$0.522\ litres/\ litre\ of\ water$$

The full amount of CO_2 that should dissolve in water doesn't do so in practice, largely because all the CO_2 is not absorbed during the residence time of CO_2 in the tower. It is therefore necessary to have a double staged scrubbing.

Since 1000 litres of biogas is to be scrubbed which contains 400 litres of CO_2 (0.4 X 1000 Litres)

At 1.5 atm, 0.522 litres of CO_2 will dissolve in 1 litre of water

1 litre of CO_2 will dissolve in $\frac{1}{0.522}\, litres\ of\ water$

Therefore 400 litres of CO_2 will dissolve in $\frac{1}{0.522} \times 400\ litres\ of\ water$

= 766.28 litres of water.

To determine the rate at which 766.28 litres of water must be supplied, the rate of supply of the gas is important.

The gas is supplied at the rate of 25 L/min which corresponds to water supply at the rate of $\frac{25}{0.522} = 47.89 \frac{Litres}{min} \approx 50\ Litres/min$

For packed bed scrubbers, the recommended $\boldsymbol{F_l}/\boldsymbol{F_g} \approx 10$ (Kramers and Westerterp, 1961)

$\boldsymbol{F_l}$= Molar flow rate of water being used to scrub Biogas is 20 kmol/s

$\boldsymbol{F_g}$= Molar flow rate of biogas is 200 mol/s

3.4.1.4 Determination of Mass balance

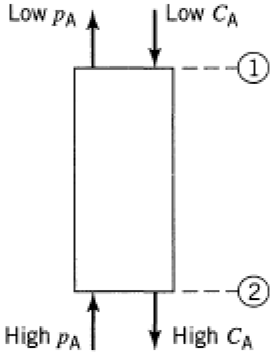
Material Balance Equation

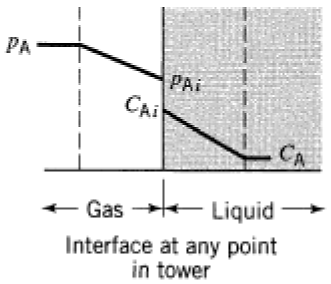
The scrubbing process can be represented by equation (3.10)

$$(A\ lost\ by\ gas) = (A\ gained\ by\ liquid) = (-r_a'''')dV_r \qquad (3.10)$$

Which becomes

$$P_{A2} - P_{A1} = \frac{F_l \pi}{F_g C_T}(C_{A1} - C_{A2}) \qquad (3.11)$$





Where P_{A_2}= Inlet pressure= Partial pressure of CO_2 at inlet = 40% of 150 kPa= 60 kPa

(Scrubber inlet pressure of biogas = 150 kPa)

P_{A_1}= Outlet Pressure = Partial Pressure of CO_2 at outlet = 0.1 × $150\ kPa = 15\ kPa$

F_l = Flow rate of water into the scrubber= 20 mol/s

F_G= Flow rate of gas in the scrubber= 200 mol/s

π= Total Pressure of gas in the scrubber = 150 kPa

C_T = Total Concentration of water= 56000 mol/m^3

C_{A_1}= Concentration of CO_2 in water at inlet= 0

C_{A_2}= Concentration of CO_2 in water at outlet= Unknown

Substituting values in equation (3.11)

$$(60-15)\times 10^3 = \frac{200\times 150\times 10^3}{20\times 56000}[CA_2 - 0]$$

CA_2 =168.00 mol/m^3

The Concentration of water at the interface was obtained from Henry's Law equation (3.6) as 21 mol/m^3 = 0.378 kg/m^3

3.4.1.5 Determination of Mass transfer Coefficient

The mass transfer coefficient was obtained from equation (3.12)

$$NA_L = K_L.a(C_{AL} - C_{ALi}) \qquad (3.12)$$

Where NA_L= number of moles in liquid

K_L= Mass transfer coefficient across liquid phase

a= Interfacial contact area per unit volume of reactor

From chemical equation (3.3), $CO_2 + H_2O \rightarrow H_2CO_3$ (3.13)

NA_L= 27.78 mols; C_{AL}= 168.00 mol/m^3; C_{ALi} =21mol/m^3;

a= 190m^2/m^3 for packed bed (Peters *et al.,* 2004)

Quantity of water required for scrubbing is

27.78= k_L. 190(168 - 21)

$k_L = \frac{27.78}{27930}$

$k_L = 9.95 \times 10^{-4}$

$k_L = k_G$ Based on the assumption that the rate of mass transfer across gas phase film = rate of mass transfer across the liquid phase film

3.4.1.6. Selection of Packing Material

Packing materials are normally used to increase the residence time of the gas in the water scrubber by increasing the interfacial area. Pall rings were selected as the packing material for the scrubber because it has a high percentage of free space which allows easy movement of the gas and liquid. The packing material is also made of PVC which is light and does not corrode. The Pall rings used were manufactured by Poly Injection Mould Making Services (PIMMS) PTY LTD, South Africa with the following specifications:

2 mm diameter, 91% free space and specific weight of 70 kg/m.

The pall rings used are shown in Plate 3.2.

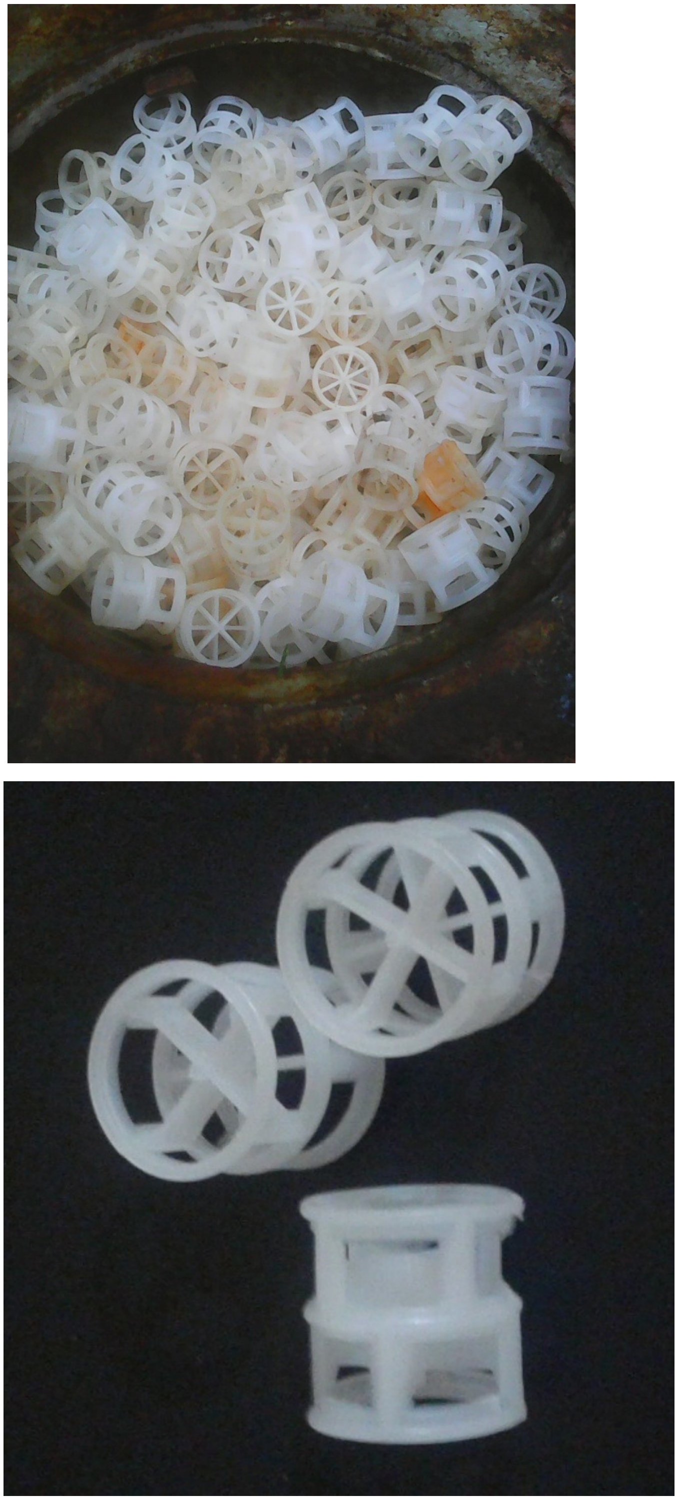


Plate 3.2: Pall Rings used as Packing Material in the Water Scrubber

3.4.1.7 Determination of the Reactor Volume

The reactor volume was estimated using equation (3.14)

$$V_r = hA_{cs} = \frac{F_g}{\pi K_{Ag} a}\frac{(dP_A)}{(P_{A2}-P_A^*)} \qquad (3.14) \quad \text{(Levenspiel, 1999)}$$

Where K_{Ag} = Overall mass transfer coefficient on gas basis

P_A^* = Pressure of gas at the gas-liquid interface

To obtain the overall mass transfer coefficient on gas basis, $K_{Ag,}$ equation (3.15) was used

$$\frac{1}{KAg} = \frac{1}{kAg} + \frac{H_A}{k_{Al}} \qquad (3.15)$$

$$= \frac{1}{0.1} + \frac{2857}{0.025} = 1005.03 + 28570 = 29575.03$$

$$K_{Ag=} \frac{1}{29575.03}$$

$K_{Ag} = 3.38 \times 10^{-5}$

To determine pressure in the scrubber, P_A , equation (3.16) was used

$$P_A - P_A^* = P_A - H_A C_A \qquad (3.16)$$

Where P_A^* = Pressure of gas at the gas-liquid interface

P_A = Pressure in the scrubber

H_A = Henry's coefficient

C_A = Concentration of water in scrubber

For any point in the tower P_A and C_A are related by the equation below:

$$P_{A3} - P_{A1} = \frac{(F_l/A_{cs})\pi}{(F_g/A_{cs})C_T}(C_{A3} - C_{A1})$$

$$P_{A3} - 15 \times 10^3 = \frac{(200/A_{cs})150 \times 10^3}{(20/A_{cs})56000}(C_{A3} - 0)$$

$$P_{A3} - 15 \times 10^3 = 0.2679(C_{A3} - 0)$$

$$C_{A3} = 3.73P_{A3} - 55991.041$$

$$P_A - P_A^* = P_A - 2857\,(3.73P_A - 55991.041)$$

$$P_A = \frac{-159966404.137}{-10655.61} = 15{,}012.411 \text{ Pa}$$

The values were then inserted into equation (3.15) to obtain the volume of the reactor

$$V_r = \frac{20}{150 \times 10^3 \times 3.38 \times 10^{-5} \times 190}\frac{(60-15)\times 10^3}{15{,}012.411}$$

$$V_r = 0.02076(2.9975)$$

$$V_r = 0.0622\text{m3}$$

Volume of Reactor = **62.23 Litres**

3.4.1.8 Determination of the packed bed height

Since the scrubber is cylindrically shaped, the volume of the scrubber was calculated from equation (3.17)

Volume of reactor= $\boldsymbol{hA_{cs}} = \pi r^2 h$ (3.17)

Where r= radius of scrubber

and h= packed bed height

A diameter of 0.26m (260 mm) was selected. The radius is therefore 0.130 m.

The calculated volume of reactor = 0.06223m

$$0.06223 = \pi 0.130^2\text{h}$$

$$h = \frac{0.06223}{\pi \times 0.130 \times 0.130}$$

$$h = 1.17m \approx 1.2m$$

3.4.1.9 Selection of packing support and water distributor

Metal sieves were placed at the top and bottom of the middle section of the scrubber to act as support for the raschig ring-packed bed.

Water was supplied to the scrubbing tower by means of an overhead 500 litre tank and the water was distributed by means of a water sprayer connected to the top section of the scrubber.

3.4.1.10 Material Selection

The designed scrubber will be handling water and raw biogas which contains hydrogen sulphide which is corrosive in nature. A non-corrosive material would then be appropriate such as aluminium or stainless steel. However, due to economic considerations, Galvanised steel was selected for the development of the scrubber. The scrubber was then painted both internally and externally after fabrication.

3.4.1.11 Shell design

The minimum thickness of the shell (t_s) of the scrubber was determined using equation (3.18)

$$t_s = \frac{P.D_i}{2fJ-P} \tag{3.18}$$

Where P= Design pressure= 1.1 x Operating pressure of the scrubber= 1.1 x 150 kPa

Di= Inside diameter = 0.26 m

J = Joint efficiency = 80 %

f= Allowable stress for galvanized steel

Yield strength for galvanized steel= 470- 550 MPa (ASME Code VIII)

Allowable stress= $\frac{Yield\ strength}{Factor\ of\ safety} = \frac{470}{4} = 117.5\ MPa$

$$t_s = \frac{165000\ \times 1.1}{2\ \times 117.5\ \times 10^6 \times 0.8 - 165000} = 0.0002283\ m$$

Corrosion allowance = 2 mm

ts = 2 + 0.228 mm = 2.23 mm

Gauge of galvanized steel used= Gauge 13 which is 2.3724 mm (www.machinemfg.com)

3.4.1.12 Stresses developed in the column

Axial and Circumferential Stresses

Axial stress (f_{as}) resulting from the internal pressure in a closed cylindrical shell is given by equation (3.19)

$$f_{as} = \frac{PD_0}{4Jt_s} \tag{3.19}$$

The Outer diameter Do can be estimated using equation (3.20)

$$D_O = D_i + 2t_s \tag{3.20}$$

Do = 0.265 m

$f_{as} = \frac{165000\ \times o.265}{4 \times 0.8 \times 0.00237}$ = 5765427.21 Pa = 5.76 MPa

Circumferential Stress (f_{cs}) was estimated using equation (3.21)

$$f_{cs} = 2\ \times f_{as} \tag{3.21}$$

$$f_{cs} = 2\ \times 5.76\ MPa = 11.53\ MPa$$

Compressive Stresses caused by dead loads

The dead loads in the scrubber are the weight of the shell, the dead weight of the liquid and dead weight of attachments on the scrubber.

Dead weight of shell

Weight of the shell is given in equation (3.22) (Sinnott, 1999)

$$W = m_{shell} \times g = \left(\frac{\pi}{4}(Do^2 - Di^2)h\,\rho_s\right) \times g \qquad (3.22)$$

Where:

W= weight of shell

Do= Outer diameter

Di= Inner diameter

h= Packed bed height of shell= 1.21 m

ρ_s= Density of shell= density of galvanized steel= 8030 kg/m^3

g = Acceleration due to gravity = 9.81 m/s^2

$$W = \left(\frac{\pi}{4}(0.265^2 - 0.260^2) \times 1.2 \times 8030\right) \times 9.81 = 198.38 \text{ N}$$

$$W_{shell} = W \times 75\% \text{ (extra weight for top section, bottom section, flanges, bolts etc)}$$

$$W_{shell} = 198.38 \times 1.75 = 343.87 \text{ N}$$

Shell weight stress, ($f_{\text{dead wt, shell}}$) was determined using equation (3.23)

$$f_{\text{dead wt,shell}} = \frac{W_{shell}}{\frac{\pi}{4}(Do^2 - Di^2)} \qquad (3.23)$$

$$= \frac{343.87}{\frac{\pi}{4}(0.265^2 - 0.260^2)} = 166924.77 \text{ Pa}$$

Dead weight of liquid

Height of liquid in the packed bed can be assumed to be 1/3 of packed bed height

= 1/3 of 1.21 m = 0.403 m

Mass of water (m_w) was determined using equation (3.24) (Sinnott, 1999)

$$m_w = 1/3 \times V_r \times \rho_w \times 1.3 \qquad (3.24)$$

(30% additional liquid held in bottom sections)

Where:

Vr = Volume of reactor= 0.0622 m^3

$P_{w\,=}$ Density of water= 1000 kg/m^3

$$m_w = 1/3 \times 0.0622 \times 1000 \times 1.3 = 26.95 \text{ kg}$$

Dead weight of liquid ($f_{\text{dead wt,liquid}}$) was estimated using equation (3.25) (Sinnott, 1999)

$$f_{\text{dead wt,liquid}} = \frac{m_w \times g}{\pi D_O \times t_s} \qquad (3.25)$$

$$f_{\text{dead wt,liquid}} = \frac{26.95 \times 9.81}{\pi 0.265 \times 0.00237} = 134010.06 \text{ Pa}$$

Dead weight of column attachments

Stress induced by column attachments like instruments was estimated using equation (3.26)

$$f_{dead\ wt,attachments} = \frac{m_{shell} \times 1.1}{\pi D_O \times t_s} \qquad (3.26)$$

$$= \frac{35.05 \times 1.1}{\pi 0.265 \times 0.00267} = 172329.14\ Pa$$

(extra 10% of mass of column)

Total dead weight= $f_{\text{dead wt, shell}} + f_{\text{dead wt, liquid}} + f_{\text{dead wt, attachment}}$

= 166924.77 + 134010.06 + 17329.14 Pa

= 318263.97 Pa

= 318.26 kPa which is << allowable stress for shell materials

3.1.4.1.13 Determination of number of bolts in gasketed joints

Uniformity of pressure on full gasketed joints is important. There are two gasketed joints in the scrubber. There is one between the upper section and the middle section and another between the middle section and the bottom section. In order to maintain uniform pressure adjacent bolts shall not be placed more than six nominal diameters apart on a bolt circle (Budynas and Nisbett, 2008).

Diameter of bolt circle= 370 mm

Perimeter of bolt circle = $\pi \times 370 = 1162.39\ mm$

Nominal diameter of bolt= 20 mm

Recommended distance apart= $6 \times 20\ mm = 120\ mm$

Number of bolts= $\frac{1162.39}{120} =$ 9.69 bolts $\approx 10\ bolts$

3.4.2 Design of the Second stage Water Scrubber

The design was done similar to the first stage scrubber

3.4.2. 1 Assumption of basis data

Composition of Raw Biogas: 60% Methane
40% Carbon dioxide

Composition of Biogas after 1st stage scrubbing: 90% Methane
10% Carbon dioxide

Composition of Biogas after 2nd stage scrubbing: 99% Methane
01% Carbon dioxide

Operating pressure of scrubber = 150kPa; This is based on the fact that packed bed scrubbers are usually operated at pressures greater than atmospheric pressure (approx 100kPa) and temperatures near ambient (25^0C) (Peters et al, 2004)

Solubility of CO_2 in water at 1 bar and 298K is given as 2857 Pa.m^3/mol (Carroll et al, 1991)

Scrubber desired to achieve a percentage drop of 10% to 1% CO_2 in biogas.

Volume of Biogas to be scrubbed= 0.35 m^3

3.4.2.2 Determination of Solubility data

Henry's Law as presented in equation (3.27) was used to determine the concentration of CO_2 in water

$P_i = K_H C_{max}$ (3.27)

C_{max}=Saturation concentration of CO_2 in mol/m^3

K_H= Henry's coefficient [Pa.m^3/mol]= 2857Pa.m^3/mol (Carroll *et al,* 1991)

P_i= Partial pressure of CO_2 component in biogas [Pa]

= 10% of biogas at 1.5 bar= $0.10 \times 150\ kPa = 15\ kPa$

$C_{max} = \frac{60,000}{2857}$ = 21.001 mol/m^3

According to Carroll et al, 1992, equation (3.28) can be used to determine the solubility of CO_2 in water

$K_{Hcc} = \frac{C_{aq}}{C_G} = 0.8$ (3.28)

Where C_{aq} = Concentration of water for absorption

C_G = Concentration of the gas to be absorbed

That is, $0.8\ X\ 10^{-4} m^3$ of CO_2 will dissolve in $1.0\ X\ 10^{-4} m^3$ of water. Since 0.35 m^3 of biogas is to be scrubbed and this contains 0.035m^3 of CO_2 (10% of 0.35 m^3 biogas)

Volume of water needed to absorb 0.10m^3 of CO_2 = $\frac{1 \times 10^{-4}}{0.8 \times 10^{-4}}$ x 0.035

= 0.0438 m^3 of water

43.75 Litres of water needed to scrub 0.35m^3 of biogas.

To estimate the concentration of the water (C_{aq}) in moles, the mass was obtained using equation (3.29)

$\rho = \frac{mass}{volume}$ (3.29)

Where $volume\ of\ water = \ 1000 \frac{kg^3}{m}$, therefore $mass = 1000 \times 0.04375 = 43.75\ kg.$

The number of moles can then be estimated using equation (3.30)

$m = NM$ (3.30)

Where N= Number of Moles and M= Molar mass= 18kmol/kg

$N = \frac{43.75}{18}$= 2.43 mol

(Levenspiel, 1999)

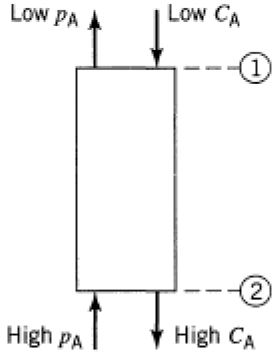
3.4.2.3 Determination of Material balance

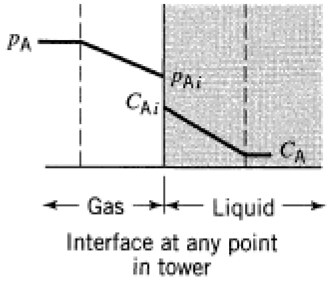
The scrubbing process can be represented by equation (3.31)

$(A\ lost\ by\ gas) = (A\ gained\ by\ liquid) = (-r_a'''')dV_r$ (3.31)

Which can be expressed as equation (3.32)

$$P_{A2} - P_{A1} = \frac{F_l \pi}{F_g C_T}(C_{A1} - C_{A2}) \quad (3.32)$$





Where P_{A_2}= Inlet pressure= Partial pressure of CO_2 at inlet = 10% of 150 kPa= 15 kPa

(Scrubber inlet pressure of biogas = 150 kPa)

P_{A_1}= Outlet Pressure = Partial Pressure of CO_2 at outlet =1% $\times$ $150\ kPa = 1.5\ kPa$

F_l = Flow rate of water into the scrubber= 20 mol/s

F_G= Flow rate of gas in the scrubber= 200 mol/s

π= Total Pressure of gas in the scrubber = 150 kPa

C_T = Total Concentration of water= 56000 mol/m^3

C_{A_1}= Concentration of CO_2 in water at inlet= 0

C_{A_2}= Concentration of CO_2 in water at outlet= Unknown

Substituting values in equation (3.23)

$$(15 - 1.5) \times 10^3 = \frac{200 \times 150 \times 10^3}{20 \times 56000}[CA_2 - 0]$$

CA_2 =504 mol/m^3

The Concentration of water at the interface was obtained from Henry's Law equation (3.27) as 21 mol/m^3 = 0.378 kg/m^3

3.4.2.4 Determination of Mass transfer Coefficient

The mass transfer coefficient can now be obtained from equation (3.33)

$$\mathrm{NA_L} = \mathrm{K_L}.\mathrm{a}(\mathrm{C_{AL}} - \mathrm{C_{ALi}}) \qquad (3.33)$$

Where NA_L= number of moles in liquid

K_L= Mass transfer coefficient across liquid phase

a= Interfacial contact area per unit volume of reactor

From chemical equation, $CO_2 + H_2O \rightarrow H_2CO_3$

NA_L= 2.43 mols; C_{AL}= 504 mol/m^3 ; C_{ALi} =21mol/m^3;

a= 190m^2/m^3 for packed bed (Peters et al, 2004)

Quantity of water required for scrubbing is

2.43 = k_L. 190 (504 - 21)

$k_L = \frac{2.43}{91770}$

$k_L = 2.65 \times 10^{-5}$

$k_G = 0.1$

3.4.2.5 Determination of the Volume of the reactor

The reactor volume was estimated using equation (3.34)

$$V_r = hA_{cs} = \frac{F_g}{\pi K_{Ag} a} \frac{(dP_A)}{(P_{A2} - P_A^*)} \qquad (3.34)$$

Where K_{Ag} = Overall mass transfer coefficient on gas basis

P_A^* = Pressure of gas at the gas-liquid interface

To obtain the overall mass transfer coefficient on gas basis, $K_{Ag,}$ equation (3.35) was used

$$\frac{1}{KAg} = \frac{1}{k_{Al}} + \frac{H_A}{k_{Ag}} \qquad (3.35)$$

$$= \frac{1}{0.0000265} + \frac{2857}{0.1} = 37735.85 + 28570 = 66305.85$$

$$K_{Ag} = \frac{1}{66305.85}$$

$$= 1.51 \times 10^{-5}$$

To determine pressure in the scrubber, P_A , equation (3.36) was used

$$P_A - P_A^* = P_A - H_A C_A \qquad (3.36)$$

Where P_A^* = Pressure of gas at the gas-liquid interface

P_A = Pressure in the scrubber

H_A = Henry's coefficient

C_A = Concentration of water in scrubber

For any point in the tower P_A and C_A are related by the equation below:

$$P_{A3} - P_{A1} = \frac{(F_l/A_{cs})\pi}{(F_g/A_{cs})C_T}(C_{A3} - C_{A1})$$

$P_{A3} - 1.5 \times 10^3 = \frac{(200/A_{cs})150 \times 10^3}{(20/A_{cs})56000}(C_{A3} - 0)$

$P_{A3} - 1.5 \times 10^3 = 0.2679(C_{A3} - 0)$

$$C_{A3} = 3.73P_{A3} - 5599.1041$$

$P_A - P_A^* = P_A - 2857\ (3.73P_A - 5599.1041)$

$P_A = \frac{-15996640.538}{-10655.61} = 1{,}501.2411$ Pa

The values were then inserted into equation (3.34) to obtain the volume of the reactor

$$V_r = \frac{20}{150 \times 10^3 \times 1.51 \times 10^{-5} \times 190}\frac{(15 - 1.5) \times 10^3}{1{,}501.2411}$$

$$V_r = 0.004647(8.9926)$$

$$V_r = 0.04179\text{m3}$$

Volume of reactor = 41.79 Litres

3.4.2.6 Determination of the packed bed height

Since the scrubber is cylindrically shaped, the volume of the scrubber was calculated from equation (3.37)

Volume of reactor= $\boldsymbol{hA_{cs}} = \pi r^2 h$ (3.37)

Where r= radius of scrubber

and h= packed bed height

A diameter of 0.30m (300 mm) was selected. The radius is therefore 0.150 m.

The calculated volume of reactor = 0.04179 m^3

$0.04179 = \pi 0.15^2 h$

h= 0.53 m

3.4.2.7 Selection of packing support and water distributor

Metal sieves were placed at the top and bottom of the middle section of the scrubber to act as support for the raschig ring-packed bed.

Water was supplied to the scrubbing tower by means of an overhead 500 Litre tank and the water was distributed by means of a water sprayer connected to the top section of the scrubber.

3.4.2.8 Material Selection

The designed scrubber will be handling water and raw biogas which contains hydrogen sulphide which is corrosive in nature. A non-corrosive material would then be appropriate such as stainless steel. However, due to economic considerations, Galvanised steel sheets were used for the development of the scrubber. The scrubber was then painted both internally and externally after fabrication.

3.4.2.9 Shell design

The minimum thickness of the shell (t_s) of the scrubber was determined using equation (3.38)

$$t_s = \frac{P.D_i}{2fJ-P} \qquad (3.38)$$

Where P= Design pressure= 1.1 x Operating pressure of the scrubber= 1.1 x 150 kPa

Di= Inside diameter = 0.27 m

J = Joint efficiency = 80 %

f= Allowable stress for galvanized steel

Yield strength for galvanized steel= 470- 550 MPa (ASME Code VIII)

Allowable stress= $\frac{Yield\ strength}{Factor\ of\ safety} = \frac{470}{4} = 117.5\ MPa$

$$t_s = \frac{165000\ \times 1.1}{2\ \times 117.5\ \times 10^6 \times 0.8 - 165000} = 0.0002283\ m$$

Corrosion allowance = 2 mm

ts = 2 + 0.228 mm = 2.23 mm

Gauge of galvanized steel used= Gauge 13 which is 2.3724 mm (www.machinemfg.com)

3.4.2.10 Stresses developed in the column

Axial and Circumferential Stresses

Axial stress (f_{as}) resulting from the internal pressure in a closed cylindrical shell is given by equation (3.29)

$$f_{as} = \frac{PD_0}{4Jt_s} \qquad (3.29)$$

The Outer diameter Do can be estimated using equation (3.30)

$$D_O = D_i + 2t_s \qquad (3.30)$$

Do = 0.275 m

$f_{as} = \frac{165000 \times 0.275}{4 \times 0.8 \times 0.00237}$ = 5982990.51 Pa = 5.98 MPa

Circumferential Stress (f_{cs}) was estimated using equation (3.31)

$$f_{cs} = 2 \times f_{as} \quad (3.31)$$

$$f_{cs} = 2 \times 5.98\, MPa = 11.96\, MPa$$

Compressive Stresses caused by dead loads

The dead loads in the scrubber are the weight of the shell, the dead weight of the liquid and dead weight of attachments on the scrubber.

Dead weight of shell

Weight of the shell is given in equation (3.32) (Sinnott, 1999)

$$W = m_{shell} \times g = \left(\frac{\pi}{4}(Do^2 - Di^2)h\, \rho_s\right) \times g \quad (3.32)$$

Where:

W= weight of shell

Do= Outer diameter

Di= Inner diameter

h= Packed bed height of shell= 1.21 m

ρ_s= Density of shell= density of galvanized steel= 8030 kg/m^3

g = Acceleration due to gravity = 9.81 m/s^2

$$W = \left(\frac{\pi}{4}(0.275^2 - 0.270^2) \times 1.2 \times 8030\right) \times 9.81 = 202.31 \text{ N}$$

$$W_{shell} = W \times 75\% \text{ (extra weight for top section, bottom section, flanges, bolts etc)}$$

$$W_{shell} = 202.31 \times 1.75 = 354.05 \text{ N}$$

Shell weight stress, ($f_{\text{dead wt, shell}}$) was determined using equation (3.33)

$$f_{\text{dead wt,shell}} = \frac{W_{shell}}{\frac{\pi}{4}(Do^2 - Di^2)} \quad (3.33)$$

$$= \frac{354.05}{\frac{\pi}{4}(0.275^2 - 0.270^2)} = 165443.93 \text{ Pa}$$

Dead weight of liquid

Height of liquid in the packed bed can be assumed to be 1/3 of packed bed height

= 1/3 of 0.53 m = 0.18 m

Mass of water (m_w) was determined using equation (3.34) (Sinnott, 1999)

$$m_w = 1/3 \times V_r \times \rho_s \times 1.3 \qquad (3.34)$$

(30% additional liquid held in bottom sections)

Where:

Vr = Volume of reactor= 0.0418 m^3

$P_{w=}$ Density of water= 1000 kg/m^3

$$m_w = 1/3 \times 0.0418 \times 1000 \times 1.3 = 18.11 \text{ kg}$$

Dead weight of liquid ($f_{\text{dead wt,liquid}}$) was estimated using equation (3.35) (Sinnott, 1999)

$$f_{\text{dead wt,liquid}} = \frac{m_w \times g}{\pi D_O \times t_s} \qquad (3.35)$$

$$f_{\text{dead wt,liquid}} = \frac{18.11 \times 9.81}{\pi 0.275 \times 0.00237} = 86783.36 \text{ Pa}$$

Dead weight of column attachments

Stress induced by column attachments like instruments was estimated using equation (3.36)

$$f_{dead\ wt,attachments} = \frac{m_{shell} \times 1.1}{\pi D_O \times t_s} \qquad (3.36)$$

$$= \frac{18.11 \times 1.1}{\pi 0.275 \times 0.00237} = 9729.27\ Pa$$

(extra 10% of mass of column)

Total dead weight= $f_{\text{dead wt, shell}} + f_{\text{dead wt, liquid}} + f_{\text{dead wt, attachment}}$

= 165443.93 + 86783.36 + 9729.27 Pa

= 261956.56 Pa

= 261.96 kPa which is << allowable stress for shell materials

3.1.4.2.11 Determination of Number of Bolts in Gasketed Joints

There are two gasketed joints in the scrubber. There is one between the upper section and the middle section and another between the middle section and the bottom section. Uniformity of pressure on full gasketed joints is important. In order to maintain uniform pressure adjacent bolts shall not be placed more than six nominal diameters apart on a bolt circle (Budynas and Nisbett, 2008).

Diameter of bolt circle= 360 mm

Perimeter of bolt circle = $\pi \times 360 = 1130.97\ mm$

Nominal diameter of bolt= 20 mm

Recommended distance apart= $6 \times 20\ mm = 120\ mm$

Number of bolts= $\frac{1130.97}{120} =$ 9.42 bolts $\approx 10\ bolts$

3.4.3 Cost Analysis for the Development of the Scrubbers

The cost analysis was done based on the market prices of the materials. The Total Capital Investment (TCI) was estimated to include the cost of purchasing the materials for the scrubbers including the direct and indirect costs associated with the fabrication and installation of the scrubbers.

TCI = PEC + DC +IC

Where:

PEC= Purchased equipment costs

DC = Direct installation costs

IC = Indirect installation costs

3.5 Single stage and Double stage Water Scrubbing of Biogas

The water scrubbing of biogas involves the absorption of CO_2 in raw biogas in water, when the water and pressurized biogas are allowed to flow into a packed bed water scrubber in a counter current way as prescribed by Dubey (2000), Shyam (2002), Vijay et al. (2006) and Bhattacharya et al. (2009). The set up for the single stage and double stage water scrubbing of biogas were as shown in Figures 3.1 and 3.2.

The first stage and second stage scrubbers with packed bed heights of 1210 mm and 510 mm, respectively, were filled with pall rings of 25mm diameter in staggered arrangement. Water flow rate and gas flow rates were adjusted using a gas and a digital water flow meter as shown in plate 3.3. Water was supplied from a 500 L overhead tank into the first stage scrubber from the top while the raw biogas was fed into the first stage scrubber of capacity $0.062m^3$, from the bottom of the tank. The scrubber was first filled with water at a flow rate of 0.000833 m^3/s (50L/min) to a height of about one-third of the packed bed with the water outlet valve at the bottom of the scrubber closed. Raw biogas was fed into the first stage scrubber by means of a compressor at a pressure of 198.066 kPa, ambient temperature of 25°C and at a flow rate of 0.000417 m^3/s (25 L/min) and the valve at the bottom of the scrubber was then opened to allow the water flow out of the scrubber. The effluent purified biogas was collected from the top of the scrubber into a modified tyre tube of capacity 0.206 m^3 to obtain Single stage Water Scrubbed Biogas (SWSB) as shown in figure 3.5.

To obtain the Double stage Water Scrubbed Biogas (DWSB), the SWSB was scrubbed in a similar way to that stated above. SWSB at a flow rate of 0.000417 m^3/s was fed into the second stage scrubber of capacity 0.042 m^3 from the bottom of the scrubber at a delivery pressure of 198.066 kPa from a 1.5 hp compressor. Water was passed through at a flow rate of 0.000833 m^3/s and allowed to flow out from the bottom of the tank. The DWSB was also collected at the top of the scrubber into a modified tyre tube of capacity 0.206 m^3 as shown in Figure 3.2.

The mass of gas lost during the scrubbing processes were estimated by measuring the masses of the gas before and after scrubbing.

Small quantities of SWSB and DWSB were collected in 500 ml Restek gas sampling bags for analysis, while the rest were stored in cylinders in preparation for the engine test.

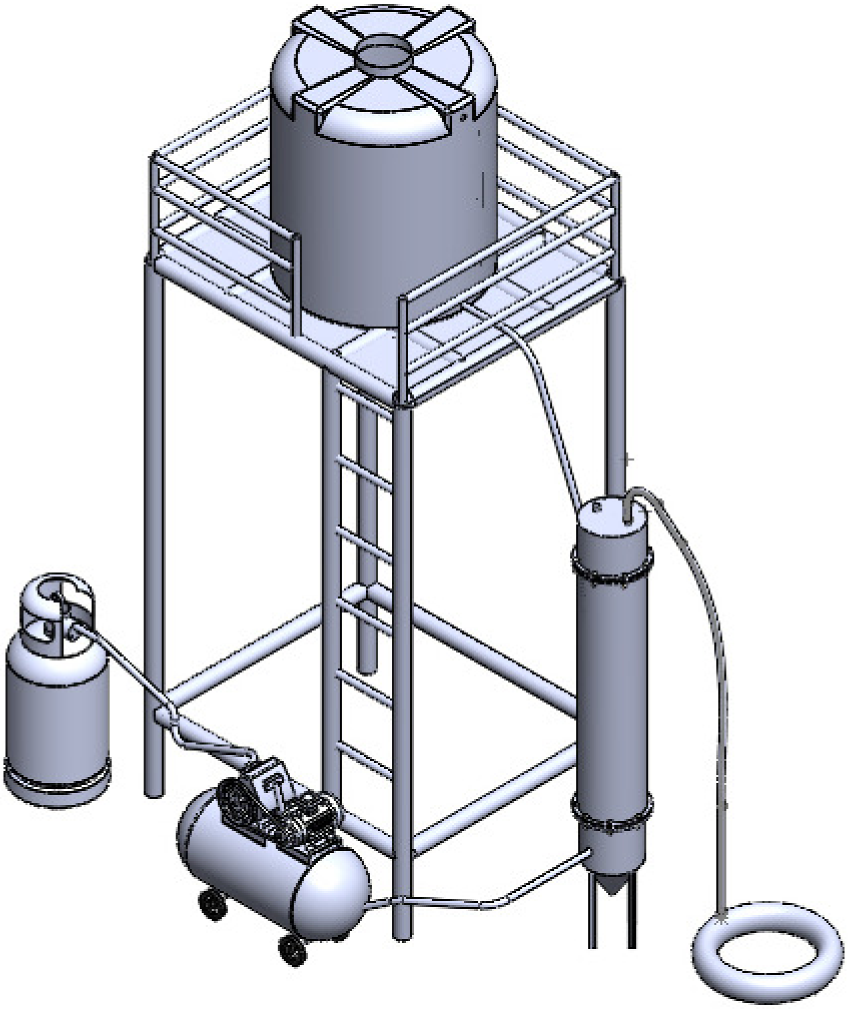


Figure 3.1: Experimental set up for Single stage water scrubbing

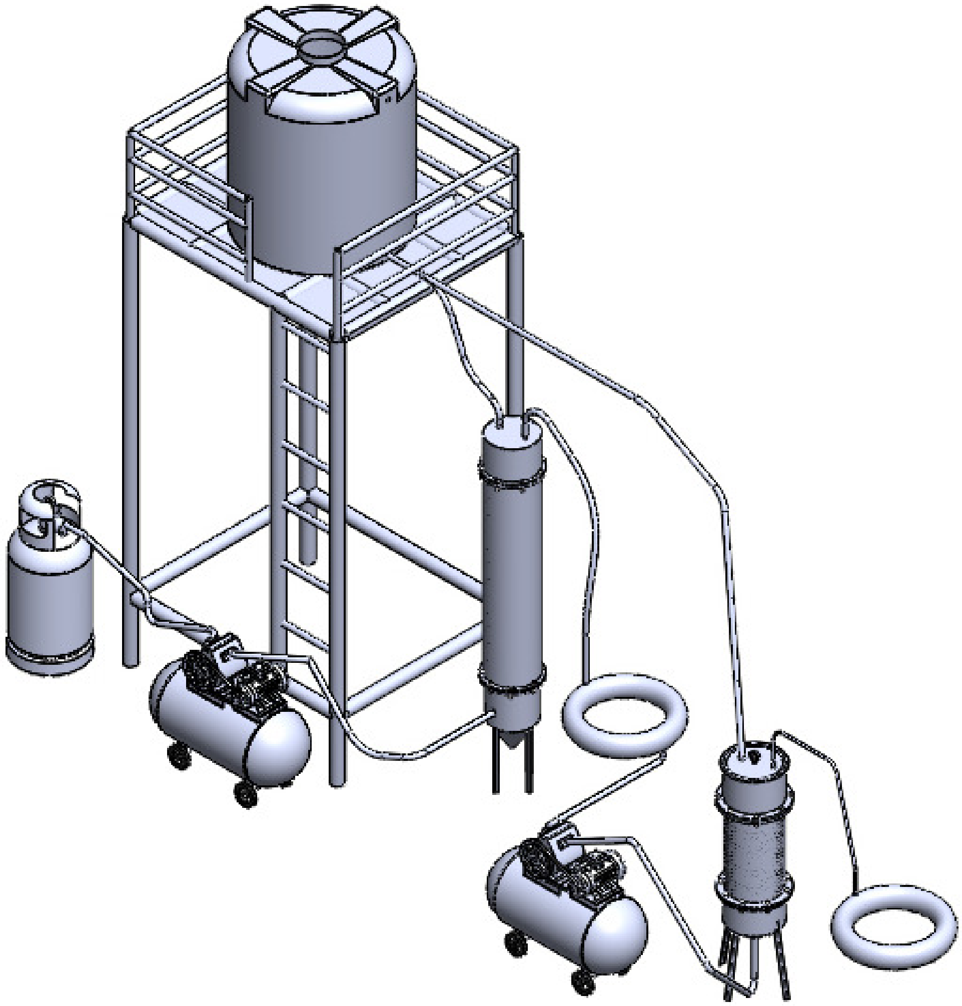


Figure 3.2: Experimental Set up for Double Stage Water Scrubbing

A: Digital water flow meter used

B: Rotameter used for the study

Plate 3.3: Flow meters used for the Water scrubbing process

3.6 Drying of the Scrubbed Biogas

The water scrubbing process involves passing the gas through water, thus increasing the moisture content of the purified gas. It is therefore important to dry the gas to reduce the moisture content of the gas which lowers the flame temperature of the gas, its calorific value as well as the stoichiometric ratio of biogas (Kuria and Maringa, 2008). Silica gel is one of the methods recommended for drying biogas (Fowler (2007) and Persson *et al*. (2006)). The purified gas was therefore dried by passing it through a dry scrubber which was filled with 100g of silica gel. Silica gel traps water molecules inside its pores yet remains dry and appears physically unchanged. A self-indicating silica gel was used for this study. The silica gel contains anhydrous cobalt chloride which exhibits blue colour. After absorbing water, the silica gel turns pink showing that it no longer has an absorbent capacity. However, if heated after thermal dehydration it regains its absorbent capacity and changes colour back to blue. In this study the dry scrubber was arranged as shown in Figure 3.3 so that the compressor forces the gas through the dry scrubber thus drying the gas in the process and it was observed that the silica gel after scrubbing had not changed completely to pink.

3.7 Compression and Storage of Purified Biogas (SWSB and DWSB)

According to Kapdi *et al.* (2005), it is important to compress biogas before storage because it has the advantages of reducing the storage requirements, concentrating the energy content and increasing the pressure to the required level for easy gas flow. The 0.8 kg of SWSB and DSWB were first passed through a silica gel filled - dry scrubber and then compressed to 375.8 kPa using a 1.5 hp compressor and delivered into 6kg gas cylinders. The compression of the gas to high pressure was done as the combustion in the engine cylinder is influenced strongly by the pressure and consequently the temperature. According to Muharam *et al.* (2015), increase in pressure at constant volume increases the kinetic energy of the gas molecules and this result in higher mass density and thus the heating value. The compression of biogas into cylinders prior to engine test goes a long way in improving the combustion quality of the gas.

ITEM NO.	PART NAME	DESCRIPTION	QTY.
1	Gas can		1
2	Tyre tube		1
3	Air compressor		1
4	Drying chamber		1
5	Silica gel container		2
6	Pressure guage		1
7	Pipe1		1
8	Pipe 2		1
9	Pipe 3		1

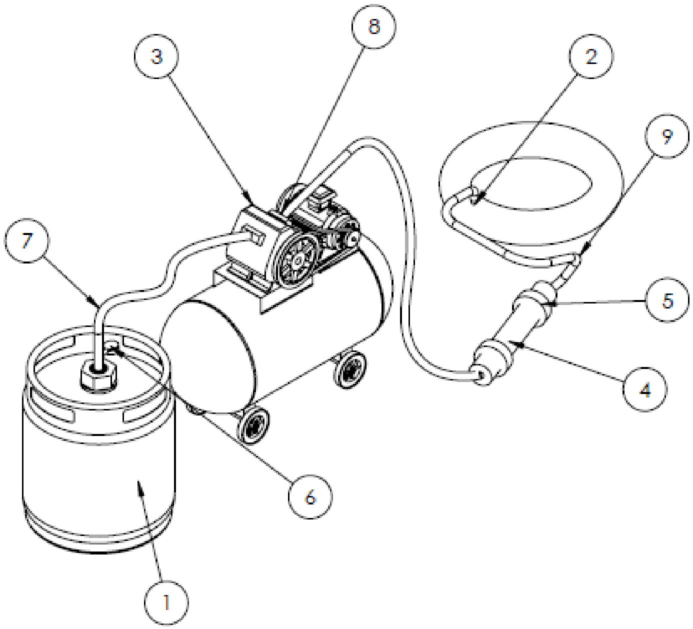


Figure 3.3: Set up for Drying, Compression and Storage of Purified Biogas

3.8 Biogas Analysis

3.8.1 Determination of the Methane Content

The CH_4 concentration in biogas is usually determined using Gas Chromatography (GC) by most researchers. This method is indeed an accurate and precise way of estimating CH_4 concentration levels in biogas (Shahriari *et al.,* 2012). However, in many developing countries where GC, with headspace for gas characterisation, may not be available, the CH_4 concentration can be determined using the liquid displacement method (LDM) (Demirer *et al.*, 2000). This was the case in this study as GC equipment was non- functional in most institutions and for those which had functioning GCs, they had no head space which is the attachment necessary for the processing of gas samples. Efforts were made to analyse the samples of this study at NNPC refinery however with no success in the long run (Appendix VII). The LDM is a wet chemistry method which involves the use of acid and bases and the accuracy of the method was found to be acceptable with the CH_4 concentration linearly related to that obtained with the use of GC and only about 3% higher than the values obtained using GC.

In the procedure, a 50 ml graduated measuring cylinder and a 1 liter container were used. About 700 ml 0.5 M hydrochloric acid (HCl) was prepared poured into the container. The P^H of the 0.5M HCl was read using a HANNA HI9828 digital P^H meter, which had first been calibrated in a buffer solution. The P_H of the HCl was 3.0. The cylindrical flask was filled with the 0.5 M HCl and inverted with the opening in the container so that the flask remained full of liquid. A tube was inserted into the cylindrical flask and the other end was attached to a gas sampling bag containing the biogas sample to be analysed. The setup is as shown in Plate 3.4. The valve of the sampling bag was opened, and the biogas sample flowed into the cylindrical flask containing the 0.5 M HCl and replaced the acid. The volume of gas released into the flask corresponds to the amount of HCl displaced and the volume was recorded as V_1 ml. 0.5 M of Potassium chloride (KOH) was added to the acid in the container to raise the pH to above 9 in order to absorb CO_2 present in the biogas sample. KOH was added to the container and was tested using a P^H meter, and it read 11. Quantities of CO_2 and H_2S were absorbed and this reduced the volume of gas in the measuring cylinder to V_2 ml. The volume V_2 is an estimate of the percentage volume of CH_4 in the gas; while the difference between initial and final volume corresponds to the CO_2 content in the biogas because the H_2S concentration was taken as being negligible compared with CO_2 concentration.

The methane content was therefore estimated using equation (3.37):

$$\text{Methane content, \% vol.} = \frac{V2}{V1} \qquad (3.37)$$

Where V_1 = Initial volume of biogas

V_2 = Final volume of biogas

3.8.2 Estimation of the Efficiencies of the scrubbers

The efficiencies, η of the scrubbers were determined using equation (3.38) as adopted in Saelee (2008). The percentage of CO_2 before and after scrubbing were obtained from the result of the LDM.

$$\eta = \frac{x_i - x_j}{x_i} \times 100\% \qquad (3.38)$$

Where x_i = percentage volume of CO_2 before scrubbing

x_j = percentage volume of CO_2 after scrubbing

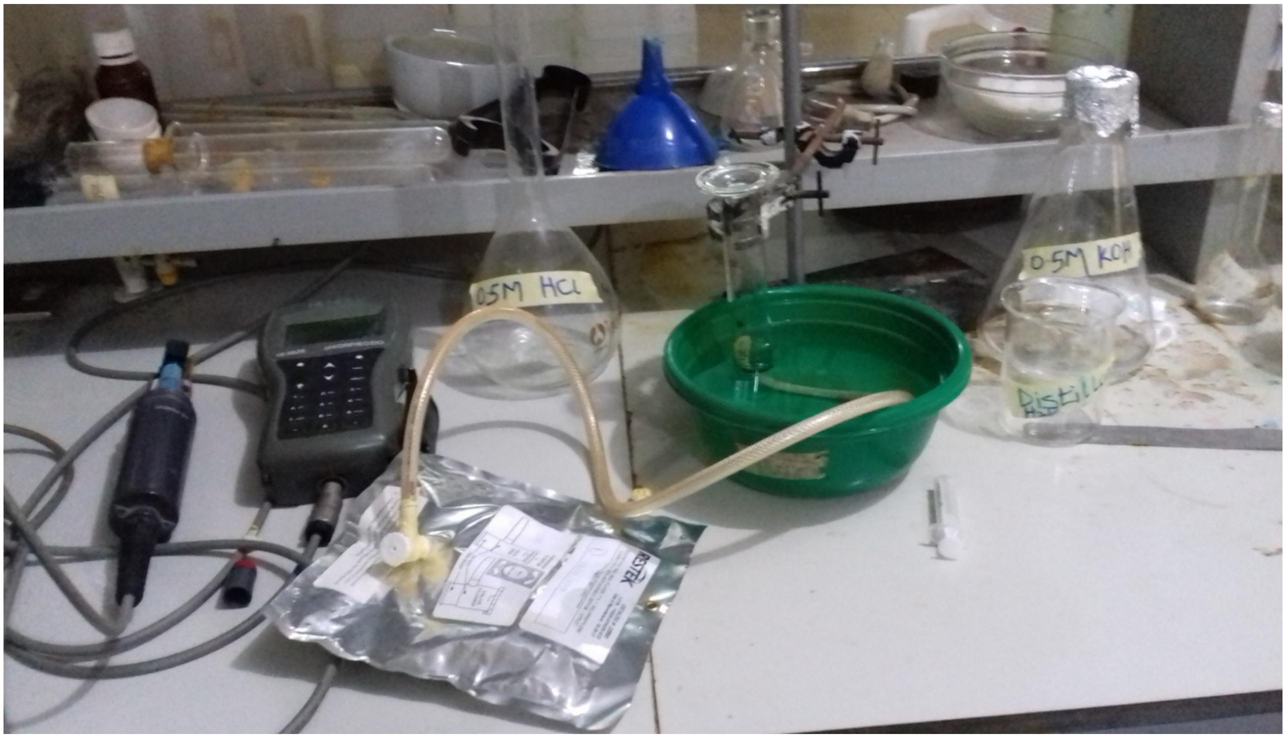


Plate 3.4: Set up for LDM Procedure

3.8.3 Determination of the Calorific Value of Biogas

This was estimated after the composition of the biogas had been determined by the LDM as reported by Demirer *et al*., 2000. The percentage by volume of methane was then inserted into the following equation (3.39) prescribed by Von Mitzklaff (1988) to estimate the heating value of the gas.

$$H_{u,act} = \frac{V_{CH4}}{V_{tot}} . \rho . CH_{4,act} . H_U \qquad (3.39)$$

H_U is the lower calorific value of biogas=50000 KJ/kg

V_{CH_4} is the volume of methane in the biogas,

V_{tot} is the total volume of the biogas,

$\frac{V_{CH_4}}{V_{tot}}$ = % Volume of methane in the biogas

$\rho_{CH_4,act}$ is the actual density of the methane in the biogas and it was estimated using equation (3.40)

$$\rho_{CH_{4,act}} = \rho_{CH_{4,std}} , . \frac{P_{act}}{P_{std}} . \frac{T_{std}}{T_{act}} \qquad (3.40)$$

$\rho_{CH_4,std}$ is the density of methane at standard condition (i.e. 298 K, 1013mbar=0.1013 MPa) and it is given by 0.72kg/m^3(SGC 2012)

P_{std} is the pressure of methane at standard condition = 1013mbar

T_{std} is the temperature of methane at standard condition = 298k

P_{act} is the actual pressure of the biogas

T_{act} is the actual temperature of the biogas

3.9 Modification of SI Engine to run on Biogas

According to Shah et al. (2016), a commercial CNG conversion kit can be used for biogas applications. Therefore, for this study, a commercial kit with Patent No. Z12013207999046 was adopted to modify the engine to run on gaseous fuel. It was designed to run either on LPG or CNG. For this study, it was adjusted to run on LPG when LPG was being used to operate the engine and it was switched to run on CNG when experimentation with raw biogas and the purified biogas were done. It consists of a carburetor and a mixing chamber. It was attached to the intake port of the carburetor (Plate 3.5).

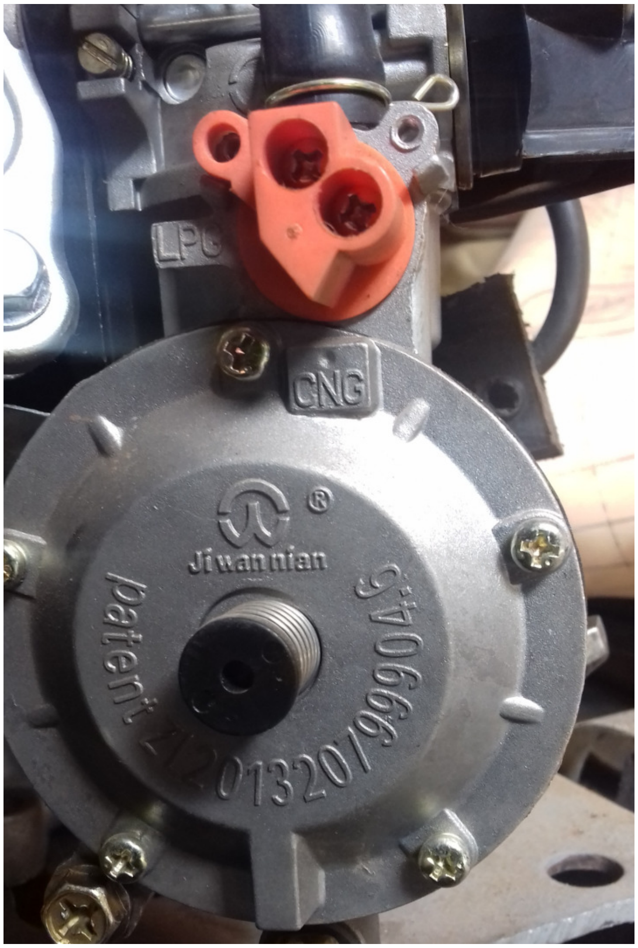


Plate 3.5: Commercial Gas Conversion Kit

3.10 Performance Tests on SI Engine operating with Biogas

The performance test was conducted with reference to SAE International standard for Engine Power Test Code for SI and CI engine (SAE J1349). The parameters to be tested were Power output, shaft speed, torque, exhaust gas temperature, fuel consumption and flue gas emission.

The test was performed on a single cylinder four-stroke SI engine rig (Plate 3.6). The experimental set up is shown in Figures 3.4 and 3.5. The rig consists of a 4.125 kW SI ignition engine (ElemaxTigmax GX 160) fitted with a commercial gas conversion kit and coupled to a TD114-hydraulic dynamometer. A PCA 3 Bacharach-flue gas analyser (Plate 3.7) was used for measurement of CO, O_2 and SO_2 emissions. The exhaust gas temperatures were measured using Chromal-Aluman (Cr-Al) type T thermocouples and the volumetric flow rate of the gas was measured with a rotameter. The CR and the ignition timing of the engine were not adjusted. The Engine specifications are presented in Table 3.1.

The engine was run at three loads- 0, 50 and 100 %. The fuels to be tested were Liquefied Petroleum Gas (for baseline study), Raw Biogas (RB), Single stage Water Scrubbed Biogas (SWSB) and Double stage Water Scrubbed Biogas (DWSB).

The fundamental variables like speed, torque and temperature were measured and the performance indices like Brake Power (BP), Brake Specific Fuel Consumption (BSFC) and Brake Thermal Efficiency (BTE) were determined using standard equations.

3.10.1 Procedure for the Engine Test

The engine test was run at constant compression ratio of 8.5:1 and 0, 50 and 100 % loading conditions.

The engine was operated with Liquid petroleum gas (LPG) for a baseline study. The engine was started on petrol and run on a no load condition for about 2 minutes after which the petrol supply was cut off and just before the engine stalled, the gas supply valve was opened and then loaded gradually from no-load condition to 100 % load. The following were measured and recorded during every run: Gas flow rates, torque, speed and exhaust gas temperature. The gas cylinder was fitted with a gas regulator to which was attached a gas flow meter and the gas was gradually increased from 0 L/Min at no load, to 5 L/min at 50 % and then to 10 L/min at full load. The engine was run with LPG, raw biogas (RB), single stage water scrubbed biogas (SWSB) and double stage water scrubbed biogas (DWSB) and measurements were taken and recorded.

Table 3.1: Specifications of 4.125 kW spark ignition engine (GX 160)

Engine Type	**Air-cooled 4-stroke OHV**
Bore x Stroke	68 X 45 mm
Displacement	163 cm^3
Net Power Output*	4.8 HP (3.6 kW) @ 3,600 rpm
Net Torque	7.6 lb-ft (10.3 Nm) @ 2,500 rpm
PTO Shaft Rotation	Counterclockwise (from PTO shaft side)
Compression Ratio	8.5 : 1
Lamp/Charge coil options	25W, 50W / 1A, 3A, 7A
Carburetor	Butterfly
Ignition System	Transistorized magneto
Starting System	Recoil Starter
Lubrication System	Splash
Governor System	Centrifugal Mechanical
Air cleaner	Dual Element
Oil Capacity	0.61 US qt. (0.58 L)
Fuel Tank Capacity	3.3 U.S. qts (3.1 liters)

(a) Coupling of engine to Dynamometer

(b) Rig set for experimentation

Plate 3.6: The TD 114 Engine test bed used for the study

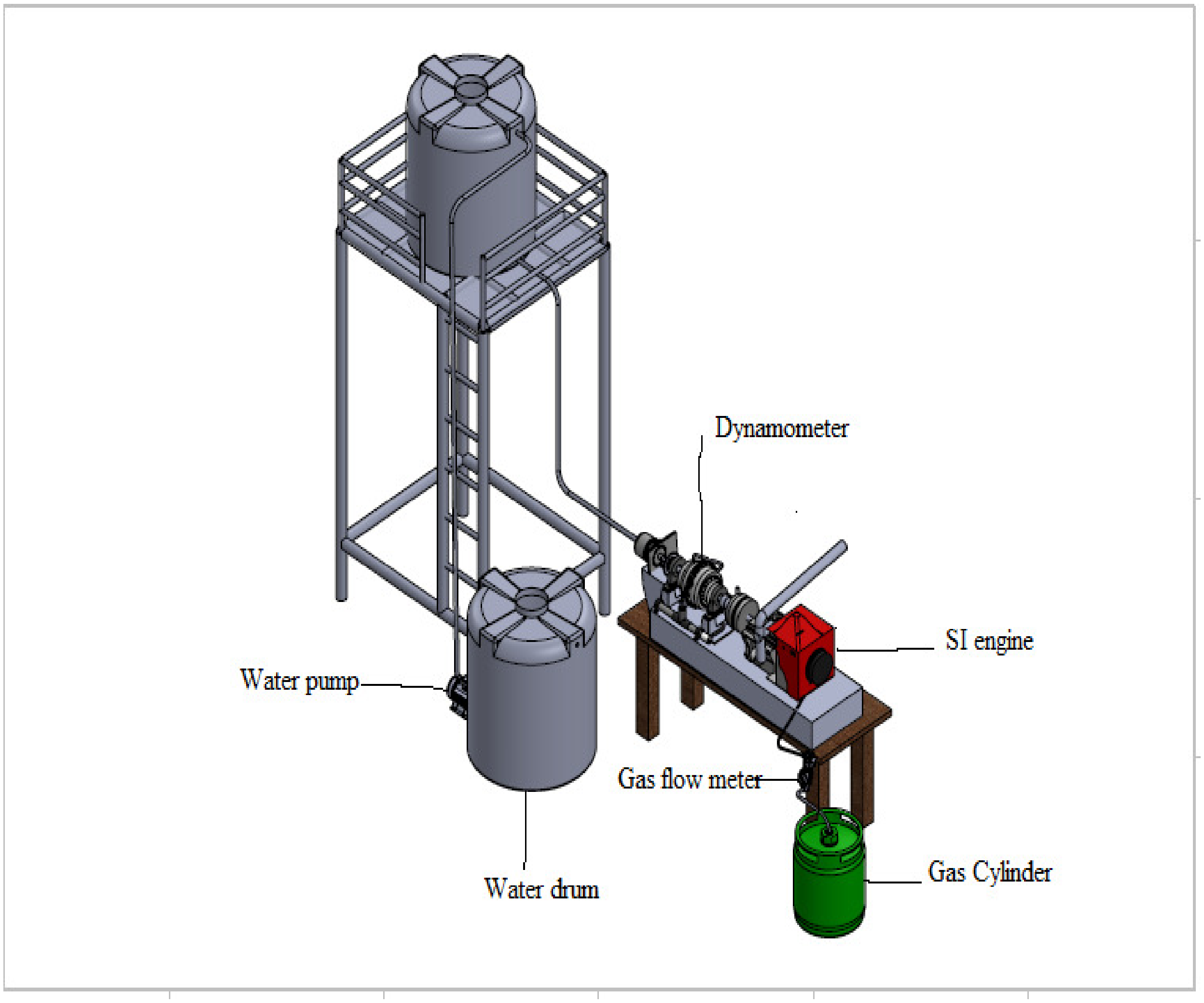


Figure 3.4: 3D Drawing of the Experimental Rig

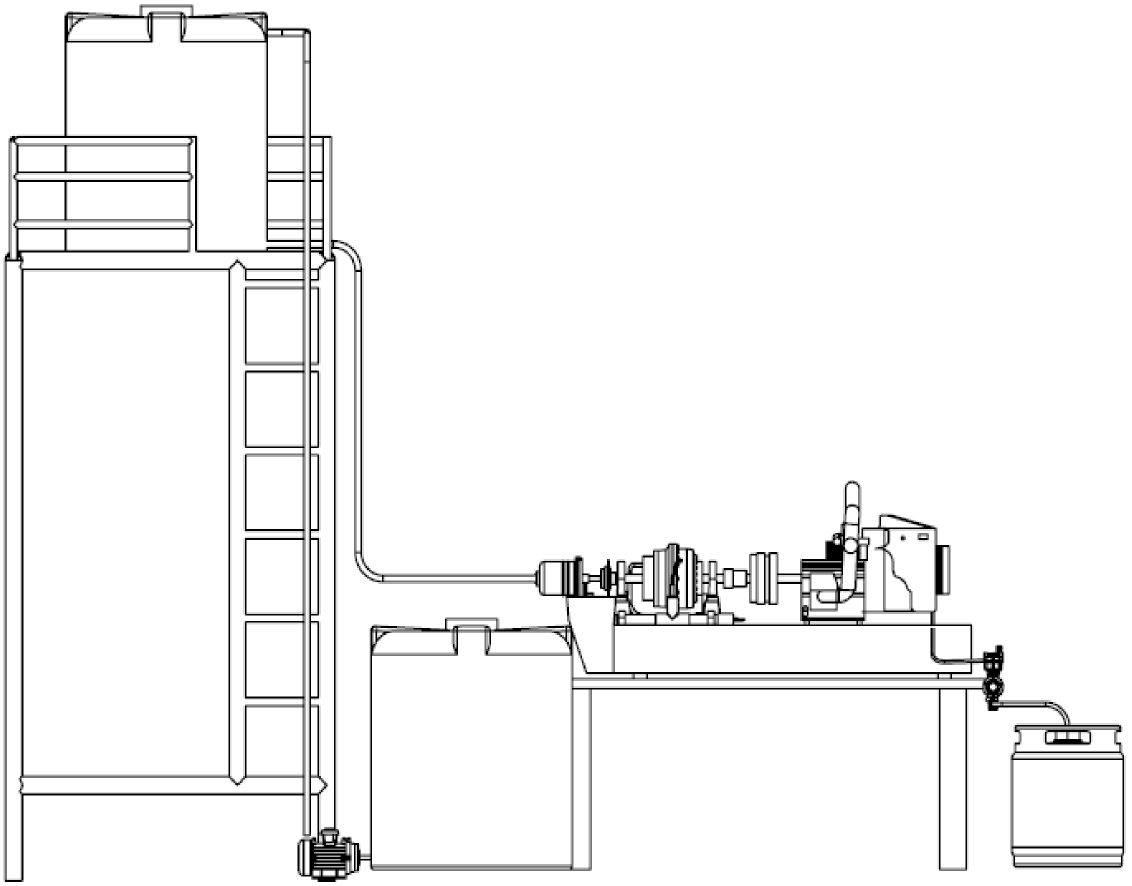


Figure 3.5: Orthographic View of Experimental Set up for the Engine Test

3.10.2 Determination of Performance Indices

3.10.2.1 Determination of Brake power

Brake power of the engine was evaluated from the equation (3.41)

$$BP = \frac{2\pi NT}{60} \qquad (3.41)$$

Where N= speed, rev/min

T = Torque, Nm

3.10.2.2 Determination of Brake specific fuel consumption

This is a measure of how efficiently the engine develops power from the fuel. It was computed using equation (3.42)

$$\mathrm{Bsfc} = \frac{\mathrm{m_f}}{\mathrm{BP}} \times 1000 \times 3600 \qquad (3.42)$$

Where:

Bsfc= Brake specific fuel consumption, g/kWh

BP = Brake power, Kw

Mf = Mass flow rate

3.10.2.3 Determination of brake thermal efficiency

It is an indication of the efficiency with which the thermodynamic input is converted to mechanical work. It was computed using equation (3.43):

$$BTE = \frac{BP}{m_f \times CV} \qquad (3.43)$$

Where:

CV =Calorific value of fuel, kJ/kg

BP = Brake power

m_f = Mass flow rate

3.10.2.4 Determination of Air Density

Air density in kg/m^3 was calculated using equation (3.44)

$$\rho_A = \frac{PA \times 1000}{287 \times (TA + 273)} \qquad (3.44)$$

Where:

P_A = Pressure of air, Pa

T_A = Temperature of air, K

3.10.2.5 Determination of Mass Flow rate of Air

Air mass flow rate was calculated using equation (3.45)

$$AMF(\dot{m}_a) = \frac{N \times \rho_A \times V_S}{2 \times 60} \qquad (3.45)$$

Where:

N= Engine speed

Vs= Swept volume

ρ_A = Air density

3.10.2.6 Determination of Air-Fuel ratio

Air-fuel ratio was determined using equation (3.46)

$$\frac{A}{F} = \frac{AMF}{FMF} = \frac{\dot{m}_a}{\dot{m}_f} \qquad (3.46)$$

$\dot{m}a$ = mass flow rate of air

$\dot{m}f$ = mass flow rate of fuel

3.10.2.7 Determination of Equivalence Ratio (ƛ)

The equivalence ratio was determined using equation (3.47)

$$\emptyset = \frac{A/F_{actual}}{A/F_{stoichiometric}} \qquad (3.47)$$

3.11 Characterization of Emission from Spark-Ignition Engine

The emission characteristics of the engine fuelled by the LPG and the three different grades of biogas RB, SWSB and DWSB were evaluated by placing a probe of a BACHARACH PCA3 Flue gas analyser, with model number 0024-8445 (See plate 3.7) in the exhaust of the engine while it was running and the values were obtained during no load, part load and full load conditions. The measurement ranges of the equipment are stated underneath.

Table 3.2: Specifications of Bacharach Flue gas Analyser

	Measurement range
Primary/ Ambient Air temperature	-4 ^{o} to 999 ^{o} F
Stack temperature	-4 ^{o} to 2192 ^{o} F
Oxygen	0 to 20.9 %
Carbon Monoxide (H_2 compensated)	0 to 4,000 ppm
Carbon Monoxide (High range)	4,001 to 20,000 ppm
Nitric Oxide	0 to 3,000 ppm
Nitrogen Dioxide	0 to 500 ppm
Sulphur Dioxide	0 to 5000 ppm
Pressure/ Draft	-72 to +72 inwc

Plate 3.7: A view of the Bacharach PCA3 Flue Gas Analyser

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Development of Facilities

The facilities developed during the course of this study were: the digester, the single stage and double staged digesters.

4.1.1 Prototype of the Digester

The dimensions of the digester are presented in Table 4.1. The digester was fabricated from a 1000L and a 500L PVC tank. The tops of both tanks were cut off, and the 500L tank was inverted into the 1000L tank as seen in plate 4.1

The digester has a substrate capacity of 0.75 m^3 and can collect gas of 0.37 m^3. There is a valve by the side of the gas cap for gas collection, an effluent pipe of diameter 10.5 cm for slurry collection and an influent pipe of diameter 11.5 cm through which the digester is loaded. This can be seen in Plate 4.1 and Figures 4.1 and 4.2.

4.1.2 Designed Scrubbers

The single stage and double stage scrubbers designed for this study are shown in Plate 4.1 and in Figures 4.3 and 4.4. They were fabricated from sheets of galvanized steel.

The first stage scrubber has a packed bed height of 1.21 m and a packed bed volume of 62 L (0.0622 m^3). The second stage scrubber has a packed bed height of 0.51 m and a packed volume of 42 L (0.0417 m^3).

4.1.3 Cost Implication of the Developed Facilities

The cost of the development of the digester and the scrubbers are as presented in Tables 4.2 and 4.3.

The Total Equipment Cost (TEC) for the digester was sixty two thousand Naira (N62,000) and the (TEC) for the scrubbers was two hundred and six thousand Naira only (N206,000).

Table 4.1: Dimensions of the Digester

Description	Value
Reactor height	145 cm
Reactor volume	1.12 m^3
Gas cap diameter	83 cm
Gas cap height	85 cm
Height of biomass support media	79 cm
Diameter of biomass support media	110 cm
Diameter of influent pipe	11.5 cm
Diameter of effluent pipe	10.5 cm

Plate 4.1: The biogas digester used for the study

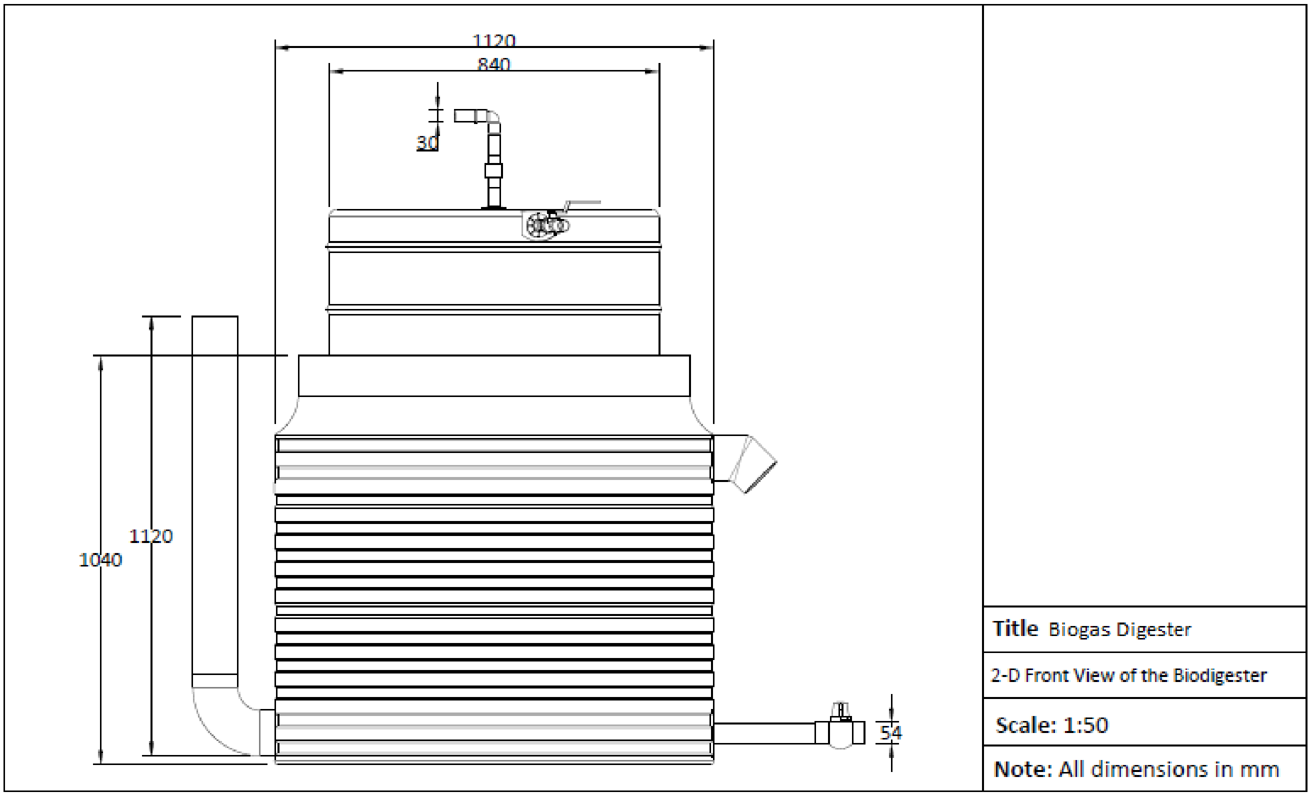


Figure 4.1: Front view of the digester

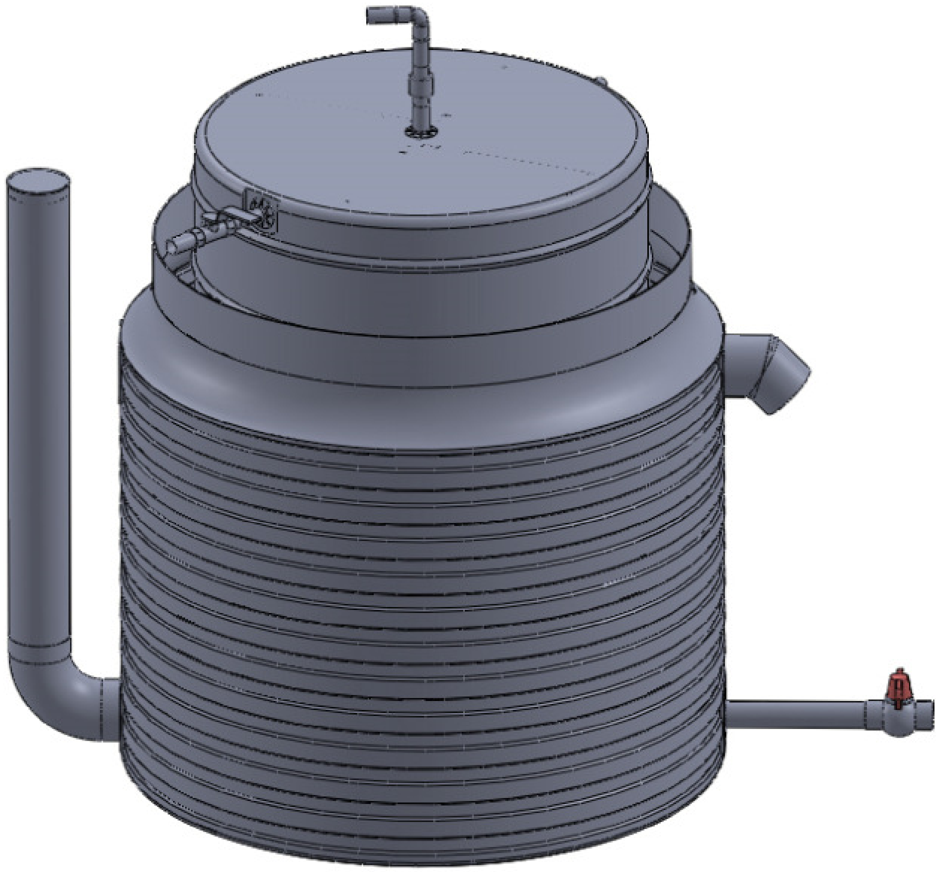
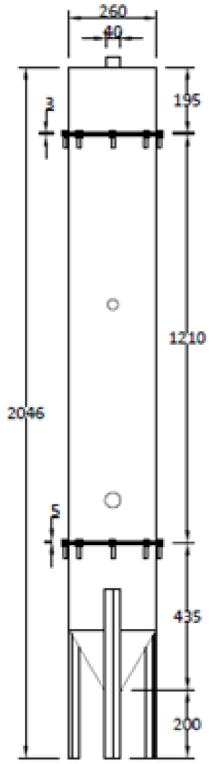


Figure 4.2: Isometric View of the digester

Plate 4.2: Developed Water scrubbers used for the study



Part list

S/N	Description	Qty
1	Top part	1
2	Middle part	1
3	Bottom part	1
4	Screw	16
5	Bolt	16
6	Gasket	2

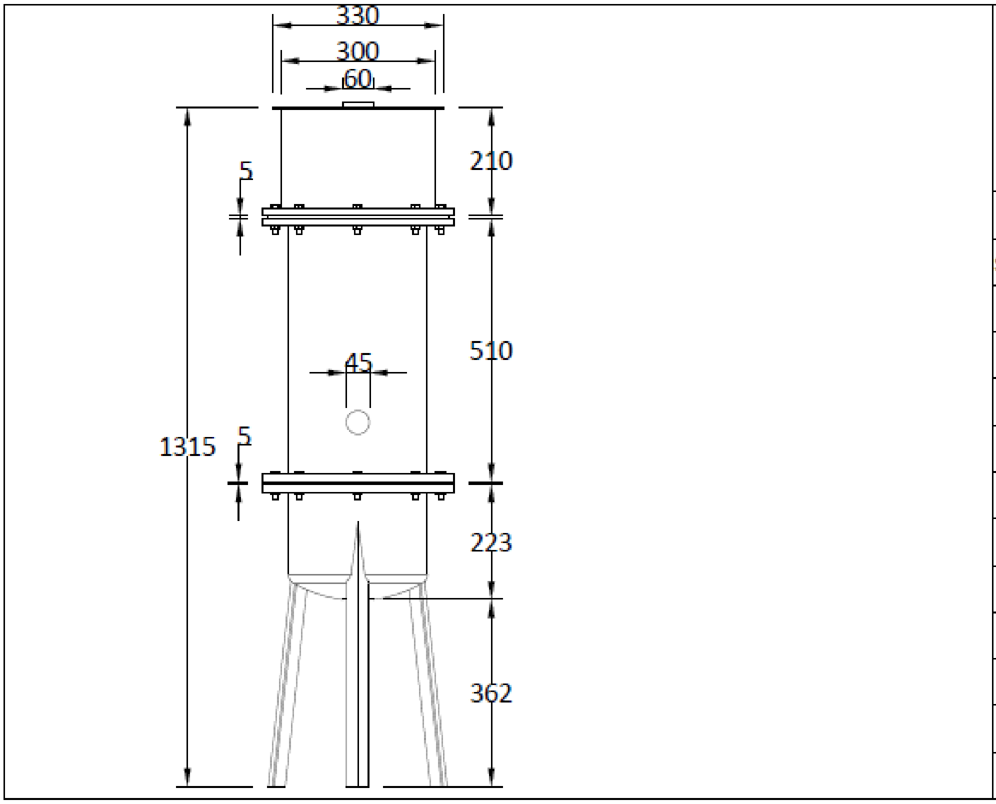
Title 1st stage Scrubber

2-D Front View of the Large Scrubber

Scale: 1:50

Note: All dimensions in mm

Figure 4.3: Front View of the Designed First Stage Scrubber



Part list

S/N	Description	Qty
1	Top part	1
2	Middle part	1
3	Bottom part	1
4	Screw	16
5	Bolt	16
6	Gasket	2

Title 2nd Stage Scrubber

2-D Front View of the Small Scrubber

Scale: 1:50

Note: All dimensions in mm

Figure 4.4: Front View of the Second Stage Water Scrubber

Table 4.2: Cost Analysis of the Development of Digester

Cost Item	**Cost**
Purchased Equipment Cost	
- 1 1000L PVC tank	N 30,000
- 1 500 L PVC tank	N 15,000
Direct Cost (Fabrication-pipes, valves, glue)	N7000
Indirect costs (Labour)	N10,000
TOTAL	**N 62,000**

Table 4.3: Cost Analysis of the Development of Scrubbers

Cost Item	**Cost**
Purchased Equipment Cost	
- Scrubber 1	N 75,000
- Scrubber 2	N 50,000
Direct Cost (Fabrication & Installation)	
Pipes	N5,000
Pressure gauges	N6,000
valves	N5,000
glue	N3,000
Flow meters	N25,000
500L overhead tank	N 15,000
Indirect costs (Labour)	N20,000
TOTAL	**N 206,000**

4.2 Analysis of Substrate

The substrate analysed was found to have the values as presented in Table 4.4. The substrate used for digestion has a P^H of 7.2, Total Solids (TS) of 17533.33 mg/L, Biological oxygen demand (BOD) of 14956.66 mg/L and Carbon to Nitrogen (C/N) ratio of 17.72:1.

According to Babaee and Shayegan (2011), Kwientniewska and Tys (2014), the important feedstock parameters are the volatile solids (VS), Chemical oxygen demand COD, the Biological oxygen demand (BOD) and the C/N.

The P^H of the substrate used for digestion lies within prescribed range by Kossmann *et al.* (1999). The P^H is adequate and of suitable condition for methanogens to thrive.

The C/N ratio indicates the relationship between the carbon and the nitrogen in a feedstock (Jingura and Kamusoko, 2017). According to Kossmann *et al*., (1999) the C/N ratio in the range 8-20 is capable of optimizing the activity of methanogens for generating biogas. The C/N ratio obtained in the analysis was 17.72: 1 which is falls within the acceptable range and is favourable to biogas generation. The typical C/N ratio for cattle manure is 13:1 as reported by Dioha *et al.* (2013) while Barik and Murugan (2012) reported that C/N ratio of 25:1. However the C/N ratio presented in table 1 seems to fall mid-way between the two values reported, which may indicated some level of acceptable variation between the two typical values reported.

The BOD is the measure of the oxygen used for organic matter decomposition by microorganisms (Jingura and Kamusoko, 2017). The typical BOD value for cattle slurry ranges between 10,000 and 20,000 mg/L (Korres *et al*., 2013). The BOD obtained in this study was 14956.66 mg/L which is within the expected values.

A value of 17533.33 mg/L was obtained for Total Solids (TS), which is relatively low and indicates the ease of biodegradability (Paran *et al*., 2000).

Table 4.4: Analysis of the substrate (cow dung)

Parameter	Value	Average Value
P_H	7.2	7.2
	7.2	
	7.2	
Total Solids (mg/L)	17500	17533.33
	17300	
	17800	
Total Nitrogen %	0.49	0.487
	0.47	
	0.50	
Total Carbon %	8.6	8.63
	8.8	
	8.5	
BOD (mg/L)	14950	14956.66
	14935	
	14985	
Carbon /Nitrogen (C/N) ratio	17.72	

4.3. Quantity of gas generated from cow dung

The digester was usually loaded every two weeks as a result of the large volume of gas required for experimentation. The estimated organic loading rate was 4.91 kgoDS/m^3/day. Table 4.5 shows the record of loading of the digester at different times during the course of this study and the quantity of gas obtained. It can be deduced from Table 4.5 that on the average about 0.0041 m^3 of biogas can be generated from 1 kg of cow dung. This is similar to the finding reported by Itodo *et al.* (1992) which states that 1 kg of cow dung generates 0.0045 m^3 of biogas.

Figures 4.5 and 4.6 show the trend in the biogas yield in the biogas plant used for this study. The study required the biogas generated to be harvested frequently for scrubbing and consequently engine testing. It can be observed in Figure 4.5 that there was an increase in biogas production as the days progressed. On day 10 there was a drastic drop in the volume of biogas because the gas in the digester was harvested for scrubbing. From day 12 there was a steady increase in biogas generated. It was observed that the rate of biogas generation after the evacuation was higher than the rate of generation before gas evacuation. This trend is similar to that observed in Okoroigwe and Agbo (2007).

Biogas usually has low pressure gradients as can be seen in Figure 4.6. All the pressures are only slightly above atmospheric pressure. The pressure increases as the volume of gas and temperature in the digester increases. There was a drop observed as a result of the harvesting of the gas generated into a cylinder. It can be observed that there was fresh gas generation by the second day and it started rising back steadily to the former pressure before harvesting took place.

Table 4.5: Quantity of gas generated from cow dung

Loading	Mass of cow dung (kg)	Volume of gas (m^3)	Mass of gas generated(kg)
1	91.5	0.384	0.5
2	97.5	0.411	0.53
3	97.8	0.410	0.53
4	102.0	0.428	0.56
5	93.5	0.405	0.53
6	82.4	0.303	0.40
Average	94.1	0.390	0.51

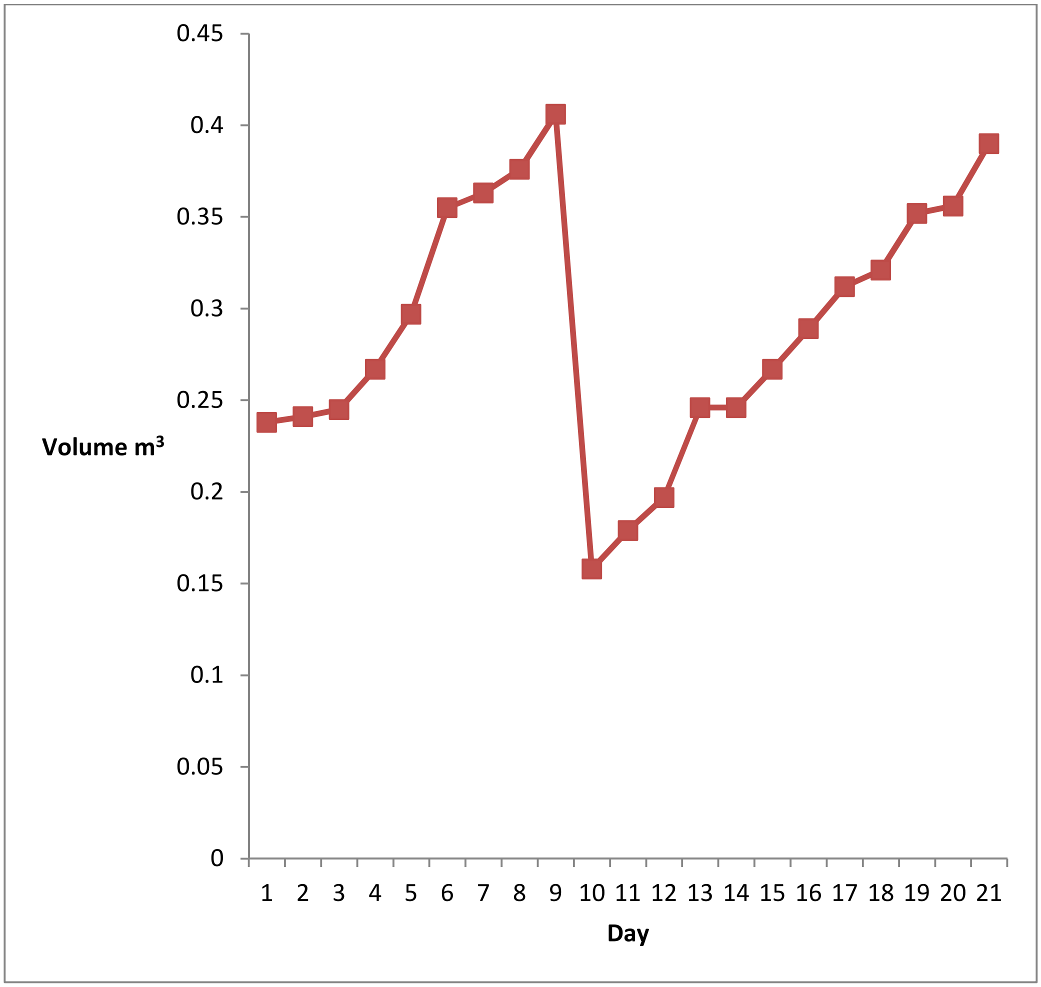


Figure 4.5: Time series Plot of Volume of Biogas Generated

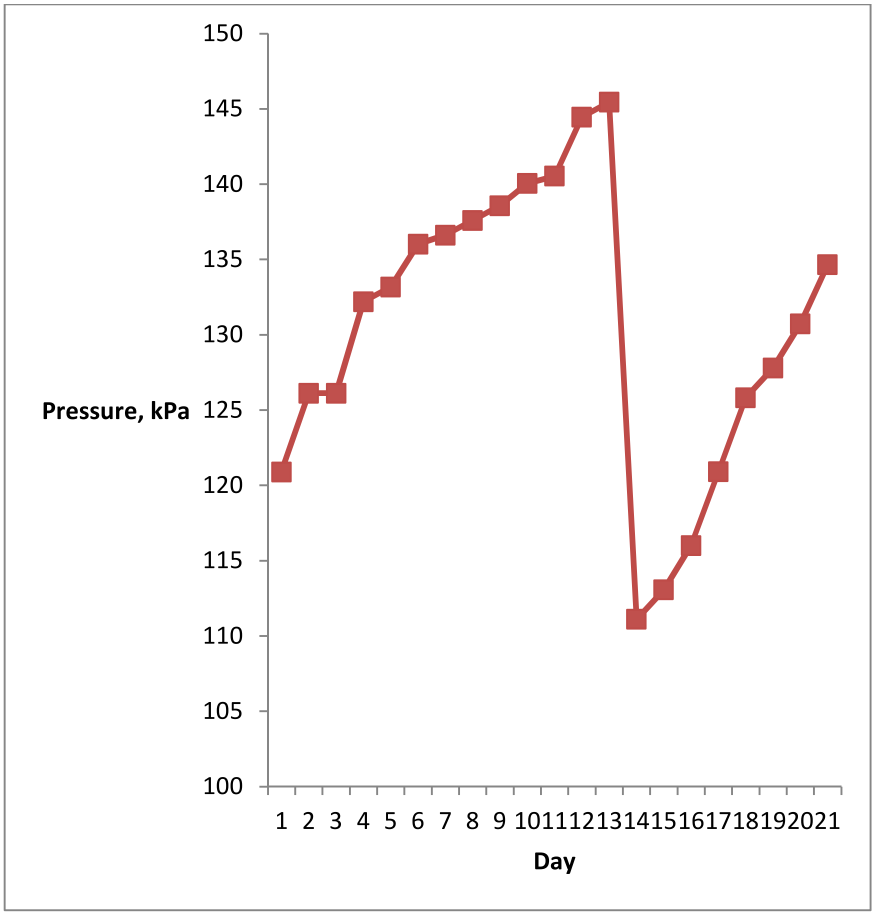


Figure 4.6: Time Series Plot of Gas Pressure in Digester

4.4 Single stage and Double stage scrubbing of Biogas

4.4.1 Estimation of gas losses associated with the scrubbing process

It is observed that there are usually losses in the quantity of gas scrubbed and the quantity of gas recovered after the scrubbing process. This is attributed to the washing away of some of the gas with the water used in the scrubbing process as well as due to the removal of the CO_2 in biogas which has more weight than methane. Table 4.6 presents the mass of biogas lost during the first stage scrubbing process. The highest percentage loss was 20% which was largely due to some leakages in the scrubber that were observed during the first run. This was corrected and there was a significant drop in percentage loss during the second run. It is also observed that the percentage loss reduces with the quantity of gas scrubbed, as seen in Table 4.6 where the lowest percentage loss (4%) was recorded when 2.5 kg of biogas was scrubbed. This suggests that scrubbing a large quantity of gas reduces the percentage loss.

Table 4.7 presents the loss in quantity of biogas after double stage scrubbing. The percentage losses seem similar to the percentage losses observed in the single-stage scrubbing process during the first two runs. However, it could be observed that a minimum percentage loss of 2.8% was recorded which could be as a result of the already decreased mass due to the first stage scrubbing which had already removed some mass of CO_2.

Double stage scrubbing will definitely increase the loss in quantity of biogas. This effect can be reduced by increasing the quantity of gas to be scrubbed.

Table 4.6: Biogas lost during single stage scrubbing

Single stage scrubbing	Mass of gas before scrubbing (kg)	Mass of gas after scrubbing (kg)	Mass of gas lost during process (kg)	Percentage loss
1	1	0.8	0.2	20%
2	2.5	2.4	0.1	4%
3	2.2	2.1	0.1	4.5%
4	1.5	1.35	0.15	10%
5	2.0	1.8	0.2	10%

Table 4.7: Biogas lost during double stage scrubbing

Double stage scrubbing	Mass of gas before scrubbing (kg)	Mass of gas after scrubbing (kg)	Mass of gas lost during process	Percentage loss
1	0.8	0.6	0.2	25%
2	2.4	2.3	0.2	4.2%
3	2.1	2.0	0.1	4.8%
4	1.35	1.3	0.05	2.8%
5	1.8	1.75	0.05	2.8%

4.4.2 Methane Content of Biogas Samples

The result of wet chemistry analysis of the biogas samples- Raw Biogas (RB), Single stage Water Scrubbed Biogas (SWSB) and Double stage Water Scrubbed Biogas (DWSB) using the LDM method are presented in Figure 4.7. The methane content of RB was rather high, 73. 5% compared to the usual value of 65% (Kishore and Srinivas, 2003). This could be as a result of the method of analysis which is said to be about 3.3% higher than values obtained when GC is used to carry out the analysis. The methane content of SWSB was 88.6 %, which is similar to results presented in Shyam (2002). The methane content of DWSB was 96.7% is high compared to SWSB which makes DWSB more suitable for use in spark ignition engines than SWSB, as only biogas of methane content of 95% can be used in spark ignition engines (Papacz, 2011).

4.4.3 Scrubber Efficiencies

The efficiency of the first stage scrubber was estimated to be 56.9% while the efficiency of the second scrubber was 70.9% showing the second scrubbing process was more efficient than the first stage. This may be because the first stage as the task of overcoming the initial resistance while the second stage cleans up what is left during the first stage scrubbing. It shows that it is necessary to multi-stage the scrubbing process for better results.

4.4.4 Calorific Value of Purified Biogas

The calorific values of RB, SWSB and DWSB were 26.01, 31.36 and 34.23 MJ/kg as presented in Figure 4.8. It can be seen when compared with raw biogas, that SWSB and DWSB have higher calorific values. The calorific value of DWSB was estimated to be 34.23 MJ/kg which is very close the calorific value of pure methane which is 37.78 MJ/m^3. According to Koornneef *et al.* (2013), the use of upgraded biogas has no significant difference from the use of natural gas in vehicles because of the similarity in their properties. There was a 20.6% increase in the calorific value of biogas when single stage scrubbing is employed while there was a 31.6% increase in the calorific value of biogas when double stage water scrubbing is employed. The calorific value obtained for DWSB was higher than SWSB, which shows that when upgrading biogas for use in SI engines, it is important to employ double stage scrubbing to obtain a purer biogas. However, for other applications such as lighting, cooking and heating SWSB can be utilized.

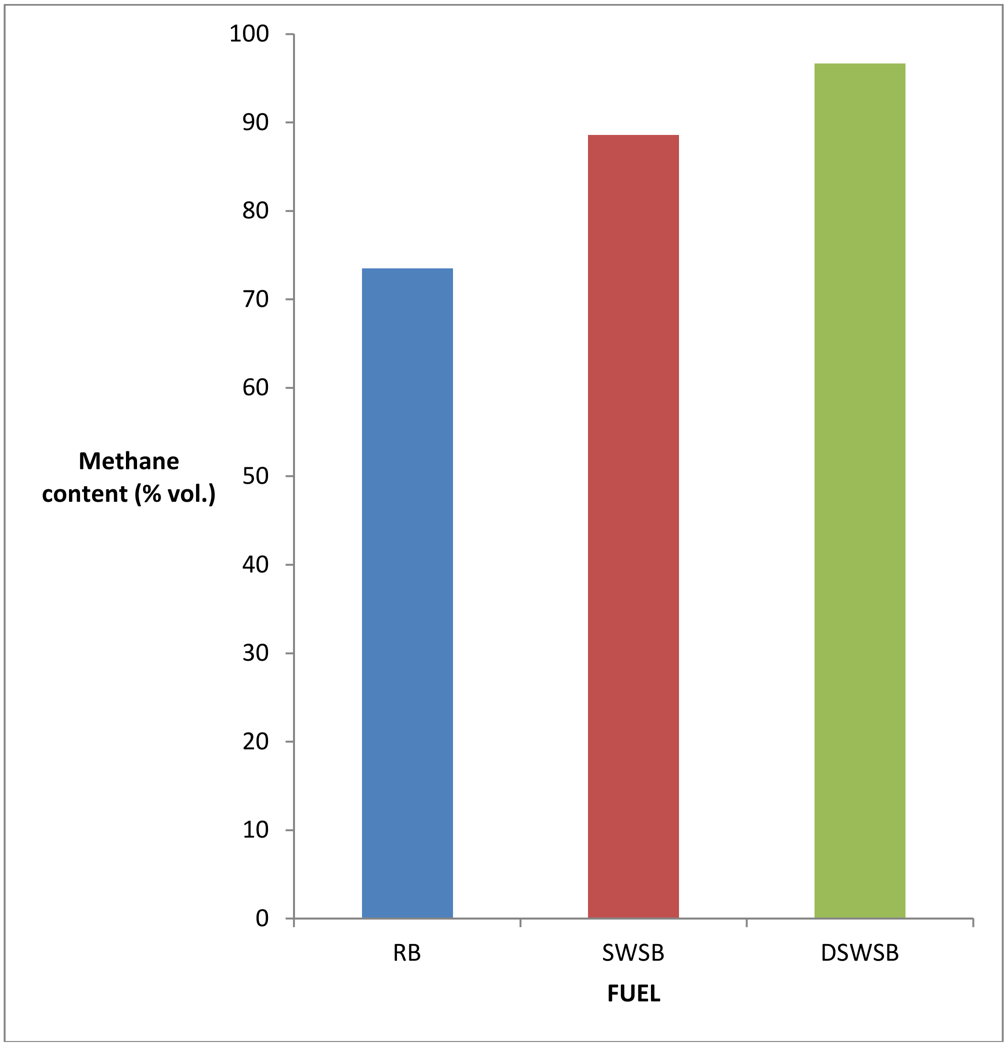


Figure 4.7: Methane Content of Biogas Samples

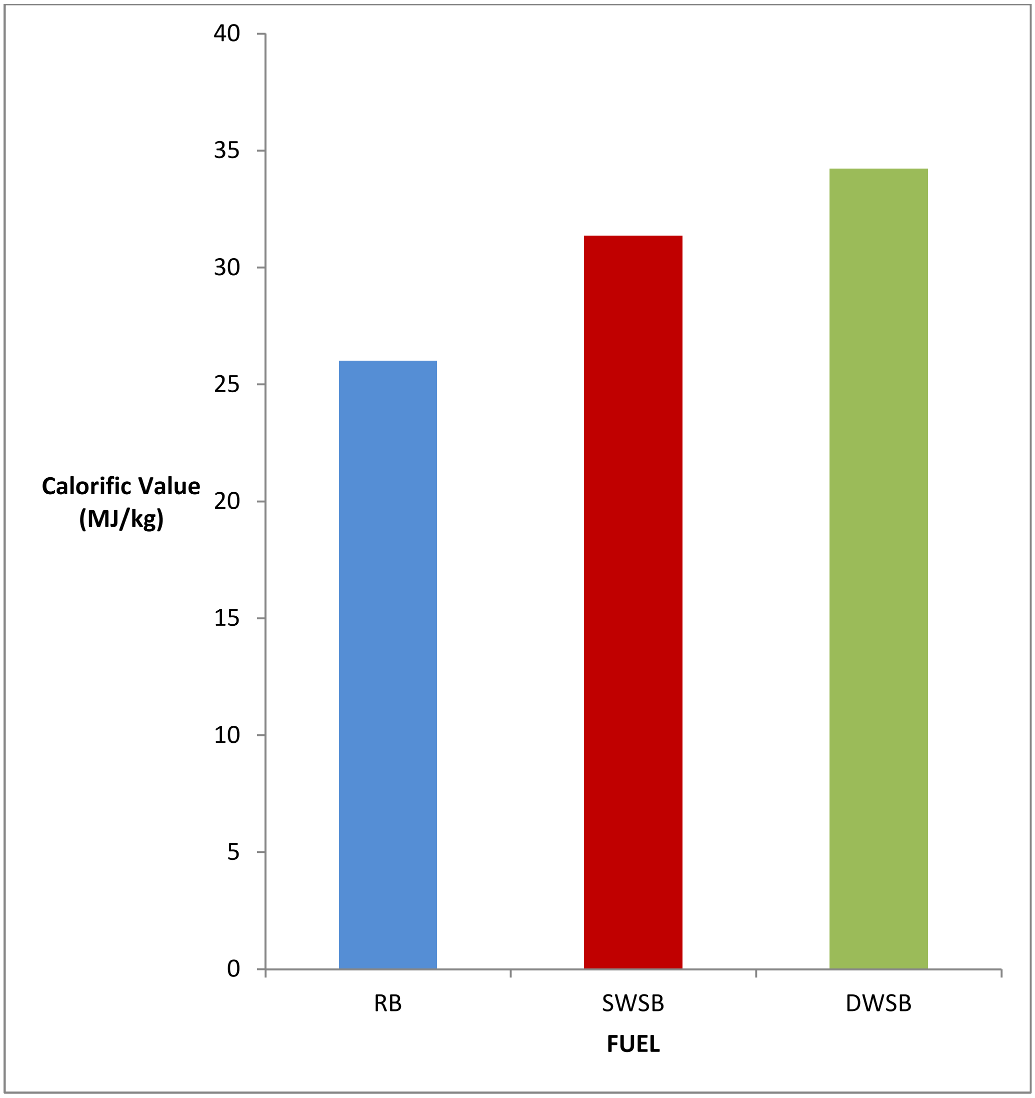


Figure 4.8: Calorific Value of Biogas Samples

4.5 Compression and Storage of Single Stage and Double Stage Water Scrubbed Biogas

The SWSB was compressed from a tyre tube of capacity 0.206 m^3 (206 L) into a 6 kg cylinder of capacity 13.5 L at 375.8 kPa

The DWSB was also compressed from a tyre tube to a pressure of 375.8 kPa of capacity 0.206m^3 (206L) into a 6 kg cylinder of capacity 13.5L**.** It was however observed that the mass of the DWSB (0.6 kg) was slightly less than that of the SWSB (0.8 kg). This was probably due to of the reduction in the quantity of the CO_2 which makes up the bulk of the density of biogas.

4.6 Performance Characteristics of a Spark Ignition Engine Fuelled with Biogas of various Purity Levels.

4.6.1 Fuel Equivalent Power

The Fuel Equivalent Power (FEP) of LPG and the biogas fuels used in this study is presented in Figure 4.9.

The FEP at no load for LPG, RB, SWSB and DWSB were 9.49, 2.48, 2.88 and 3.27 kW, respectively. The corresponding values at 50% load were 13.34, 3.49, 4.03 and 4.59 kW, respectively. The FEP at full load when the engine was operating with LPG, RB, SWSB and DWSB were 19.09, 5.00, 5.76 and 6.57 kW, respectively.

FEP is a function of the mass flow rate and the calorific value of the fuel. FEP thus increases with calorific value and with load, since the mass flow rate of the gas increases with load as well. The FEP of LPG is notably higher than that of RB, SWSB and DWSB. This is because the calorific value of LPG is about 1.3 times the calorific value of DWSB which has the highest methane content compared to RB and SWSB. The FEP of LPG is 73.83% higher than DWSB. This is because of the calorific value of LPG is higher than DWSB as well as the higher density of the LPG, which gives it a higher mass flow rate than DWSB of the same volumetric flow rate. Among RB, SWSB and DWSB it can be observed that FEP increased with methane content at the different loading conditions. Biogas purification thus increases energy supplied to the engine.

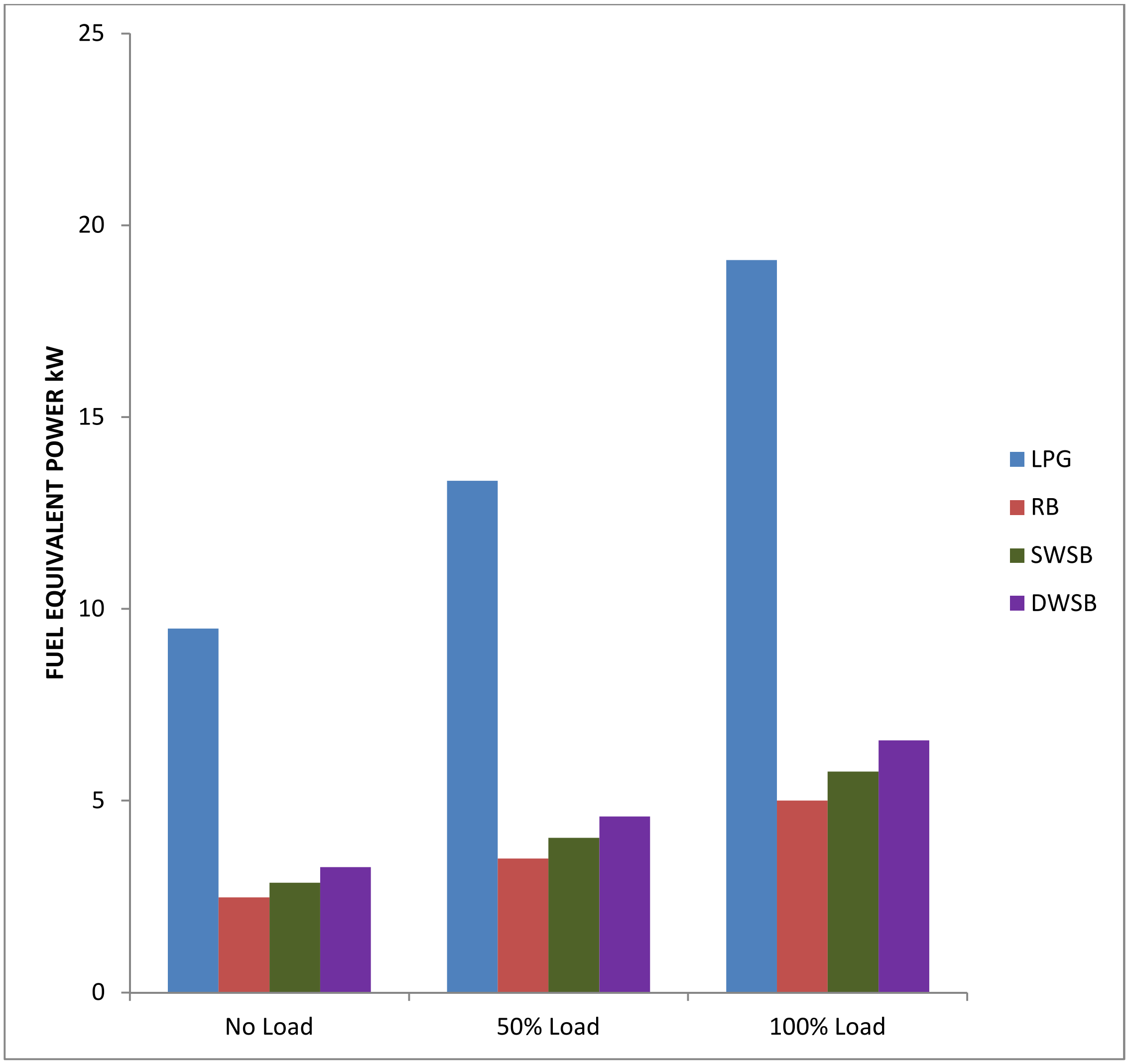


Figure 4.9: Plot of Fuel Equivalent Power against Load

4.6.2 Brake Power

The plot of Brake Power (BP) for the different fuels used at 50% load and full load is presented in Figure 4.10. The BP at 50% load for LPG, RB, SWSB and DWSB were 1.13, 0.45, 0.72 and 0.82 kW, respectively while the BP when the engine was run at full load operating with LPG, RB, SWSB and DWSB were 2.04, 1.03, 1.26 and 1.5 kW, respectively. The BP of the engine increased with the load, with the maximum BP recorded for each of the fuels at full load. At full loading, the flow rate of the fuels were 0.000414 kg/s (10 L/min) and a brake power of 2.04 kW was developed when operating with LPG, 1.5 kW when running with DWSB, 1.3 kW with SWSB and BP of 1.03 kW when operating with RB. The brake power varies directly with the torque and the speed of the engine. As a result of the increase of torque with load, the BP generally increased with an increase in loading. It was observed that BP of the engine at full load operating with DWSB was 1.5 times the brake power of the raw biogas which is similar to that reported in literature (Chandra et al, 2011, Kapdi, 2005). The BP of the engine at full load operating SWSB was 1.2 times the BP when RB was used as fuel. This shows that purifying biogas indeed increases the power output of the engine.

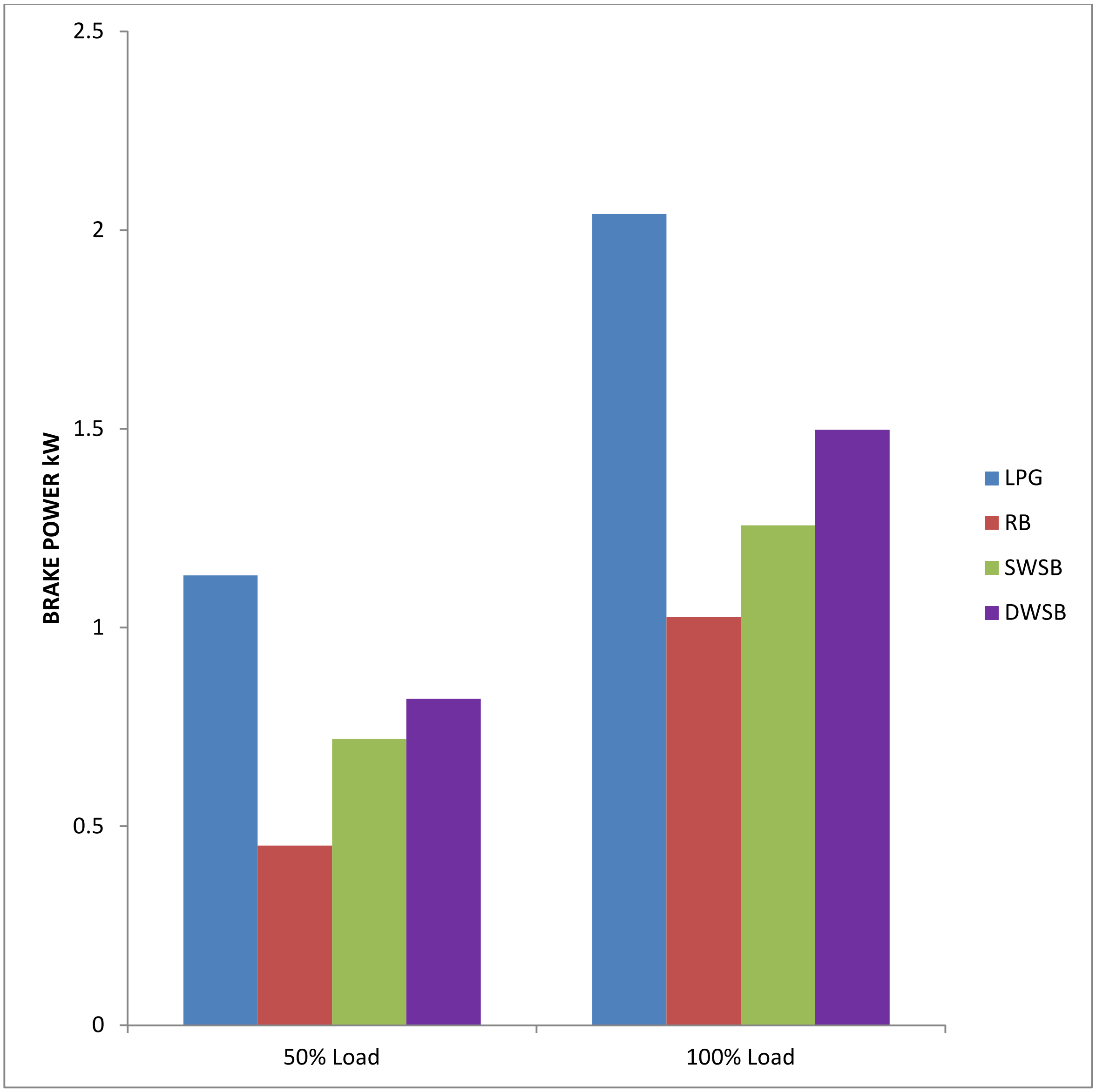


Figure 4.10: Plot of Brake Power against Load

4.6.3 Brake Specific Fuel Consumption (BSFC)

The result of the variation of BSFC with load is presented in Figure 4.11. The BSFC at 50% load for LPG, RB, SWSB and DWSB were 921.12, 1067.83, 670.99 and 588.4 g/kWh, respectively. The corresponding values at full load, when operating the engine with LPG, RB, SWSB and DWSB were 730.05, 672.92, 550.11 and 461.13 g/kWh, respectively. The BSFC indicates how efficiently an ICE burns fuel and produces power crankshaft. The lower the BSFC, the more fuel efficient the engine is. It was observed that the BSFC decreased with increasing load for all the fuels used. The BSFC of LPG at both 50% load and full load were higher than corresponding values when SWSB and DWSB were used , showing purified biogas to be more fuel efficient than LPG. At full load, even RB performed better than LPG in terms of fuel efficiency. When biogas fuels RB, SWSB and DWSB were used, the BSFC reduced with the increase in methane content of the fuels at both 50% loading and full loading as can be seen in Figure 4.11. DWSB is the most efficient gas. BSFC decreases with the level of purity of biogas.

This observation is similar to the observation made in Ambarita (2017) that BSFC tends to reduce with load and speed as a result of better combustion associated with increased load and speed. Incomplete combustion is often encountered at low engine loads and speeds. The research work of Reddy *et al.* (2016) on the comparative study of a SI engine running on LPG and biogas also shows a reduction in BSFC values with the loading. In Reddy et al (2016), where there was a comparison in performance of LPG and biogas, the LPG seemed to have lower BSFC values than biogas, though the biogas used in the study was raw biogas unlike the purified biogas used in this study. This further establishes the fact that a SI engine operating with purified biogas is more fuel efficient than one running on RB. Furthermore, the results show that DWSB is a more fuel efficient than SWSB.

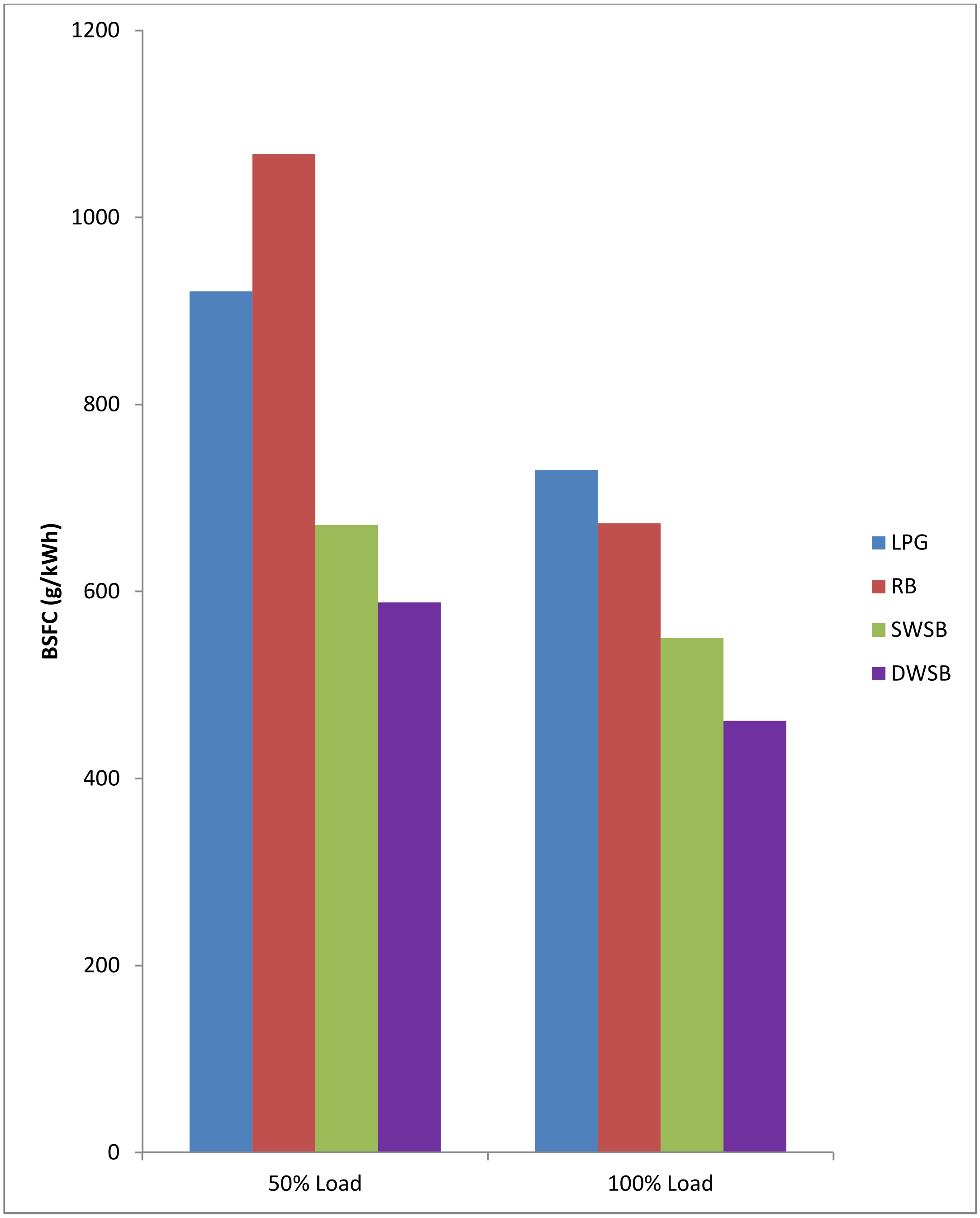


Figure 4.11: Plot of Brake Specific Fuel Consumption against Load

4.6.4 Brake Thermal Efficiency

The Brake Thermal Efficiency (BTE) of the engine at 50 and 100% load when operating with LPG, RB, SWSB and DWSB are presented in Figure 4.12. The BTE at 50% load for LPG, RB, SWSB and DWSB were 8.48, 12.96, 17.88 and 17.88%, respectively. The corresponding values obtained when operating at full load using LPG, RB, SWSB and DWSB were 10.71, 20.57, 21.81 and 22.78%. The BTE of an engine depends on the BP of the engine and the calorific value of the fuel used in the engine. A high BP gives a high BTE For this reason; the BTE of LPG was expected to be higher than that of the other fuels as a result of its high BP as seen in Figure 4.10. The BTE of LPG was very low compared to RB, SWSB and DWSB. The low BTE could be as a result of the high heat of vapourization of LPG (Ray et al, 2013), which reduces its volumetric efficiency and consequently its BTE.

The BTE was observed to increase with load for all the fuels. This is as a result of improved combustion associated with increased load and speed (Ambarita, 2017), as well as an increased in the temperature within the cylinder temperature and heat release rate as a result of an increase in load (Reddy *et al.,* 2016).

The highest BTE was 22.78% at full load when the engine was operating with DWSB. This shows that the purification of biogas does increase its energy content and thus its thermal efficiency. The BTE of raw biogas at 50% load (12.96%) and 100% load (20.57%) was similar to the BTE of a SI engine operating with raw biogas at 50% load (13.1 %) and 100% load (19%) obtained in Reddy *et al.* (2016). The compression of SWSB and DWSB into cylinders had improved its performance in terms of the BTE obtained. Reddy *et al*. (2016) observed an increase in power and BTE as a result of the compression of the biogas.

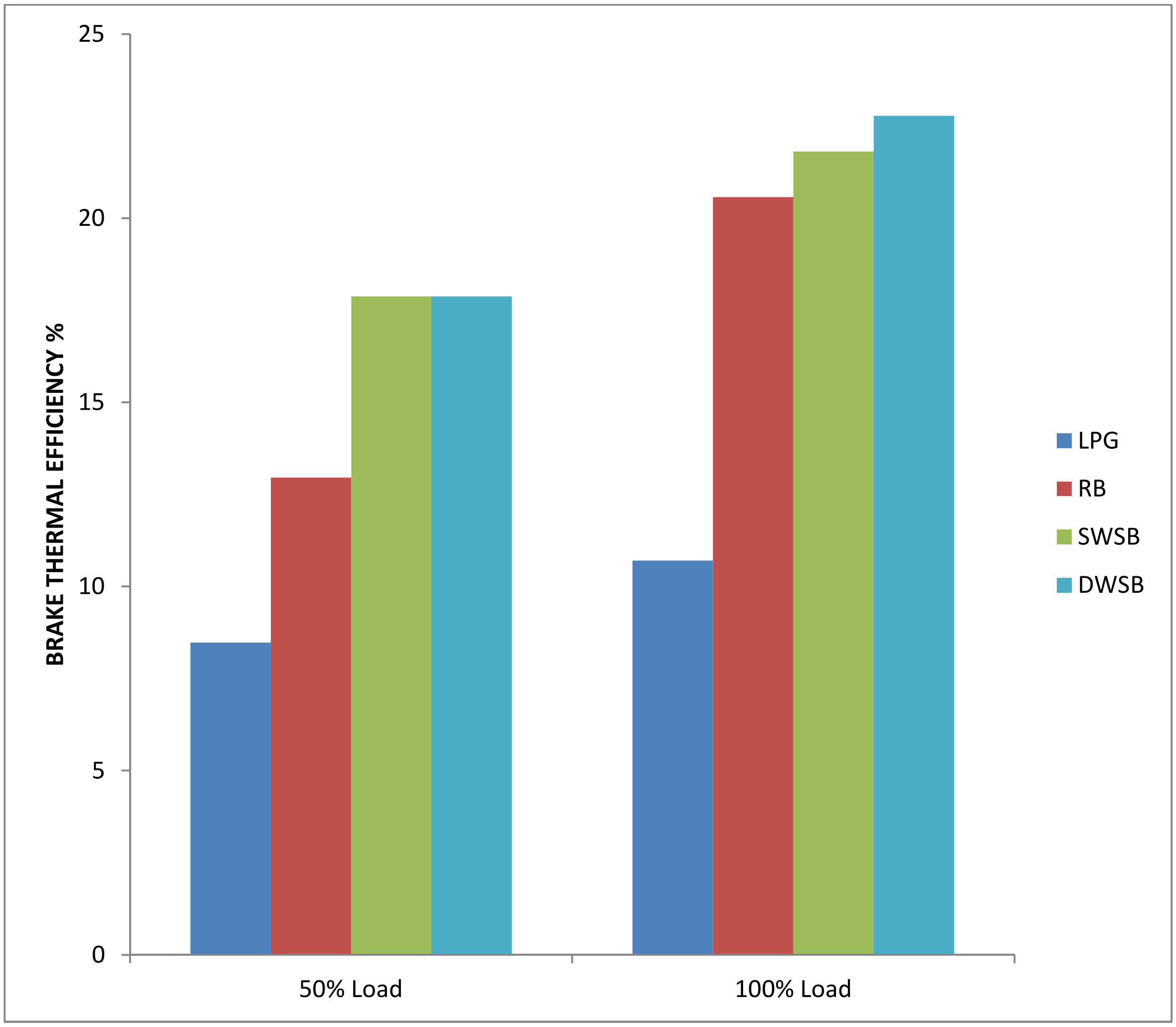


Figure 4.12: Plot of Brake Thermal Efficiency against Load

4.7 Air Mass flow rate, Air/ Fuel and Equivalence Ratio

The mass flow rate of air in the engine, the air fuel ratio and the equivalence ratio were determined using standard equations and the results are presented in Tables 4.8, 4.9, 4.10 and 4.11

It can be seen from Table 4.9 that at no load the equivalence ratios for LPG, RB, SWSB and DWSB were above 1. This shows that it was a lean burn that there was excess oxygen than required to burn the amount of fuel completely. The consequence of this is excess oxygen in the exhaust. This is further established by Figure 4.16.

In Table 4.10 at 50% loading, it was observed that the equivalence ratio was greater than 1 for RB, SWSB and DWSB, while it was less than 1 for LPG. This shows that the combustion of LPG was rich. That is there was insufficient air to burn the amount of fuel completely. While for RB, SWSB and DWSB, the combustion was lean. Table 4.10 can be compared with Figure 4.16 and it can be seen that the percentage O_2 emission from LPG was lower than the values obtained for the other fuels.

The air fuel ratio and equivalence ratio at 100% loading is presented in Table 4.11. It can be seen that the trend was similar to that observed at 50% loading, with combustion of LPG being rich and RB, SWSB and DWSB having a lean burn. It could be observed however that the equivalence ratio of the biogas fuels- RB, SWSB and DWSB had reduced considerably to 1.4 which was getting close to the ideal value of 1. This shows that for all the fuels there was an improvement in combustion at full load. Figure 4.16 shows the O_2 concentrations at full load were the lowest compared to concentrations at no loading and 50% loading.

Siripornakarachai and Sucharitakul (2007) observed the optimal engine performance at excess air ratio of 1.097. Rich mixture generates an increase in exhaust temperature, NOx and CO emissions, while lean burning causes incomplete combustion (Siripornakarachai and Sucharitakul, 2007).

However, Zhang et al. (2017) reported best performance of a SI engine running on simulated biogas at an equivalence ratio of 1.4. This establishes that though 1.4 is not the ideal air fuel ratio, but it could at certain conditions still bring about satisfactory performance in a SI engine.

Table 4.8: Air Mass Flow Rate in SI Engine

Fuel	Air Pressure (P_A), kPa	Air Temperature (Ta), K	Equivalence Ratio (ℓa)	Speed	Swept Volume (Vs), m^3	Air Mass Flow rate (ṁa)
LPG	101.3	35	1.146	3000	0.0001634	0.00468133
RB	101.3	35	1.146	2800	0.0001634	0.00436924
SWSB	101.3	35	1.146	3000	0.0001634	0.00468133
DWSB	101.3	35	1.146	3000	0.0001634	0.00468133

Table 4.9: Air Fuel ratio and Equivalence ratio at No loading

FUEL	ṁa	ṁf	A/F	A/F Stoich	λ
LPG	0.005	0.0002058	22.74	17.2	1.322
RB	0.004	0.00009545	45.78	17.2	2.662
SWSB	0.005	0.00009545	49.03	17.2	2.851
DWSB	0.005	0.00009545	49.03	17.2	2.851

Table 4.10: Air Fuel ratio and Equivalence ratio at 50% loading

FUEL	ṁa	ṁf	A/F	A/F Stoich	λ
LPG	0.005	0.000289	16.19	17.2	0.941
RB	0.005	0.000134205	34.87	17.2	2.027
SWSB	0.005	0.000134205	34.87	17.2	2.027
DWSB	0.005	0.000134205	34.87	17.2	2.027

Table 4.11: Air Fuel ratio and Equivalence ratio at 100% loading

FUEL	ṁa	ṁf	A/F	A/F Stoich	λ
LPG	0.005	0.000414	11.30	17.2	0.657
RB	0.005	0.00019205	24.37	17.2	1.417
SWSB	0.005	0.00019205	24.37	17.2	1.417
DWSB	0.005	0.00019205	24.37	17.2	1.417

4.8 Emission Characteristics of Spark Ignition Engine fuelled with biogas of various purity Levels.

4.8.1 Exhaust Temperature

The exhaust temperature obtained at no load, 50% load and full load conditions are presented in Figure 4.13. The exhaust temperature developed by the engine at no load when operating with LPG, RB, SWSB and DWSB, were 460^{o}C, 450^{o}C, 350^{o}C and 230^{o}C, respectively. The lowest exhaust temperature at no load was developed when operating with DWSB. At 50 % load, the corresponding values for LPG, RB, SWSB and DWSB were 560^{o}C, 490^{o}C, 410^{o}C and 350^{o}C, respectively. The lowest exhaust temperature was developed when DWSB was used as fuel and the highest was when LPG was used. At full load, the exhaust temperature developed were 610^{o}C, 530^{o}C, 500^{o}C and 400^{o}C, respectively for LPG, RB, SWSB and DWSB. At full load the lowest exhaust temperature was developed when DWSB was used again, while the highest was recorded when LPG was again used as fuel.

It was observed that the exhaust temperatures developed by the engine when all the fuels were used, increased with loading. The exhaust temperatures which were obtained in the engine when the biogas fuels (RB, SWSB and DWSB) were used at all loading conditions were lower than that obtained using LPG. According to Reddy et al. (2016), the emission of NOx usually increases with exhaust temperature thus indicating that one could predict that the low exhaust temperatures obtained when biogas fuels are used definitely shows that NOx emissions will be lower than LPG NOx emissions.

Studies have shown that the performance of purified biogas is similar to the performance of an engine run with CNG. Based on this, the exhaust temperature of an SI engine running on CNG at no load as reported by Paul *et al*. (2013) was compared to an engine operating with DWSB (which had a methane content of 96.7%) the exhaust temperature of 350^{o}C was reported which was similar to that obtained by DWSB at no load.

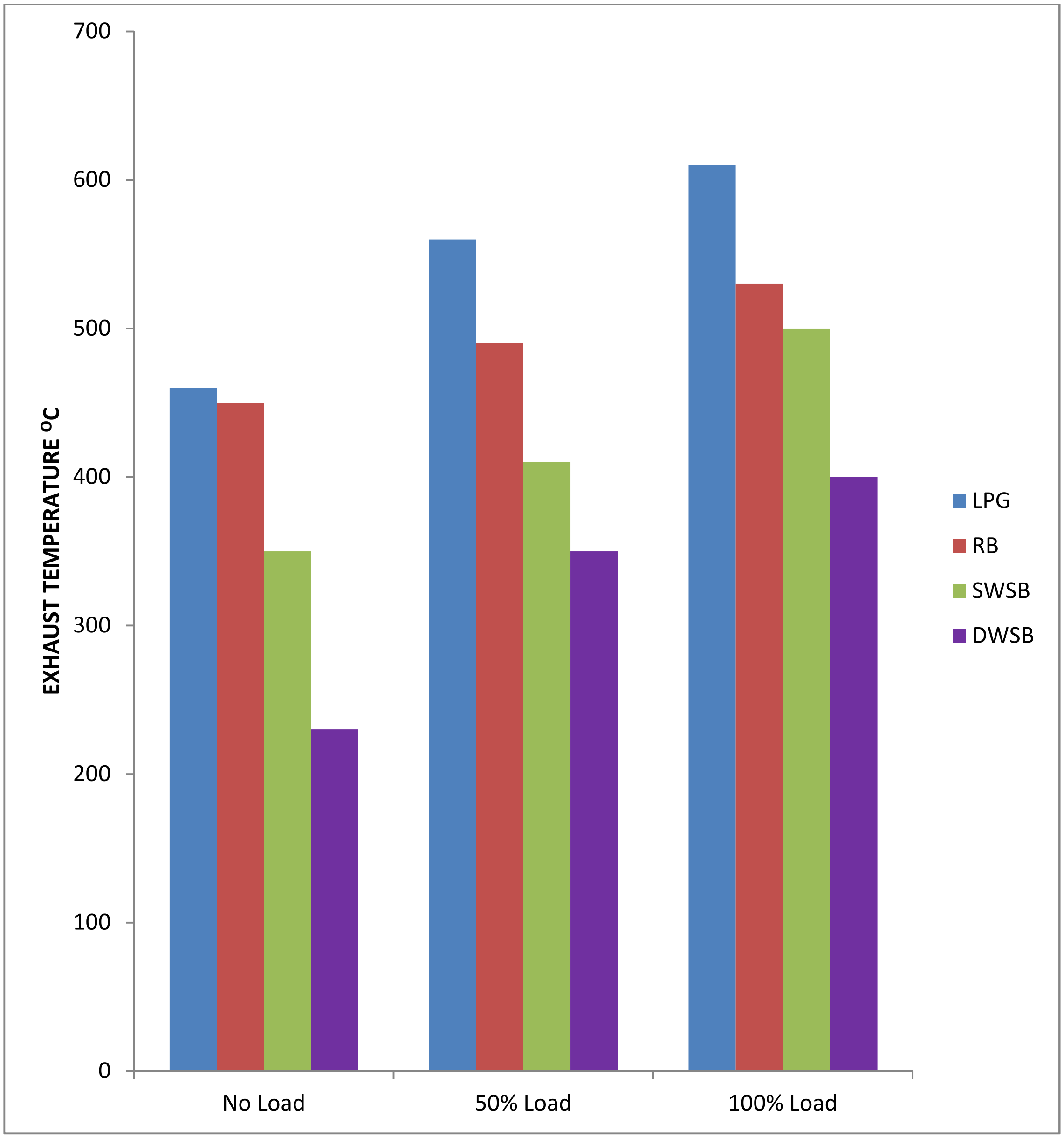


Figure 4.13: Plot of Exhaust Temperature against Load

4.8.2 SO_2 Emissions

The SO_2 emitted in the exhaust is as a result of the presence of hydrogen sulphides in biogas, which brings about the formation of SO_2 during combustion, the SO_2 in turn reacts with water to form sulphurus acid (H_2SO_3) which is very corrosive to engine parts. The mean value of SO_2 emitted at no load, 50% Load and 100% load is shown in figure 4.14. At no load, the SO_2 emission for LPG, RB, SWSB and DWSB were 68, 105, 89.23 and 86.26 ppm, respectively. At 50% loading the emissions were 63, 86.78, 82.55 and 50.57 ppm, respectively. The SO_2 emissions at full load for LPG, RB, SWSB and DWSB were 51.80, 73.60, 71.33 and 41.67 ppm, respectively.

It can be seen that the amount of SO_2 emitted is higher in RB and SWSB than in LPG. This is because sulphur is present only in traces in LPG. The value of SO_2 emission when DWSB is used as fuel is the lowest at both 50% and 100% load, this was probably, as a result of more elimination of H_2S in biogas. The mean value of SO_2 emission was the highest in all loading conditions when raw biogas is used as fuel. This is because of the presence of hydrogen sulphide in raw biogas which is about 0.1 % or 10 ppm.

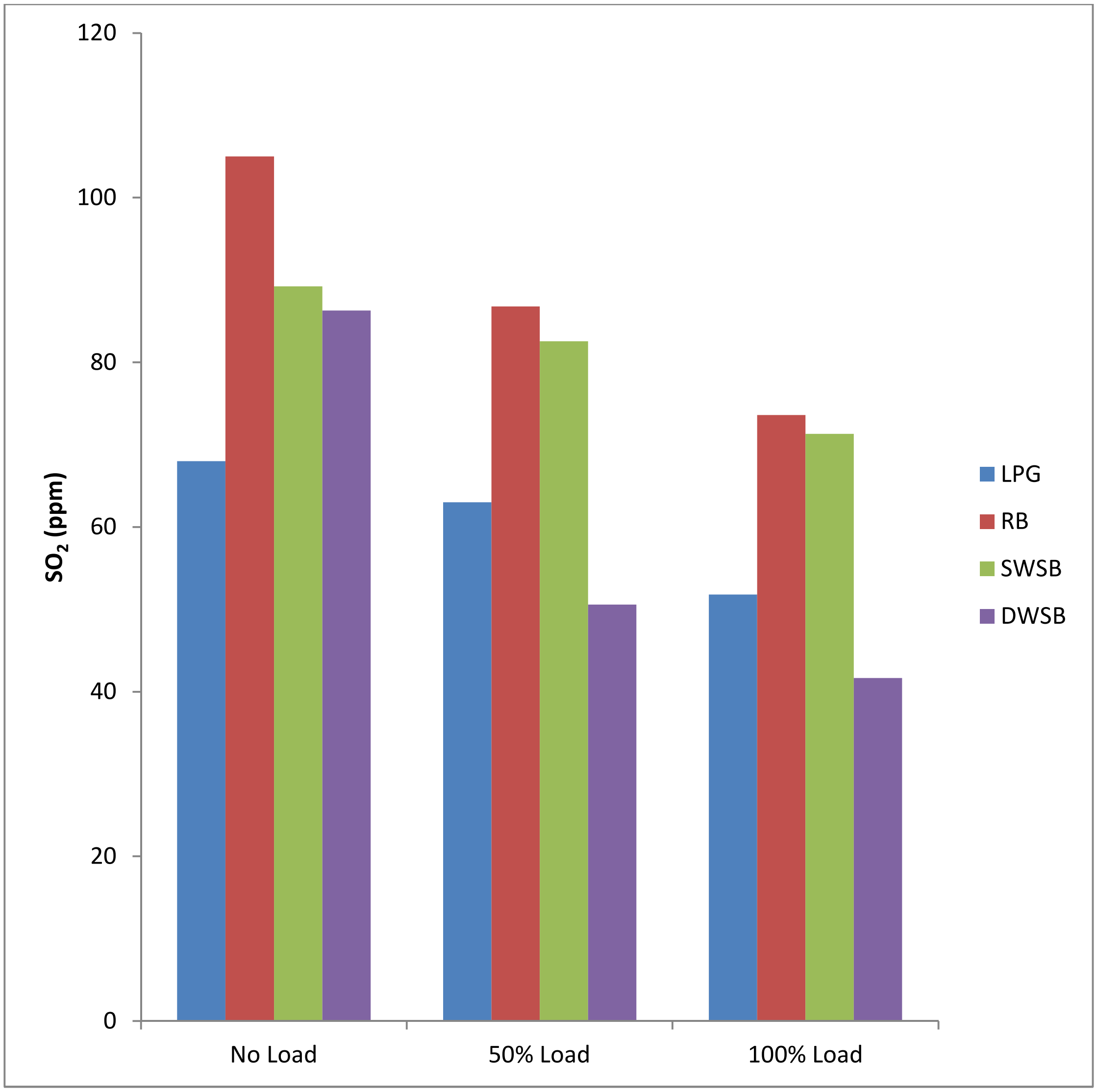


Figure 4.14: Plot of SO_2 Emissions against Load

4.8.3 CO Emissions

CO emissions are evidences of incomplete combustion of CO_2. The plot of CO emissions with load for all the fuels is presented in Figure 4.15. The percentage CO at no load when the engine was operating with LPG, RB, SWSB and DWSB were 0.38, 0.364, 0.4 and 0.080233 %, respectively. The corresponding values at 50% load for LPG, RB, SWSB and DWSB were 0.4, 0.348, 0.356 and 0.0758 %, respectively. Full load CO emission values for LPG, RB, SWSB and DWSB were 0.42, 0.31, 0.225 and 0.0658 %, respectively.

According to Reddy *et al. (*2016), CO emission decreases with an increase in load. This can be observed in Figure 4.15. The CO emissions when biogas (RB, SWSB, DWSB) was used as fuel in all the loading conditions, was observed to be lower than the mean value of CO emissions when LPG was used. This further corroborates the observation of Ray et al (2013), that CO emissions in biogas are smaller than CO emissions in gasoline or LPG (Reddy et al. 2016). The values obtained for Percentage CO emissions for LPG and biogas are similar as reported in Reddy *et al. (*2016).

This shows that biogas is indeed an eco-friendly fuel as can be seen in the reduction of CO which is a major greenhouse gas (GHG).

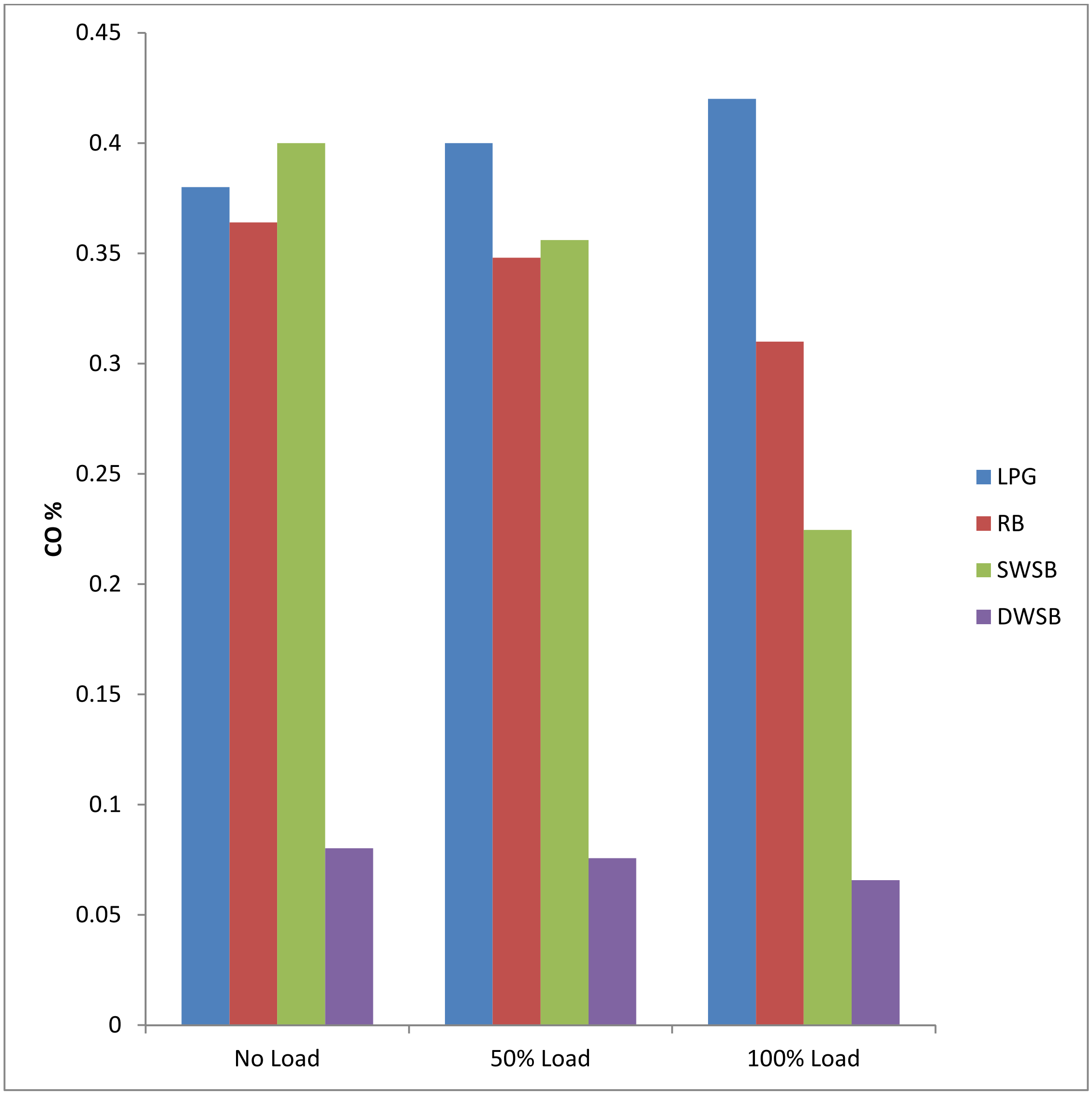


Figure 4.15: Plot of CO Emissions against Load

4.8.4 O_2 Emissions

The presence of O_2 among the exhaust gases could be an indication of some incomplete combustion of the fuel. The emission of O_2 at all loading conditions is presented in Figure 4.16. The emission of O_2 when the engine was at no load and fuelled with LPG, RB, SWSB and DWSB were 0.002063, 0.002178, 0.002098 and 0.002076%, respectively. At 50% load, the corresponding values for LPG, RB, SWSB and DWSB were 0.002064, 0.002164, 0.002087 and 0.002075 %, respectively while at full load, O_2 emission values were 0.00205, 0.00209, 0.00207 and 0.00206 %.

It was observed that the O_2 emission in LPG is lower than that in RB, SWSB and DWSB, an indication of a better combustion quality. The percentage O_2 emissions was observed to decrease in all fuels as the load increased and this was consistent with the works of Siripornakarachai and Sucharitakul (2007) and Paul *et al.* (2013). This shows the quality of the combustion seemed to improve with loading.

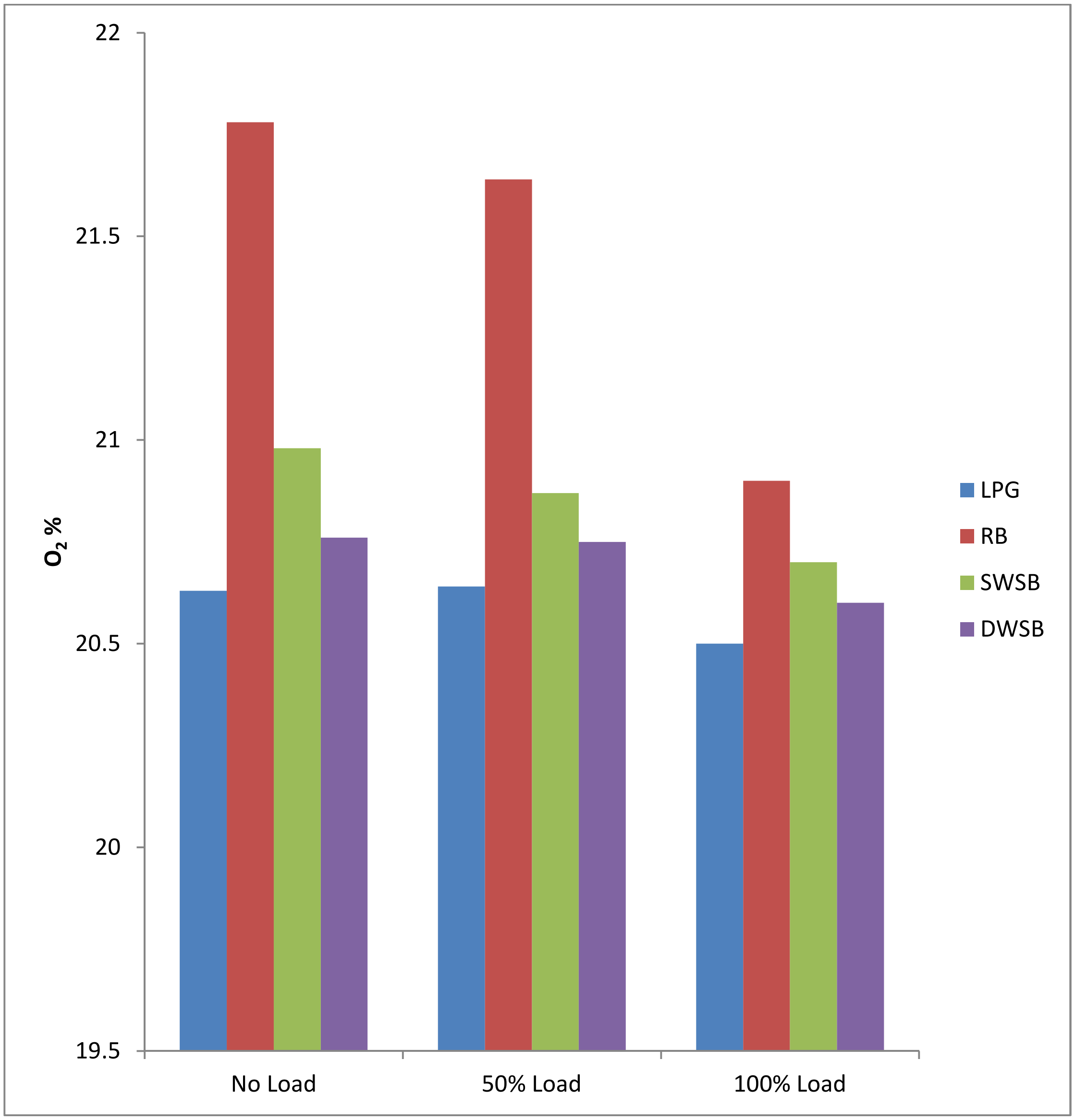


Figure 4.16: Plot of O_2 Emissions against Load

CHAPTER FIVE

CONCLUSION, CONTRIBUTION AND RECOMMENDATIONS

5.1 Conclusion

This study purified biogas in two stages using water scrubbing technology and investigated the effect of the two levels of purification on performance characteristics and emission profile of the SI engine operating with the derived fuels. It was established that water scrubbing technology purified biogas more effectively using a double stage method compared to a single stage method. The purified biogas was subsequently dried using silica gel and compressed into standard gas cylinders for running SI engines. The purified biogas fuel has provided a clean alternative source of energy for powering SI engine. It is therefore concluded that:

(i) Single staged water scrubber purified biogas to achieve methane content of 88.57% by volume compared with 96.67% achieved through double stage scrubbing. This shows the suitability of water scrubbing technology in purifying biogas to attain high methane content for use in SI engines.

(ii) Purified and dried biogas compressed for storage into 6 kg standard gas cylinders at 375.790 kPa pressure were suitable for powering SI engines.

(iii) Higher brake thermal efficiencies of 20.87 and 22.78%, respectively were achieved with single staged and double staged water scrubbed biogas compared with raw biogas (20.57%) and liquefied petroleum gas (10.70%) in SI engine.

(iv) Lower CO and SO_2 emissions were achieved through double stage water scrubbed biogas. This suggests that double staged water scrubbing technology produces outcomes of more effective overall desirable qualities on SI engines.

(v) Biogas was more fuel efficient than LPG, with lower BSFC values.

5.2 Contributions to Knowledge

The study has made the following contributions to knowledge:

- Biogas purity was increased from 73.47% to 88.52% vol. CH_4 by single-stage water scrubbing.
- Biogas purity was increased to 96.6% methane/volume following double-stage water scrubbing.
- Purified biogas at 375.79 kPa pressure effectively powered SI engine.
- This study demonstrated that the waste generated at the University of Ibadan Teaching and Research farm can be used to produce electric power.
- Demonstration that a spark ignition engine fitted with a commercial CNG conversion kit without compression ratio adjustment can perform satisfactorily when operating with purified biogas.
- Development of two water scrubbers and provision of recommended operating conditions and engineering drawings which can be a useful reference for further work on biogas purification.
- Literature is sparse on the performance and emission characteristics of SI engines operating with purified biogas. Most researches involve raw biogas only; raw biogas with addition of fuels such as petrol, diesel, LPG or CNG or simulated purified biogas (which deals with ideal and not the actual gas). This study therefore contributes greatly to knowledge on the performance of SI engines operating with the actual purified biogas and the emissions associated with the combustion process.

5.3 Recommendations

Based on the findings of this work, it is recommended that the farm waste generated at the University of Ibadan Teaching and Research Farm be utilized for biogas generation and purification. Biogas purified to have a CH_4 content of 97 % vol. could be compressed and stored for generating electricity to augment the deficient power supply from the national grid. Some infrastructures already exist in the University which makes it easier and cost effective. There are two biogas digesters at the teaching and research farm (Poultry farm and cattle farm) and the farm generates an average of 237.2 kg, 136.6 kg and 252.2 kg of waste daily from the cattle, swine and poultry farms, respectively. This is an average of 626kg daily which is sufficient to sustain biogas generation. This will have the following advantages for the University:

(i) It will help to manage the waste generated on the farms. Thereby reducing the odour, health risks and emission of greenhouse gases associated with piling them in heaps on the farms.

(ii) It will help provide an alternative source of power which will help alleviate the problems associated with erratic power supply from the national grid as well as reduce the cost of generating power using diesel.

(iii) Biogas is a clean fuel. Its use reduces the emission of greenhouse gases that are usually emitted by fossil fuels used in conventional generators.

It is recommended that further research work be done in the following areas:

(i) Investigation of the effect of pre-heating on combustion of spark ignition engines fuelled with biogas in order to improve the cold starting of small SI engines fueled with biogas.

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APPENDIX I

EXCEL SHEETS USED FOR CALCULATING THE CALORIFIC VALUE OF THE BIOGAS SAMPLES

Gas	**VCH4/VTot**	**ρCH4 act**	**Hu, KJ/kg**	**Hu, act (KJ/kg)**
Raw	0.7347	0.708119	50000	26012.75147
SWSB	0.8857	0.708119	50000	31359.04992
DWSB	0.9667	0.708119	50000	34226.93187

GAS	**ρCH4 std**	**P act, kPa**	**Pstd, kPa**	**T,std**	**T, act**	**Pact/Pstd**	**Tstd/Tact**	**ρCH4 act**
RAW	0.72	101.3	101.3	298	303	1	0.983498	0.708119
Stage 1	0.72	101.3	101.3	298	303	1	0.983498	0.708119
Stage 2	0.72	101.3	101.3	298	303	1	0.983498	0.708119

APPENDIX II

EXCEL SHEETS FOR CALCULATING THE PERFORMANCE CHARACTERISTICS

AT NO LOAD

FUEL				
Parameters	LPG	RB	SWSB	DWSB
Volumetric Flow rate m^3/s	0.000083	0.000083	0.000083	0.000083
Mass Flow rate, kg/s	0.00020584	0.00009545	0.00009545	0.00009545
Heating Value, J/kg	46100000	26012750	30010083	34226930
Fuel Equivalent Power, W	9489.2240	2482.9170	2864.4624	3266.9605
Speed, rpm	3000	2800	3000	3000
Torque, Nm	0	0	0	0

50% LOAD

Parameters	FUEL			
	LPG	**RB**	**SWSB**	**DWSB**
Volumetric Flow rate m^3/s	0.0001167	0.0001167	0.0001167	0.0001167
Mass Flow rate, kg/s	0.000289416	0.000134205	0.000134205	0.000134205
Heating Value, J/kg	46100000	26012750	30010083	34226930
Fuel Equivalent Power, W	13342.0776	3491.0411	4027.5032	4593.4251
Speed, rpm	2700	2400	2750	2800
Torque, Nm	4	1.8	2.5	2.8
Brake Power, W	1131.12	452.448	720.0417	821.1093
Brake Power, kW	1.1311	0.4524	0.7200	0.8211
Brake Specific Fuel Consumption, g/kWh	921.1203	1067.8301	670.9862	588.3967
Heating Value, kJ/kg	46100	26012.75	30010.083	34226.93
Brake Thermal Efficiency, %	8.478	12.960	17.878	17.876

100% LOAD

Parameters	FUEL			
	LPG	**RB**	**SWSB**	**DWSB**
Volumetric Flow rate m^3/s	0.000167	0.000167	0.000167	0.000167
Mass Flow rate, kg/s	0.00041416	0.00019205	0.00019205	0.00019205
Heating Value, J/kg	46100000	26012750	30010083	34226930
Fuel Equivalent Power, W	19092.776	4995.7486	5763.4364	6573.2819
Speed, rpm	2600	2180	2500	2600
Torque, Nm	7.5	4.5	4.8	5.5
Brake Power, W	2042.30	1027.434	1256.80	1497.69
Brake Power, kW	2.0423	1.0274	1.2568	1.4977
Brake Specific Fuel Consumption, g/kWh	730.05	672.92	550.11	461.63
Heating Value, kJ/kg	46100	26012.75	30010.083	34226.93
Brake Thermal Efficiency, %	10.70	20.57	21.81	22.78

APPENDIX III

EMISSION CHARACTERISTICS

Date	Time	Fuel	%O2	ppm CO	TStk	TAir	SO2	NOx O2Ref	SO2 O2Ref	Pressure	NO Temp
12/14/2017	1:49:47 PM	Petrol	20.9	14	266	32.8	1	6	6	101	29.7
12/14/2017	1:49:51 PM	Petrol	20.9	8	271	32.8	1	6	6	226	29.7
12/14/2017	1:49:56 PM	Petrol	20.9	9	278	32.8	2	6	6	172	29.7
12/14/2017	1:50:00 PM	Petrol	20.9	16	281	32.9	2	6	6	110	29.7
12/14/2017	1:50:04 PM	Petrol	20.9	26	281	32.9	2	6	6	136	29.7
12/14/2017	1:50:08 PM	Petrol	20.9	42	283	32.9	2	6	6	63	29.7
12/14/2017	1:50:20 PM	Petrol	20.9	47	216	32.9	2	6	6	-1	29.8
12/14/2017	1:51:56 PM	Petrol	20.8	238	207	33.2	7	6	6	46	30.1
12/14/2017	1:52:02 PM	Petrol	20.7	508	293	33.2	12	6	6	75	30.1
12/14/2017	1:52:05 PM	Petrol	20.8	786	312	33.2	15	6	6	58	30.1
12/14/2017	1:52:14 PM	Petrol	20.7	1593	290	33.2	25	6	6	83	30.1
12/14/2017	1:52:18 PM	Petrol	20.5	2159	299	33.3	30	6	6	74	30.2
12/14/2017	1:52:23 PM	Petrol	20.3	2824	324	33.3	38	6	6	90	30.2
12/14/2017	1:52:26 PM	Petrol	20.2	3285	328	33.3	44	6	6	94	30.2
12/14/2017	1:52:30 PM	Petrol	20.1	3959	314	33.3	50	6	6	134	30.2
12/14/2017	1:52:43 PM	Petrol	20.9	XXX	237	33.3	152	6	6	26	30.2
12/14/2017	1:52:45 PM	Petrol	20.9	XXX	231	33.3	164	6	6	6	30.2
12/14/2017	1:57:32 PM	LPG	18.3	XXX	199	34.4	293	6	6	346	31.2
12/14/2017	1:57:36 PM	LPG	18.1	XXX	244	34.4	275	6	6	175	31.1

12/14/2017	1:57:40 PM	LPG	19.6	XXX	240	34.4	276	6	6	35	31.1
12/14/2017	1:57:43 PM	LPG	20.2	XXX	223	34.4	266	6	6	292	31.1
12/14/2017	1:57:48 PM	LPG	20.6	XXX	206	34.5	235	6	6	-6	31.1
12/14/2017	1:57:53 PM	LPG	20.9	XXX	212	34.5	223	6	6	14	31.2
12/14/2017	1:58:02 PM	LPG	20.9	XXX	197	34.5	219	6	6	132	31.2
12/14/2017	1:58:10 PM	LPG	20.7	XXX	230	34.6	220	6	6	-6	31.2
12/14/2017	2:01:29 PM	LPG	20.1	XXX	138	35.5	122	6	6	123	31.9
12/14/2017	2:01:33 PM	LPG	20.3	XXX	181	35.6	118	6	6	146	31.9
12/14/2017	2:01:39 PM	LPG	20.5	XXX	204	35.6	102	6	6	-10	32
12/14/2017	2:01:45 PM	LPG	20.6	XXX	186	35.6	94	6	6	283	32
12/14/2017	2:01:50 PM	LPG	20.4	XXX	195	35.7	87	6	6	-9	32
12/14/2017	2:01:55 PM	LPG	20.3	XXX	176	35.7	68	6	6	-8	32
12/14/2017	2:02:00 PM	LPG	20.8	XXX	162	35.7	34	6	6	53	32.1
12/14/2017	2:02:04 PM	LPG	20.5	XXX	182	35.7	34	6	6	76	32.1
12/14/2017	2:02:06 PM	LPG	20.5	XXX	170	35.8	36	6	6	-9	32.1
12/14/2017	3:33:38 PM	Dig Gas	20.1	***	180	36.7	18	6	6	86	34
12/14/2017	3:33:43 PM	Dig Gas	20.3	***	221	36.7	10	6	6	145	34
12/14/2017	3:33:47 PM	Dig Gas	20.5	***	236	36.7	11	6	6	102	34
12/14/2017	3:33:54 PM	Dig Gas	20.6	***	187	36.7	6	6	6	-3	34
12/14/2017	3:34:11 PM	Dig Gas	20.7	***	240	36.7	0	6	6	82	34
12/14/2017	3:34:16 PM	Dig Gas	20.7	***	224	36.7	0	6	6	-1	34.1
12/14/2017	3:37:36 PM	Dig Gas	20.9	***	180	36.9	0	6	6	109	34.3
12/14/2017	3:37:44 PM	Dig Gas	20.8	***	233	36.9	0	6	6	39	34.4
12/14/201	3:37:49	Dig Gas	20.9	***	255	36.	0	6	6	267	34.4

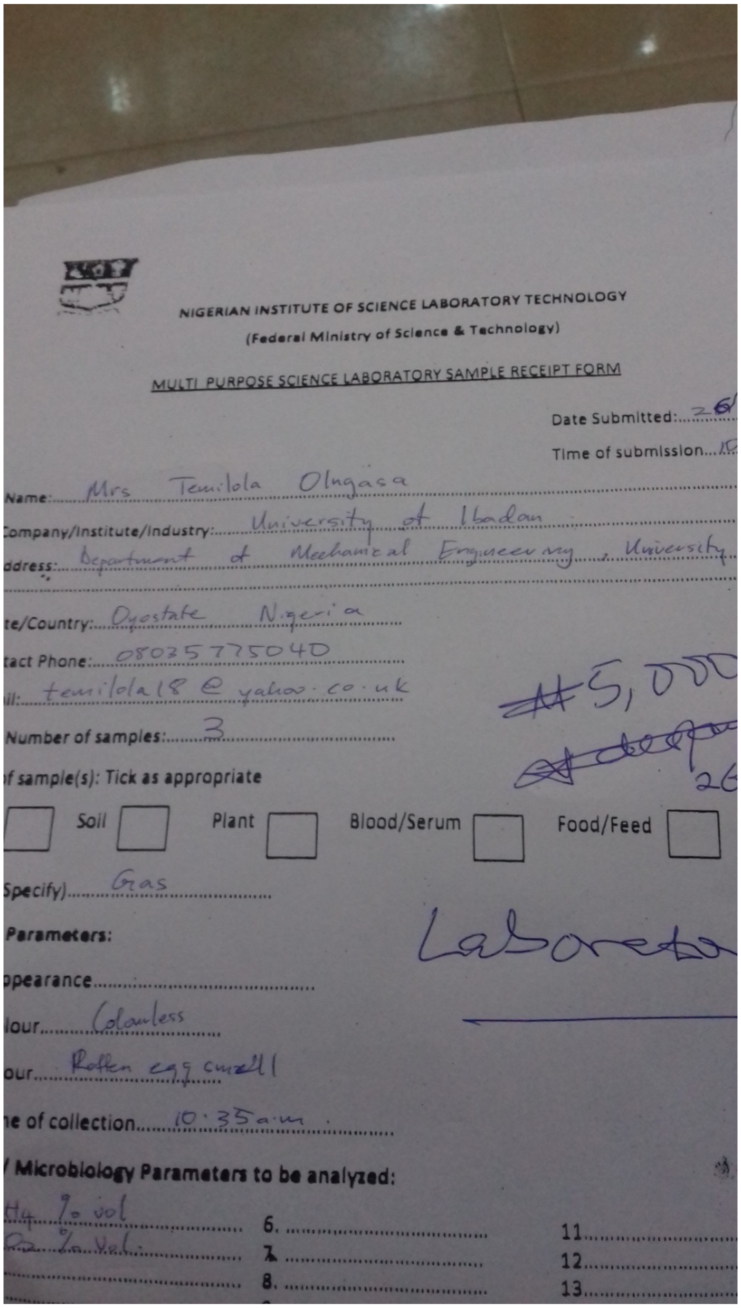
7	PM					9					
12/14/2017	3:37:52 PM	Dig Gas	20.9	***	274	36.9	0	6	6	11	34.4
12/14/2017	3:37:56 PM	Dig Gas	20.9	***	257	37	0	6	6	66	34.4
12/14/2017	3:38:01 PM	Dig Gas	20.9	***	230	37	0	6	6	31	34.4
1/16/2018	1:23:39 PM	Bio Methane 2	20.8	115	103	33.1	3	6	6	61	31.6
1/16/2018	1:23:46 PM	Bio Methane 2	20.8	70	155	33.1	7	6	6	99	31.6
1/16/2018	1:24:19 PM	Bio Methane 2	20.7	379	83	33.1	39	6	6	-1	31.6
1/16/2018	1:24:45 PM	Bio Methane 2	20.9	619	62	33.1	33	6	6	-1	31.7
1/16/2018	1:25:48 PM	Bio Methane 2	20.8	767	95	33.3	16	6	6	122	31.7
1/16/2018	1:25:53 PM	Bio Methane 2	20.7	774	140	33.3	63	6	6	162	31.7
1/16/2018	1:25:57 PM	Bio Methane 2	20.5	1272	172	33.3	75	6	6	128	31.7
1/16/2018	1:26:00 PM	Bio Methane 2	20.5	1695	173	33.3	70	6	6	-2	31.7
1/16/2018	1:26:43 PM	Bio Methane 2	20.7	1700	80	33.4	30	6	6	-1	31.8
1/16/2018	1:27:34 PM	Bio Methane 2	20.6	1705	129	33.5	36	6	6	-1	31.9
1/16/2018	1:27:41 PM	Bio Methane 2	20.6	1954	116	33.6	39	6	6	-1	31.9
1/16/2018	1:28:05 PM	Bio Methane 2	20.6	1869	74	33.6	31	6	6	-1	31.9
1/16/2018	1:37:33 PM	Bio Methane 1	20.4	1261	152	34.7	86	6	6	120	32.2
1/16/2018	1:37:39	Bio	20.2	313	179	34.	78	6	6	19	32.2

	PM	Methane 1		4		7					
1/16/2018	1:37:43 PM	Bio Methane 1	20.3	3644	184	34.7	50	6	6	93	32.2
1/16/2018	1:37:48 PM	Bio Methane 1	20.5	3470	173	34.7	28	6	6	-2	32.2
1/16/2018	1:41:44 PM	Bio Methane 1	20	1978	148	34.9	113	6	6	63	32.3
1/16/2018	1:41:48 PM	Bio Methane 1	20	3745	180	34.9	91	6	6	242	32.3
1/16/2018	1:41:54 PM	Bio Methane 1	20.8	XXX	193	34.9	62	6	6	107	32.2
1/16/2018	1:42:57 PM	Bio Methane 1	20.8	XXX	87	35	23	6	6	-3	31.9

APPENDIX IV

DETAILS OF LIQUID DISPLACEMENT METHOD ANALYSIS

LABORATORY SAMPLE RECEIPT FORM FOR LDM PROCEDURE AT NISLT



NIGERIAN INSTITUTE OF SCIENCE LABORATORY TECHNOLOGY
(Federal Ministry of Science & Technology)

MULTI PURPOSE SCIENCE LABORATORY SAMPLE RECEIPT FORM

Date Submitted: 26
Time of submission... 10

Name: Mrs Temilola Olugasa
Company/Institute/Industry: University of Ibadan
ddress: Department of Mechanical Engineering, University
te/Country: Oyostate Nigeria
tact Phone: 08035775040
il: temilola18 @ yahoo.co.uk
Number of samples: 3

~~#~~5,00

26

f sample(s): Tick as appropriate

☐ Soil ☐ Plant ☐ Blood/Serum ☐ Food/Feed ☐

Specify) Gas

Parameters:

Laboreto

ppearance

lour Colourless

our Rotten egg smell

e of collection 10:35a.m

/ Microbiology Parameters to be analyzed:

H4 % vol ... 6. ... 11...
O2 % Vol. ... 7. ... 12...
... 8. ... 13...

Carrying out of the LDM procedure at Nigerian Institute of Science Laboratory Technology (NISLT)

Calibration of PH Meter before use at NISLT

Experimental set up for LDM procedure

Wet Chemistry Analysis of the Scrubbed Biogas Samples

The wet chemistry analysis showed the following:

Raw Biogas (RB):

Volume of biogas passed into Hydrochloric acid: 49cm^3

Volume of biogas Absorbed by Potassium Hydroxide: 13 cm^3

Percentage of CO_2 in biogas = $\frac{\boldsymbol{Volume\ of\ biogas\ passed\ in - Volume\ of\ biogas\ absorbed}}{\boldsymbol{Volume\ of\ biogas\ passed\ in}} \times \mathbf{100\%}$

$$= \frac{13}{49} \times 100 = 26.53\%$$

Assuming that biogas is composed mainly of CO_2 and CH_4, therefore,

Percentage of CH_4 in the gas = (100-26.53) %

= 73.47%

Single stage Water Scrubbed Biogas (SWSB):

Volume of biogas passed into Hydrochloric acid: 52.5cm^3

Volume of biogas Absorbed by Potassium Hydroxide: 6 cm^3

Percentage of CO_2 in biogas = $\frac{\boldsymbol{Volume\ of\ biogas\ passed\ in - Volume\ of\ biogas\ absorbed}}{\boldsymbol{Volume\ of\ biogas\ passed\ in}} \times \mathbf{100\%}$

$$= \frac{6}{52.5} \times 100 = 11.43\%$$

Assuming that biogas is composed mainly of CO_2 and CH_4, therefore,

Percentage of CH_4 in the gas = (100-11.43) %

= 88.57 %

Double stage Water Scrubbed Biogas (DWSB):

Volume of biogas passed into Hydrochloric acid: 30cm^3

Volume of biogas Absorbed by Potassium Hydroxide: 1 cm^3

Percentage of CO_2 in biogas = $\frac{\boldsymbol{Volume\ of\ biogas\ passed\ in - Volume\ of\ biogas\ absorbed}}{\boldsymbol{Volume\ of\ biogas\ passed\ in}} \times \mathbf{100\%}$

$$= \frac{1}{30} \times 100 = 3.33\%$$

Assuming that biogas is composed mainly of CO_2 and CH_4, therefore,

Percentage of CH_4 in the gas = (100-3.33) %

= 96.67 %

Evaluation of Scrubber Efficiency

The scrubber efficiency for the single stage water scrubber is

$$\frac{\%change\ in\ CO_2 composition}{Original\ CO_2\ composition} \times 100\%$$

=

$$\frac{26.53 - 11.43}{26.53} \times 100\%$$

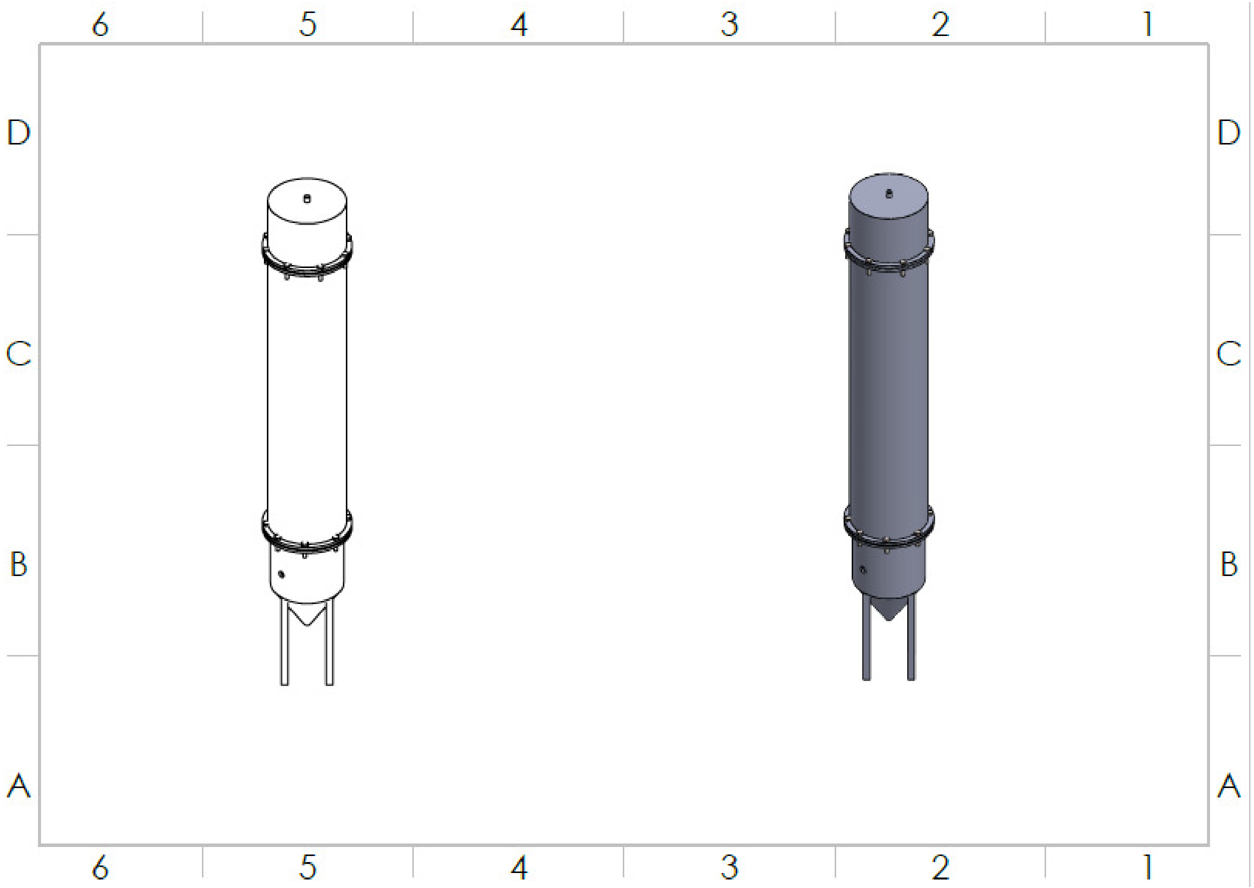
$$= \mathbf{56.92}\%$$

Efficiency of double stage water scrubber

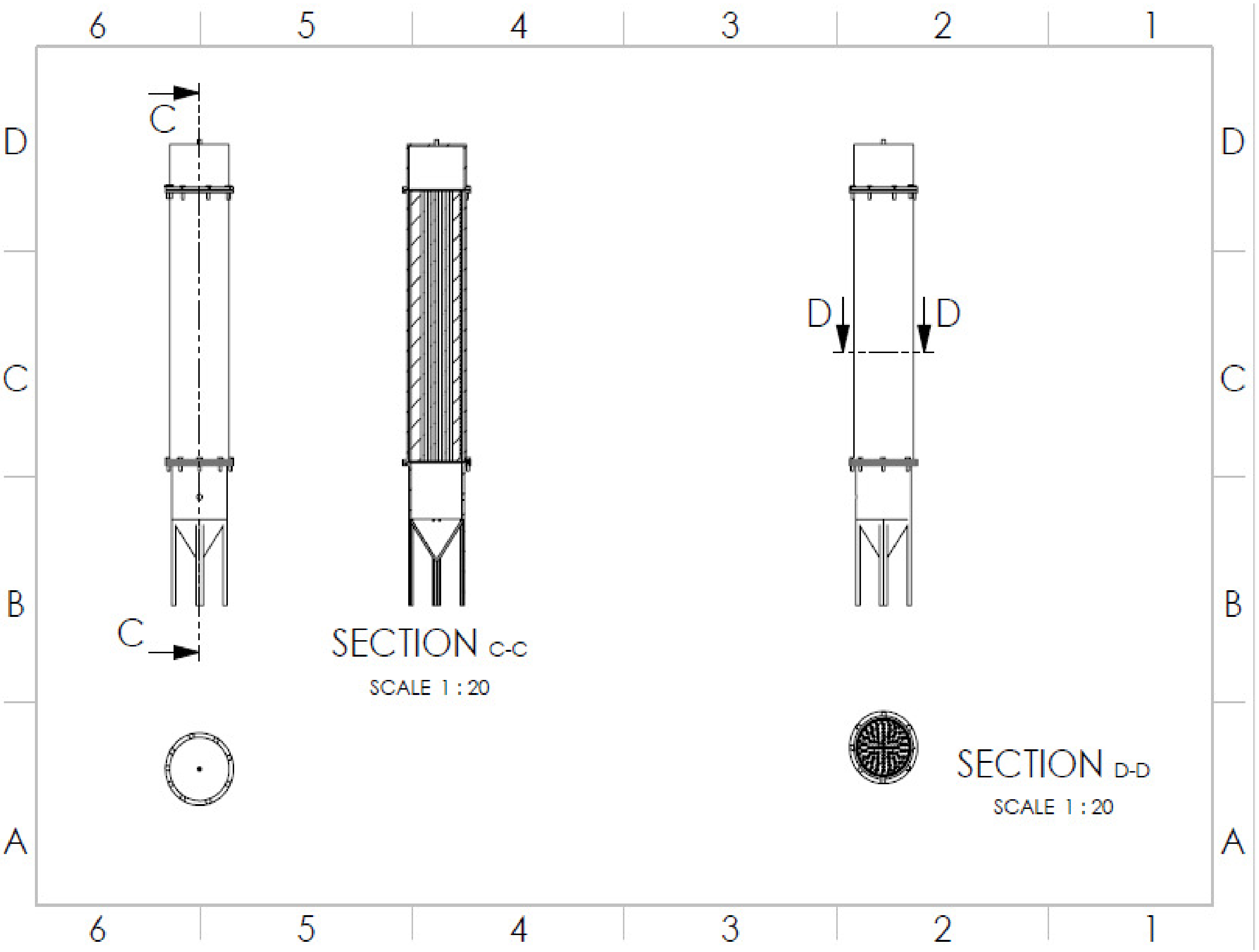
$$\frac{11.43 - 3.33}{11.43} \times 100\%$$

$$= \mathbf{70.87}\%$$

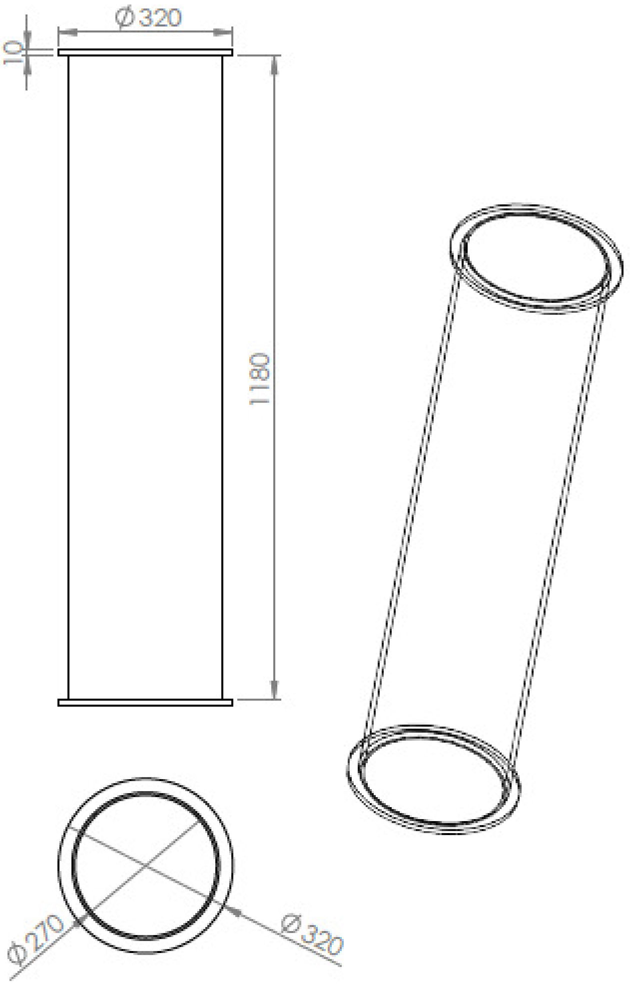
APPENDIX V: ENGINEERING DRAWINGS FOR SCRUBBERS 1 & 2



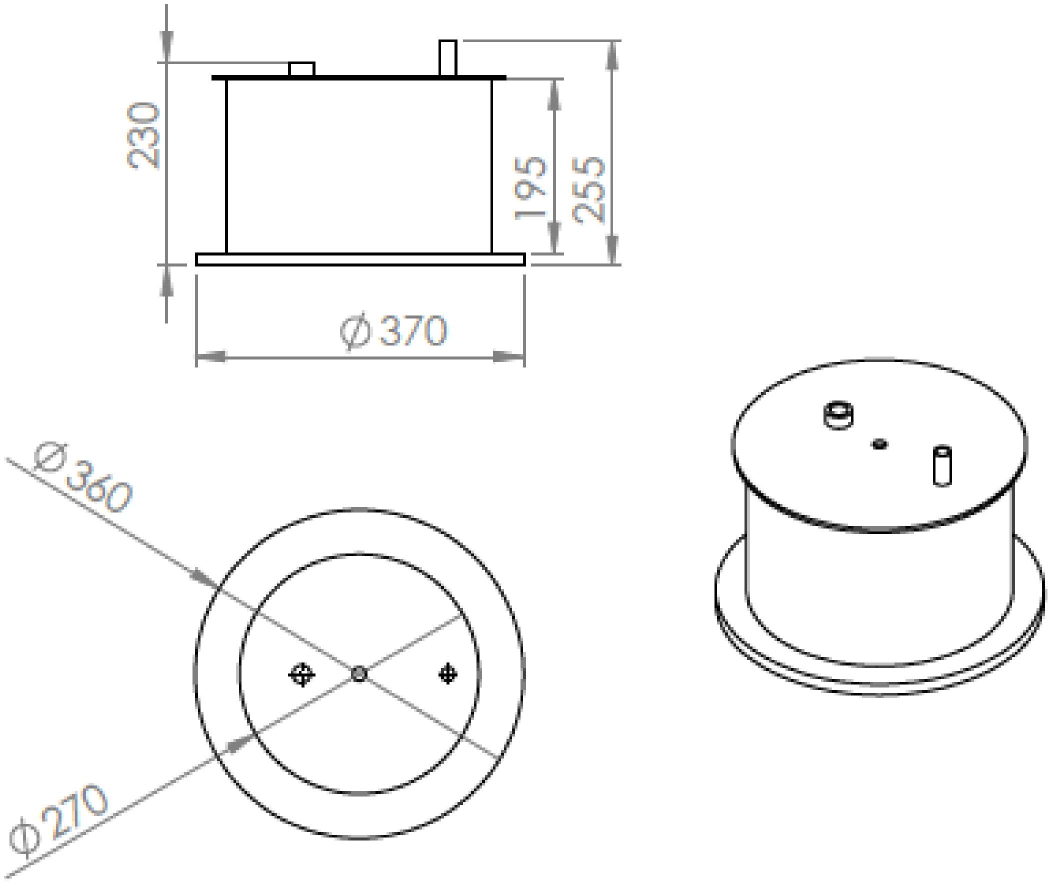
Isometric View of Scrubber 1



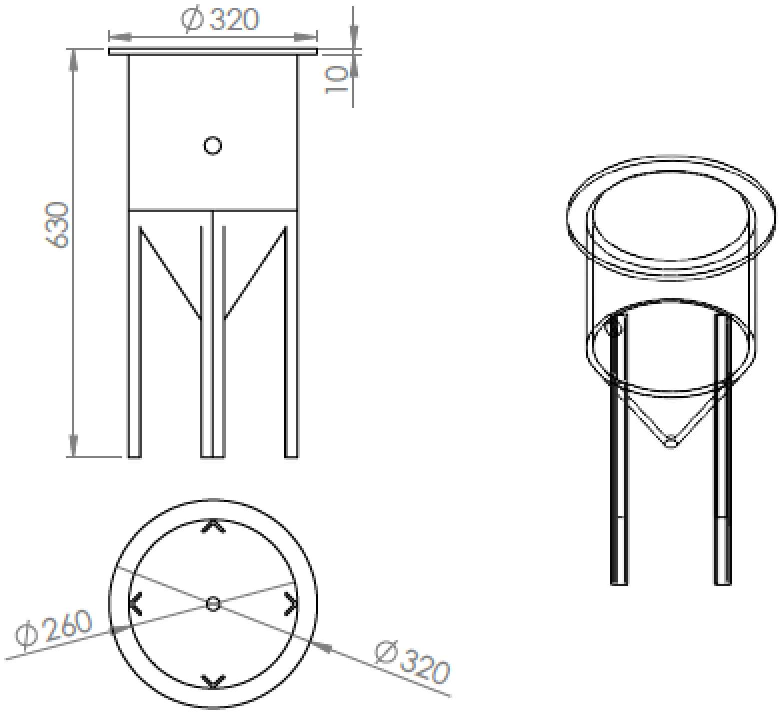
Sectional Views of Scrubber 1



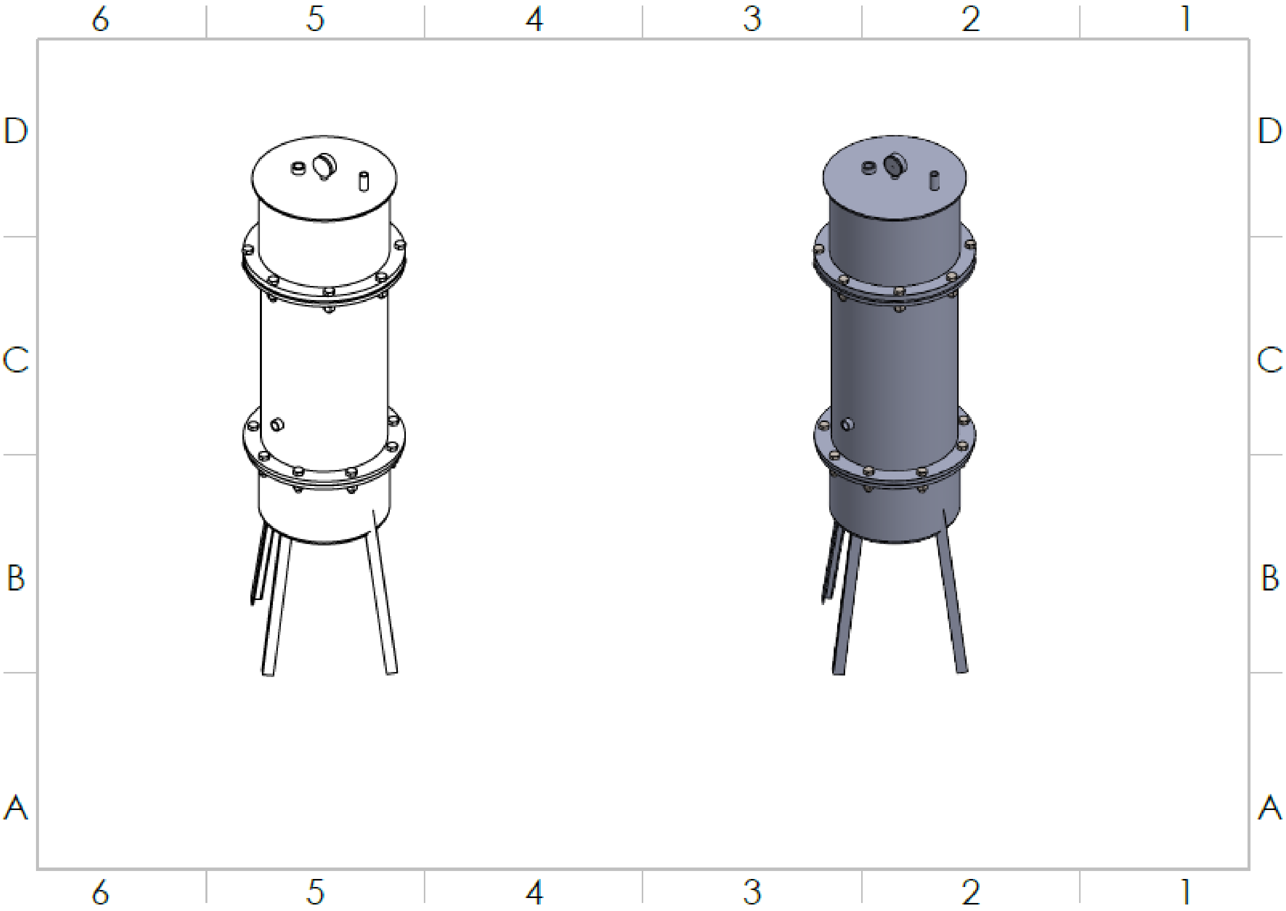
Middle section of Scrubber 1



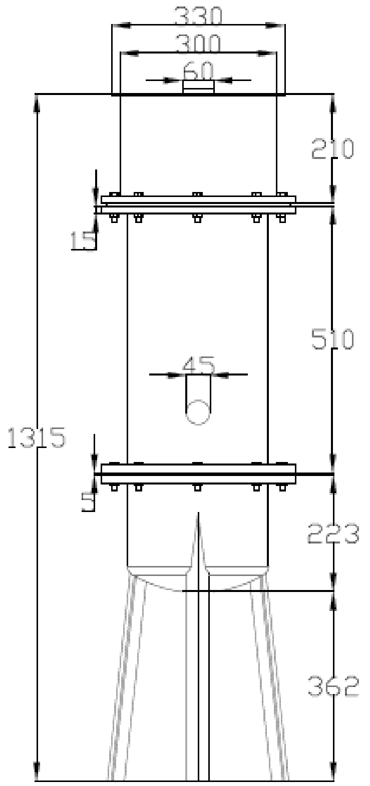
View of the Top section of Scrubber 1



Bottom section of Scrubber 1



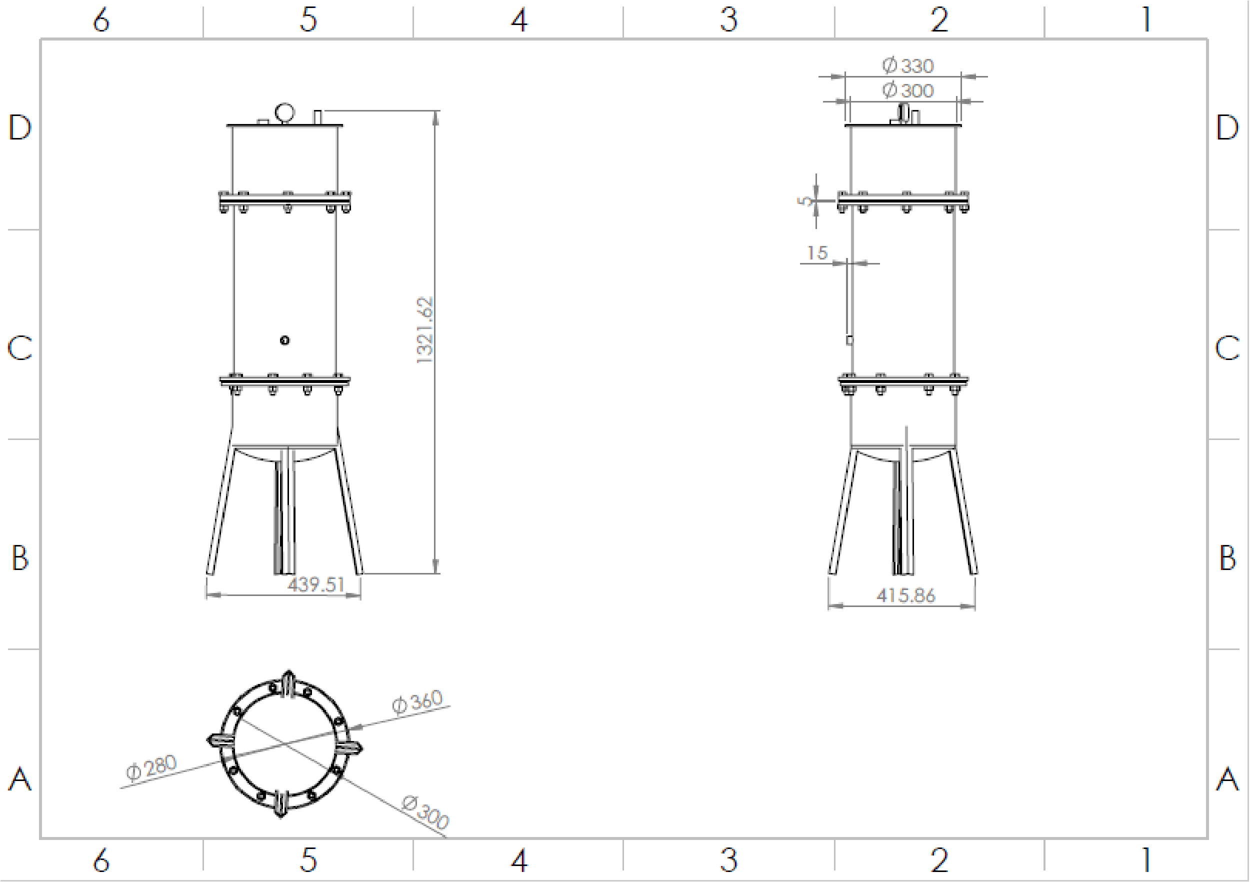
Isometric View of Scrubber 2



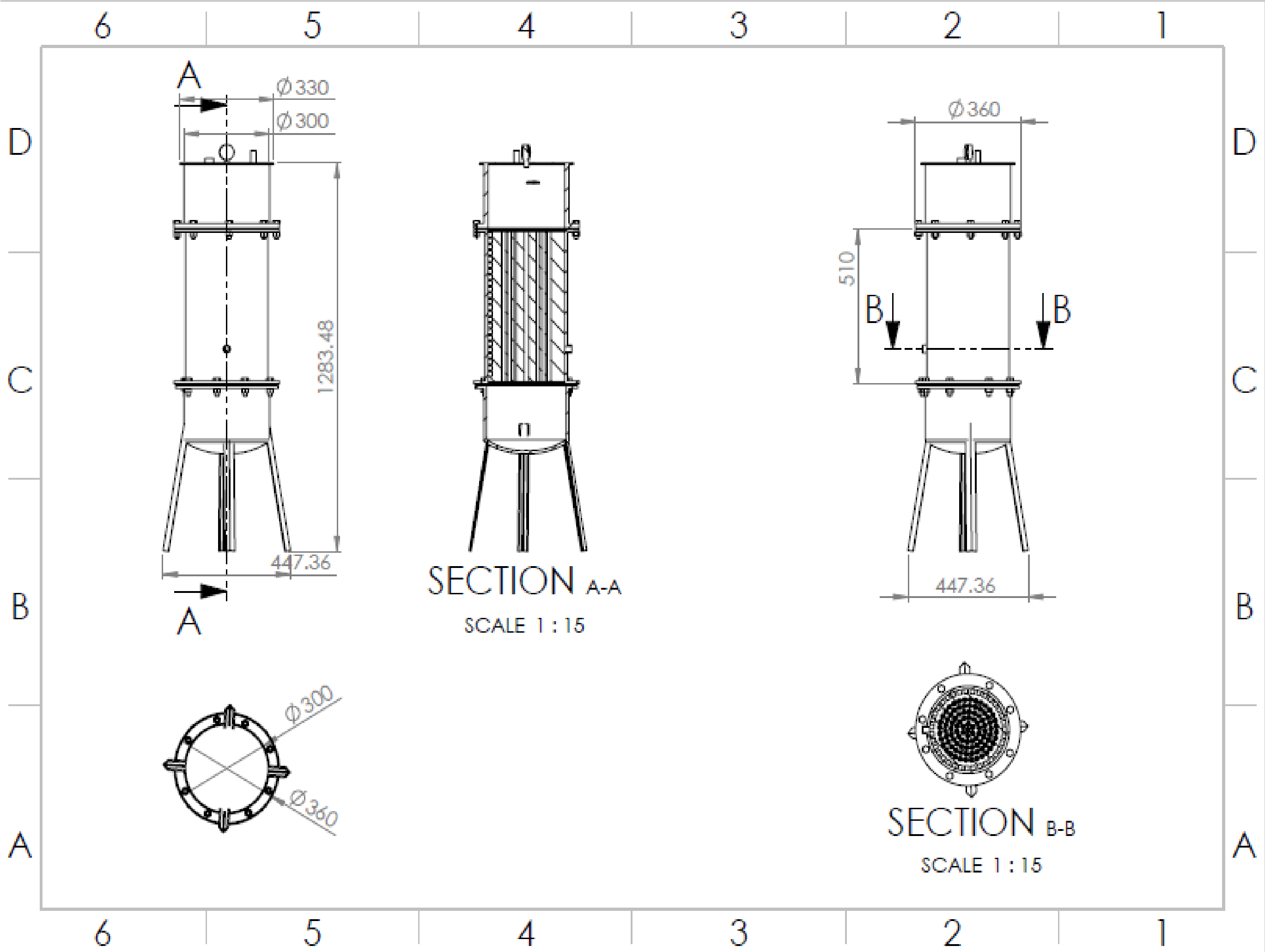
Part list		
S/N	Description	Qty
1	Top part	1
2	Middle part	1
3	Bottom part	1
4	Screw	16
5	Bolt	16
6	Gasket	2

Note: All dimensions are in mm

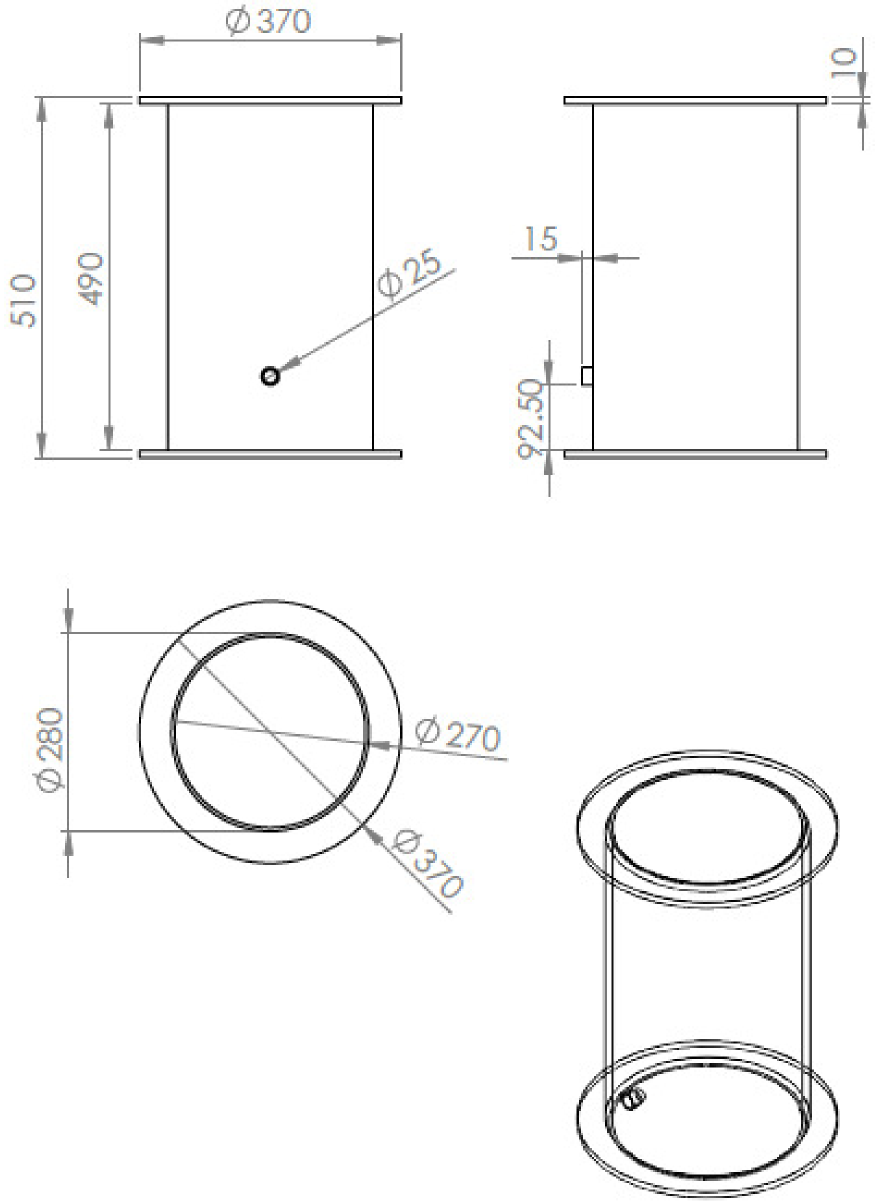
Front view of Water Scrubber 2



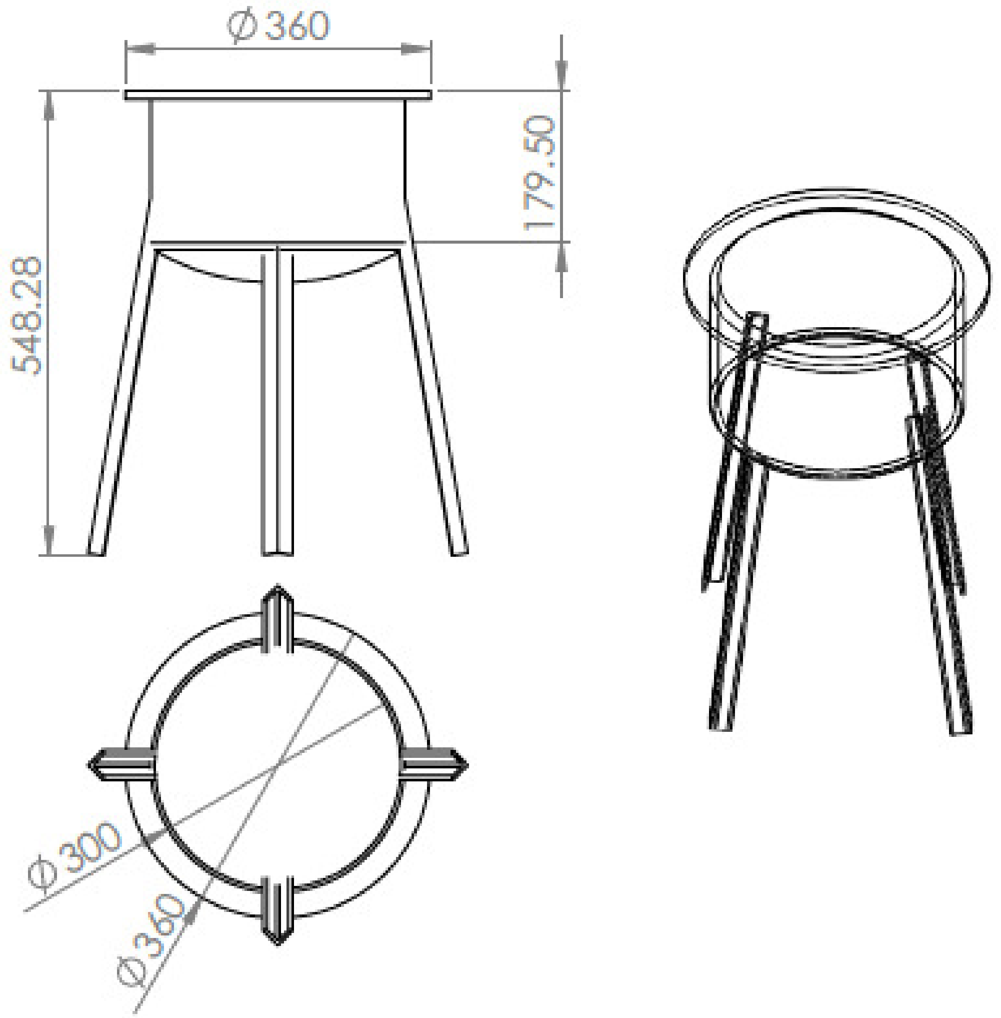
Orthographic view of Scrubber 2



Sectional Views of Scrubber 2



Orthographic view of Middle Section of Scrubber 2



Isometric View of Bottom Section of Scrubber 2

APPENDIX VI- EXPERIMENTATION PICTURES

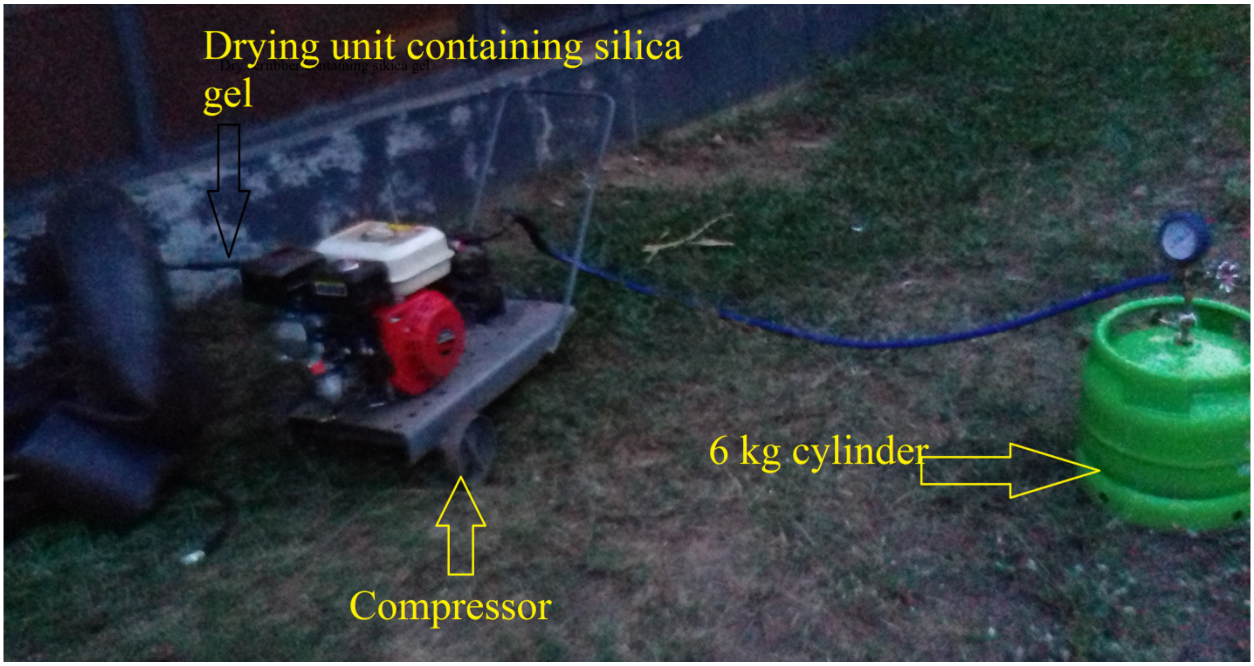
Cow dung used for the study

Digester with weight placed on the top to prevent toppling of gas cap during biogas generation

Improvement of digester with clamps and belt to hold gas cap in place

Compressor used for the study

Set up for harvesting raw Biogas into cylinder



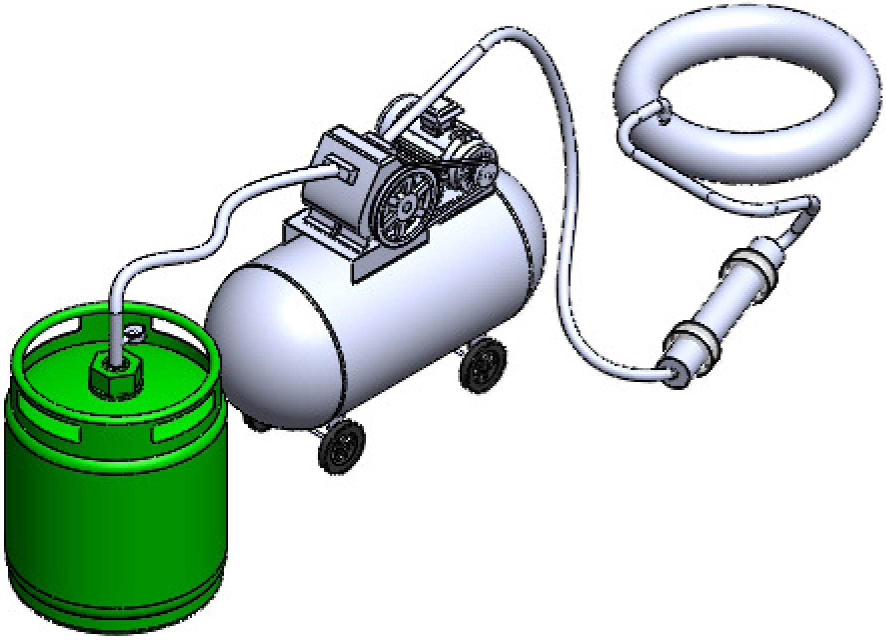
Drying and bottling of Water Scrubbed Biogas

Silica gel before using it to dry the scrubbed gas

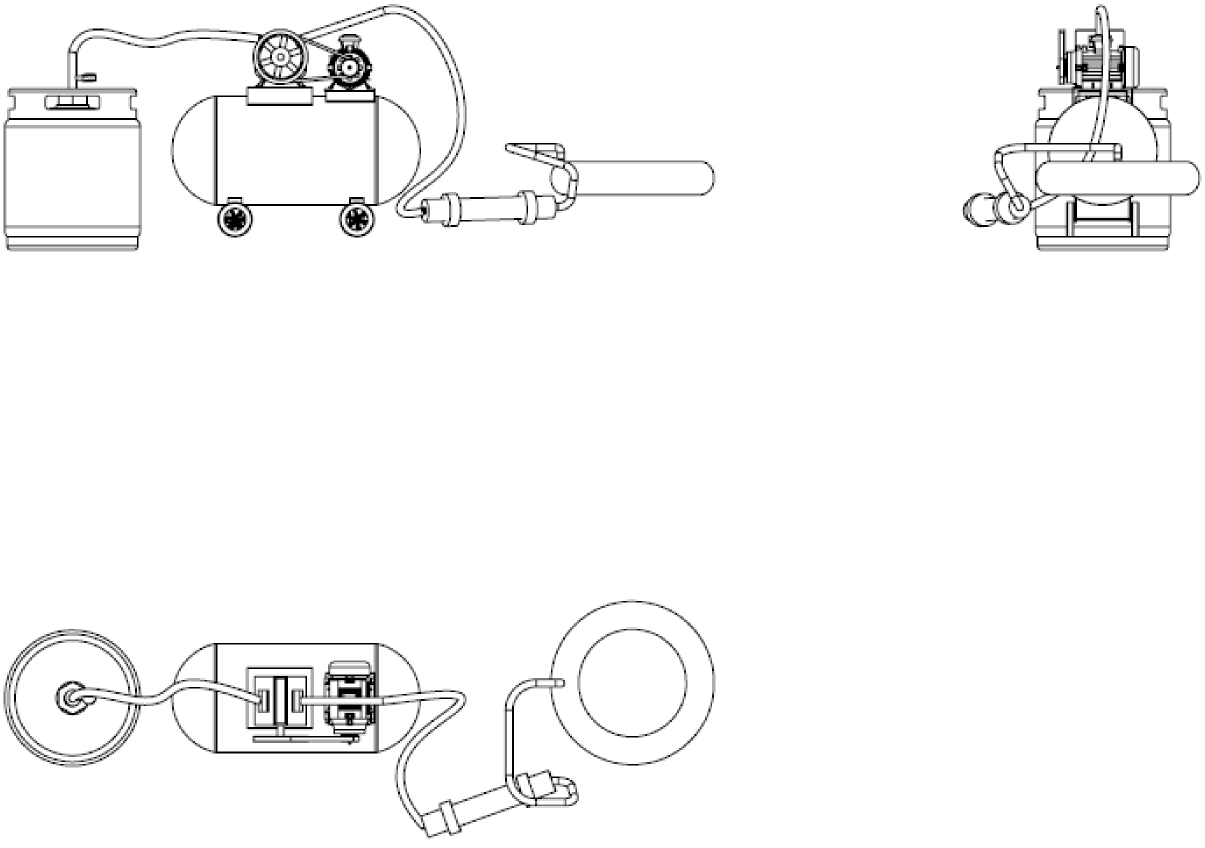
Silica gel after drying scrubbed gas

Engine on test bed

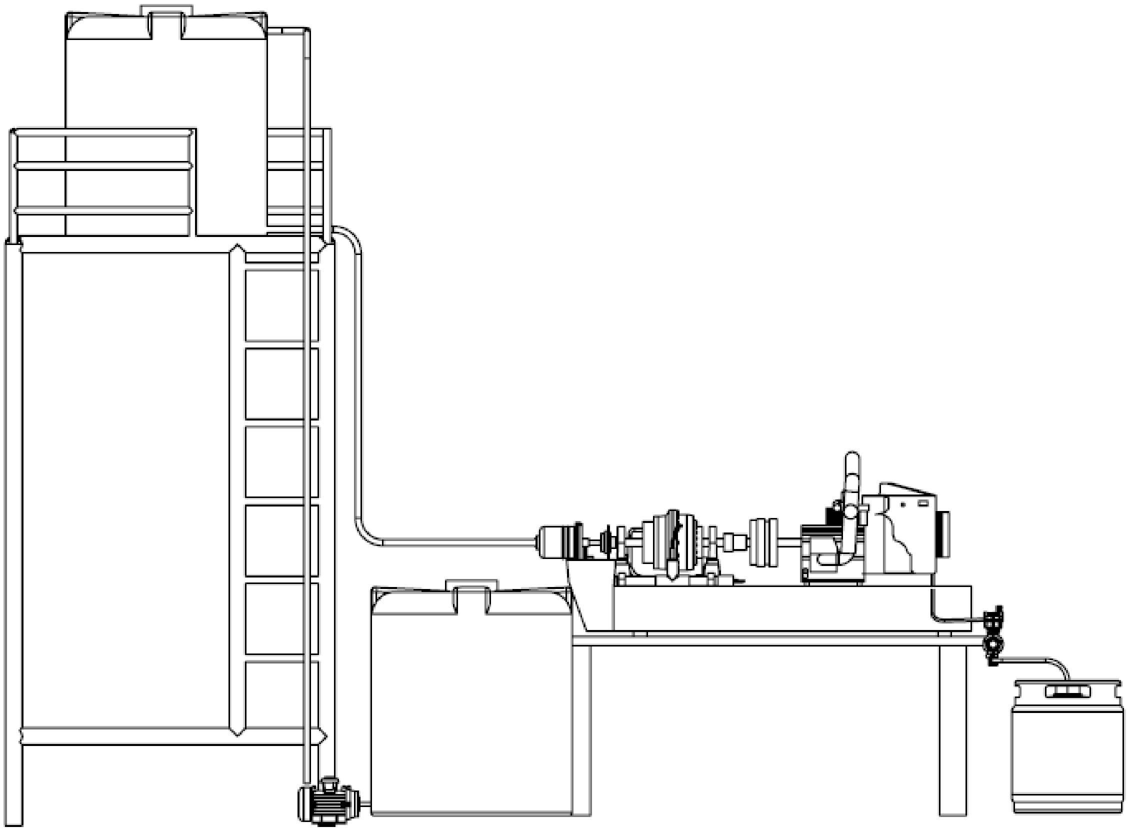
Taking readings during the engine test



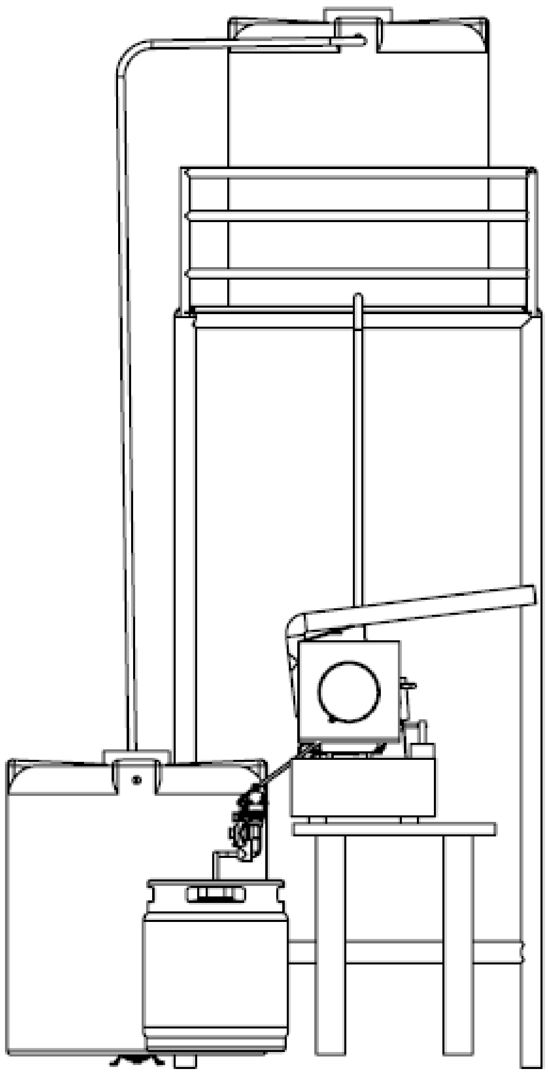
Isometric View of the set up for drying and compression of purified biogas



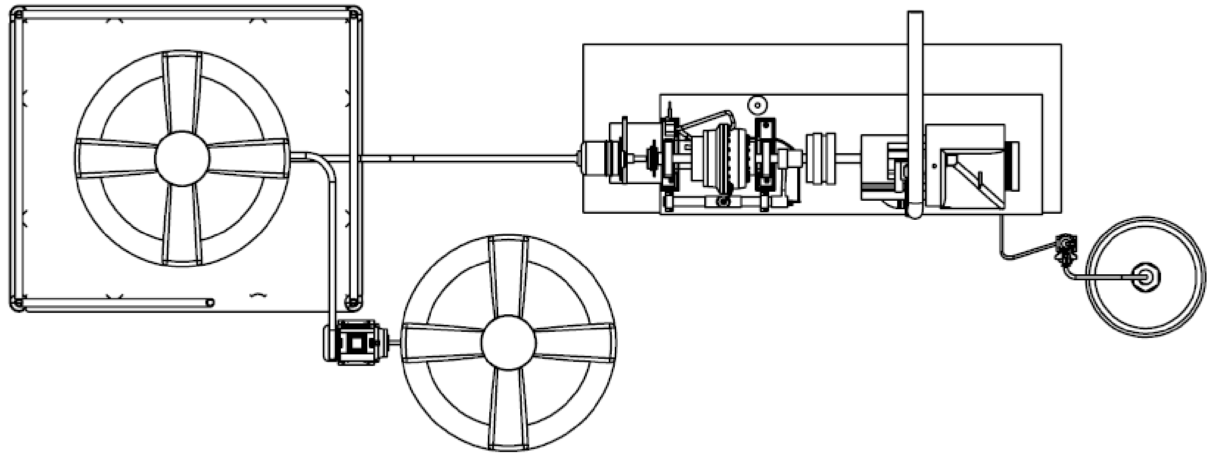
Views of the experimental set up for compression and storage of purified Biogas



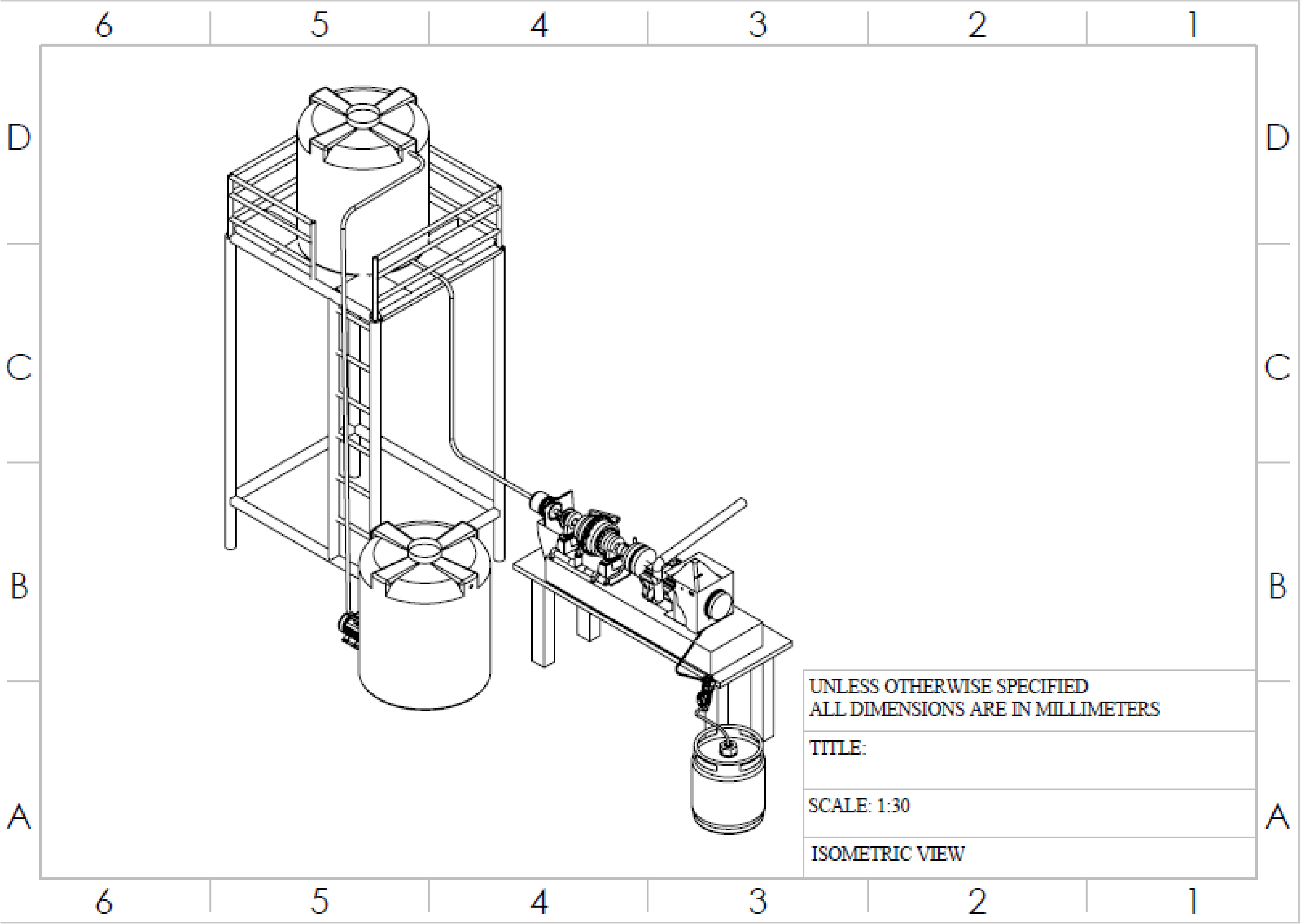
Orthographic Front view of experimental set up of the Engine Test



Orthographic side view of the Experimental set up of the engine test

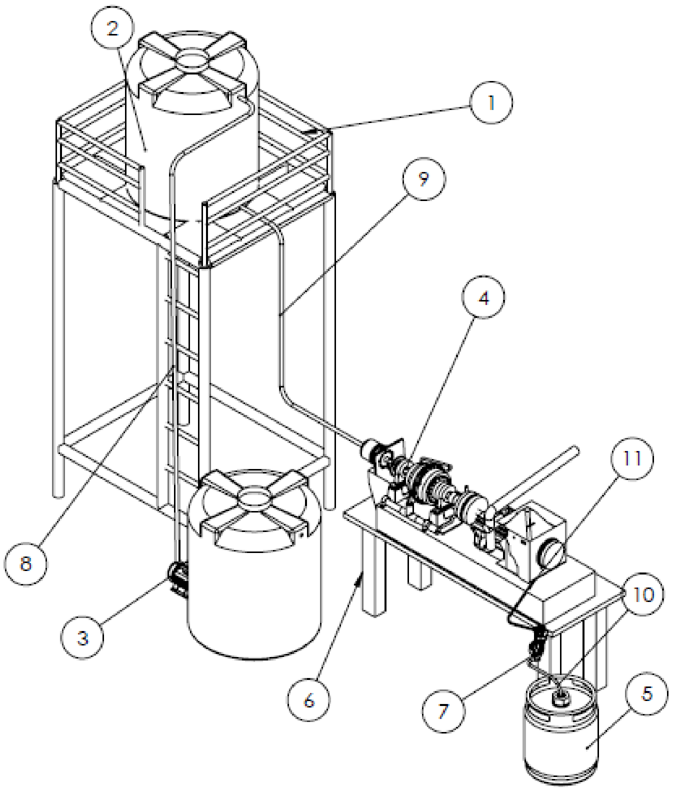


Orthographic Plan of the experimental set up of engine test

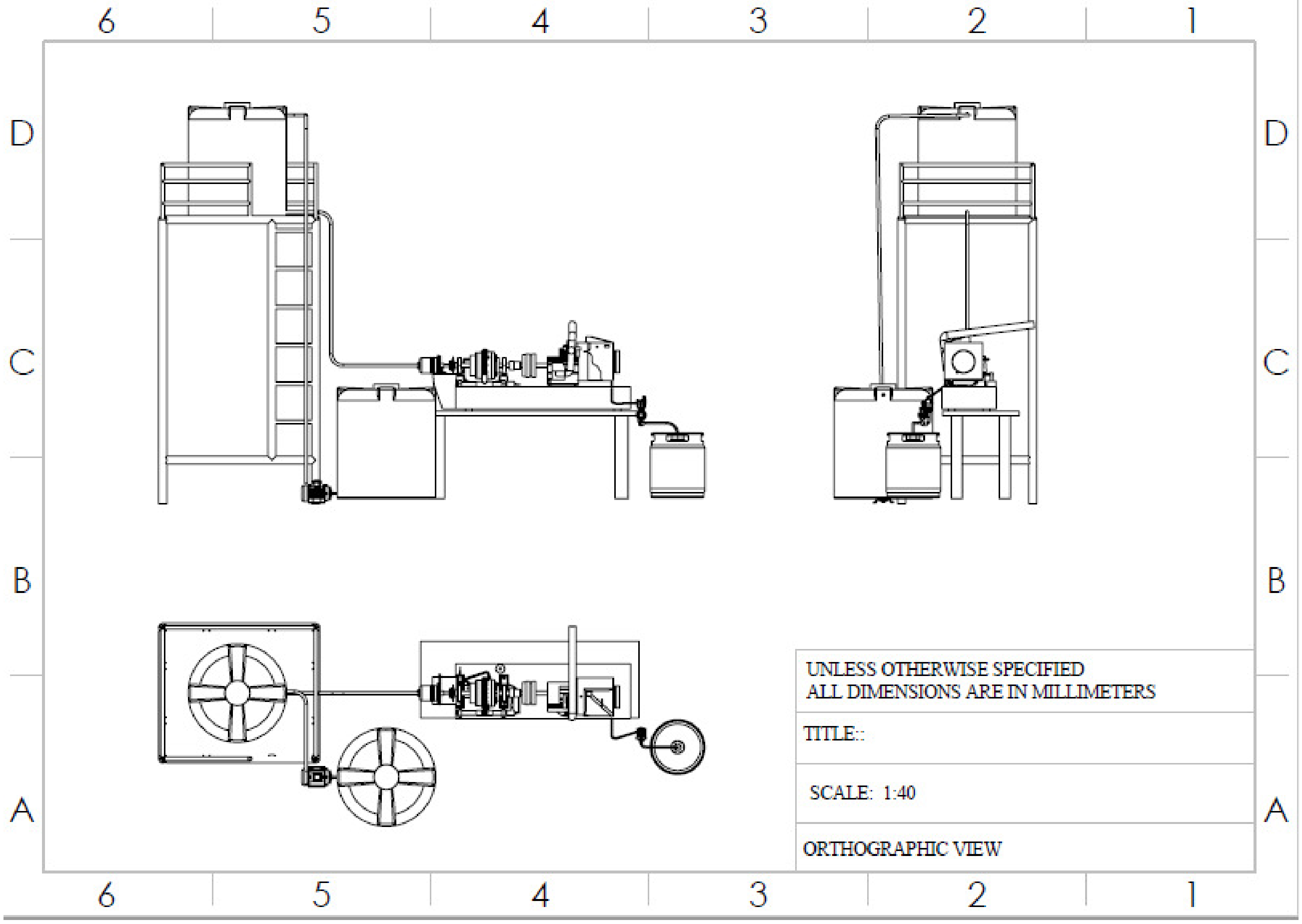


Isometric View of the Experimental set up

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Reservoir Stand		1
2	Water Tank		2
3	Pump		1
4	Dynamometer		1
5	Gas cylinder	6Kg	1
6	Bench		1
7	Gas flow neter		1
8	Pipe 9^Assem5		1
9	Pipe10^Assem5		1
10	Pipe11^Assem5		1
11	Pipe12^Assem5		1



Isometric View of the Set up for the engine test

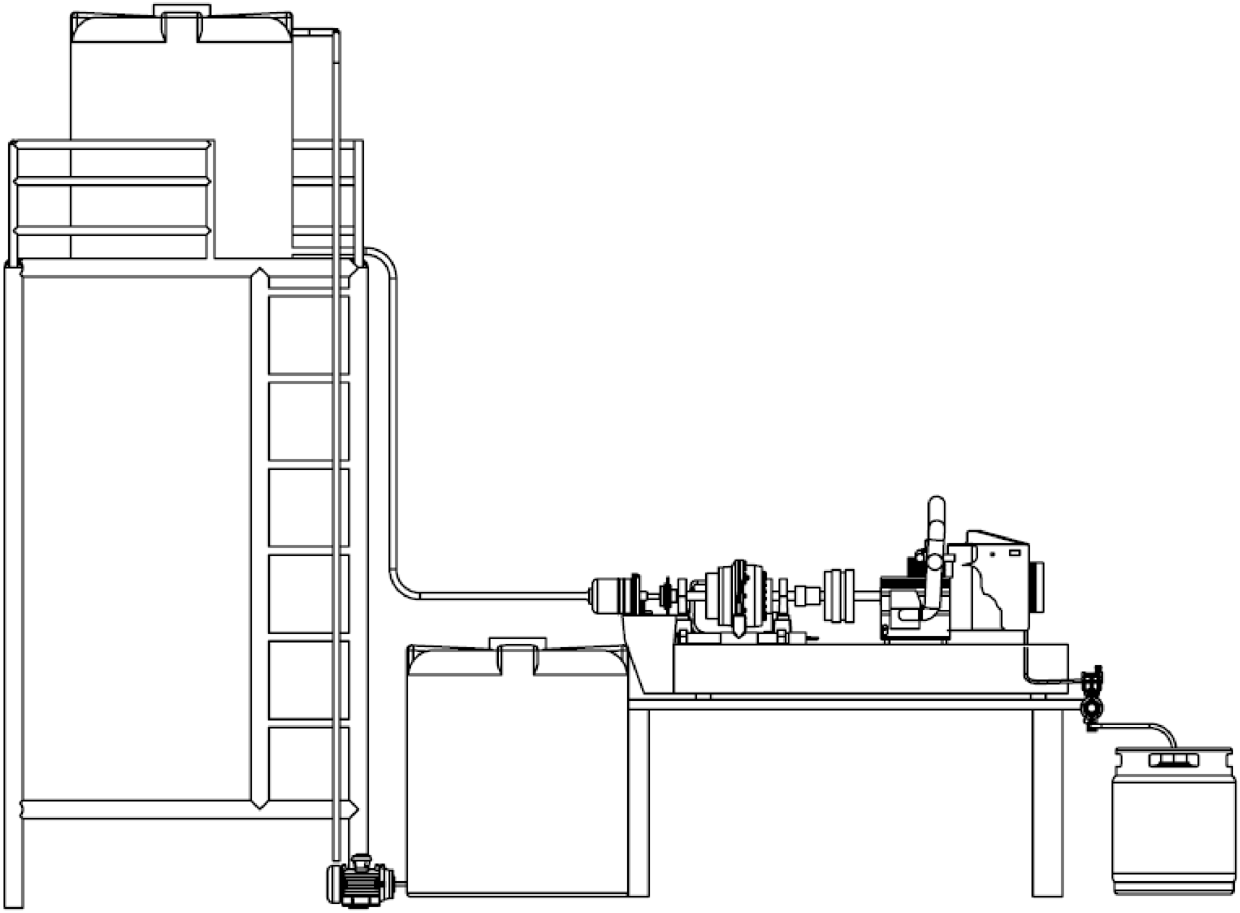


UNLESS OTHERWISE SPECIFIED
ALL DIMENSIONS ARE IN MILLIMETERS

TITLE::

SCALE: 1:40

ORTHOGRAPHIC VIEW



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Reservoir Stand		1
2	Water Tank		2
3	Pump		1
4	Dynamometer		1
5	Gas can		1
6	Bench		1
7	Gas flow neter		1
8	Pipe 9^Assem5		1
9	Pipe10^Assem5		1
10	Pipe11^Assem5		1
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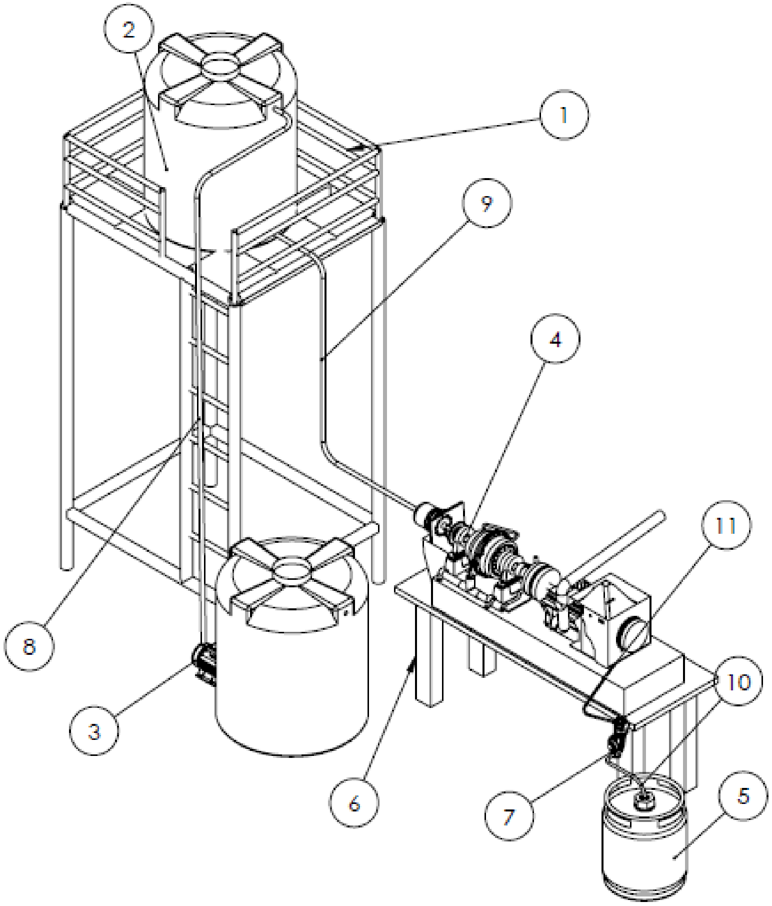
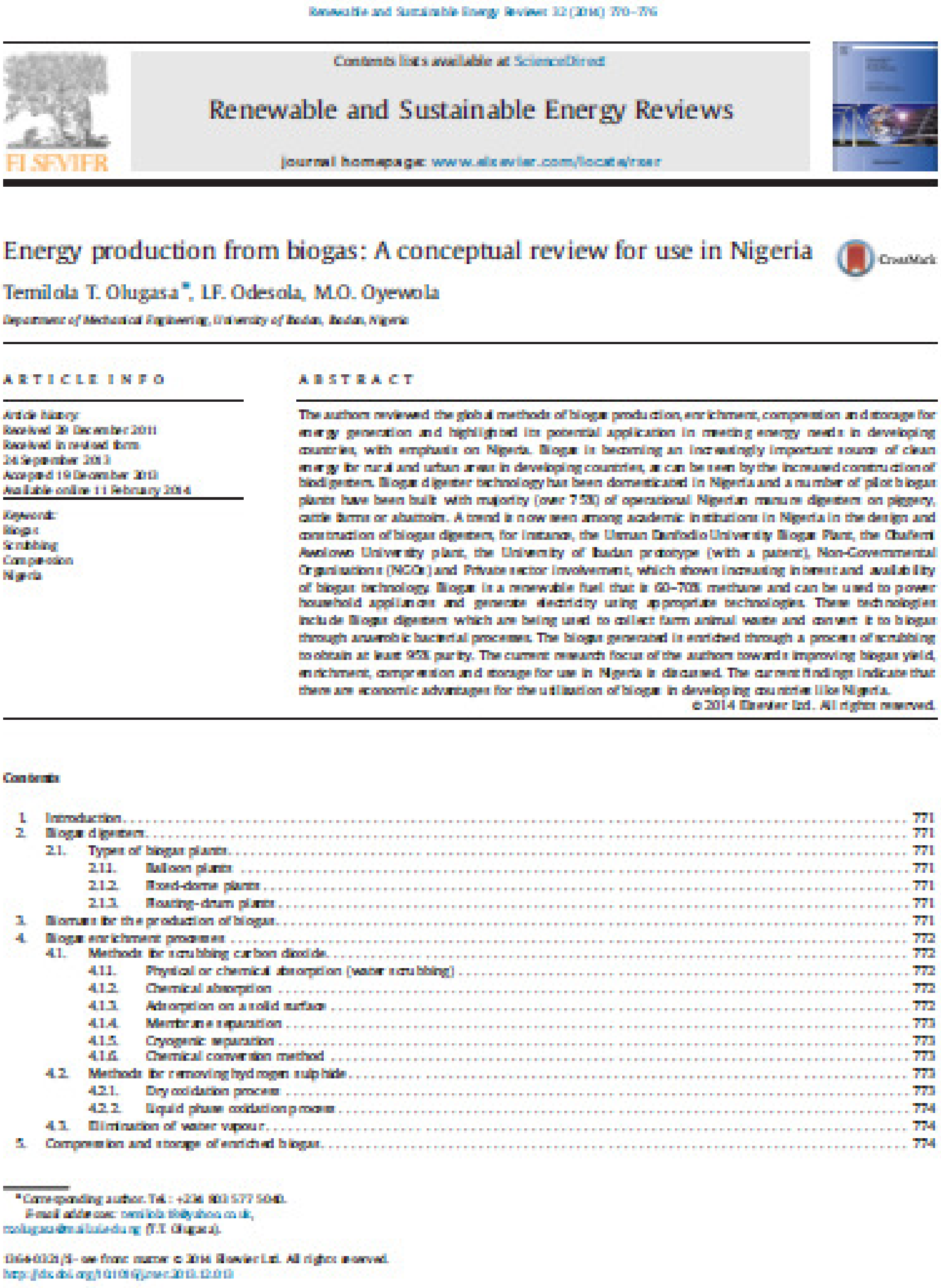


APPENDIX VII

PAPERS PUBLISHED FROM THIS STUDY

PAPER 1



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Energy production from biogas: A conceptual review for use in Nigeria

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ABSTRACT

The authors reviewed the global methods of biogas production, enrichment, compression and storage for energy generation and highlighted its potential application in meeting energy needs in developing countries, with emphasis on Nigeria. Biogas is becoming an increasingly important source of clean energy for rural and urban areas in developing countries, as can be seen by the increased construction of biodigesters. Biogas digester technology has been domesticated in Nigeria and a number of pilot biogas plants have been built with majority (over 75%) of operational Nigerian manure digesters on piggery, cattle farms or abattoirs. A trend is now seen among academic institutions in Nigeria in the design and construction of biogas digesters, for instance, the Usman Danfodio University Biogas Plant, the Obafemi Awolowo University plant, the University of Ibadan prototype (with a patent), Non-Governmental Organisations (NGOs) and Private sector involvement, which shows increasing interest and availability of biogas technology. Biogas is a renewable fuel that is 60–70% methane and can be used to power household appliances and generate electricity using appropriate technologies. These technologies include Biogas digesters which are being used to collect farm animal waste and convert it to biogas through anaerobic bacterial processes. The biogas generated is enriched through a process of scrubbing to obtain at least 95% purity. The current research focus of the authors towards improving biogas yield, enrichment, compression and storage for use in Nigeria is discussed. The current findings indicate that there are economic advantages for the utilisation of biogas in developing countries like Nigeria.

Contents

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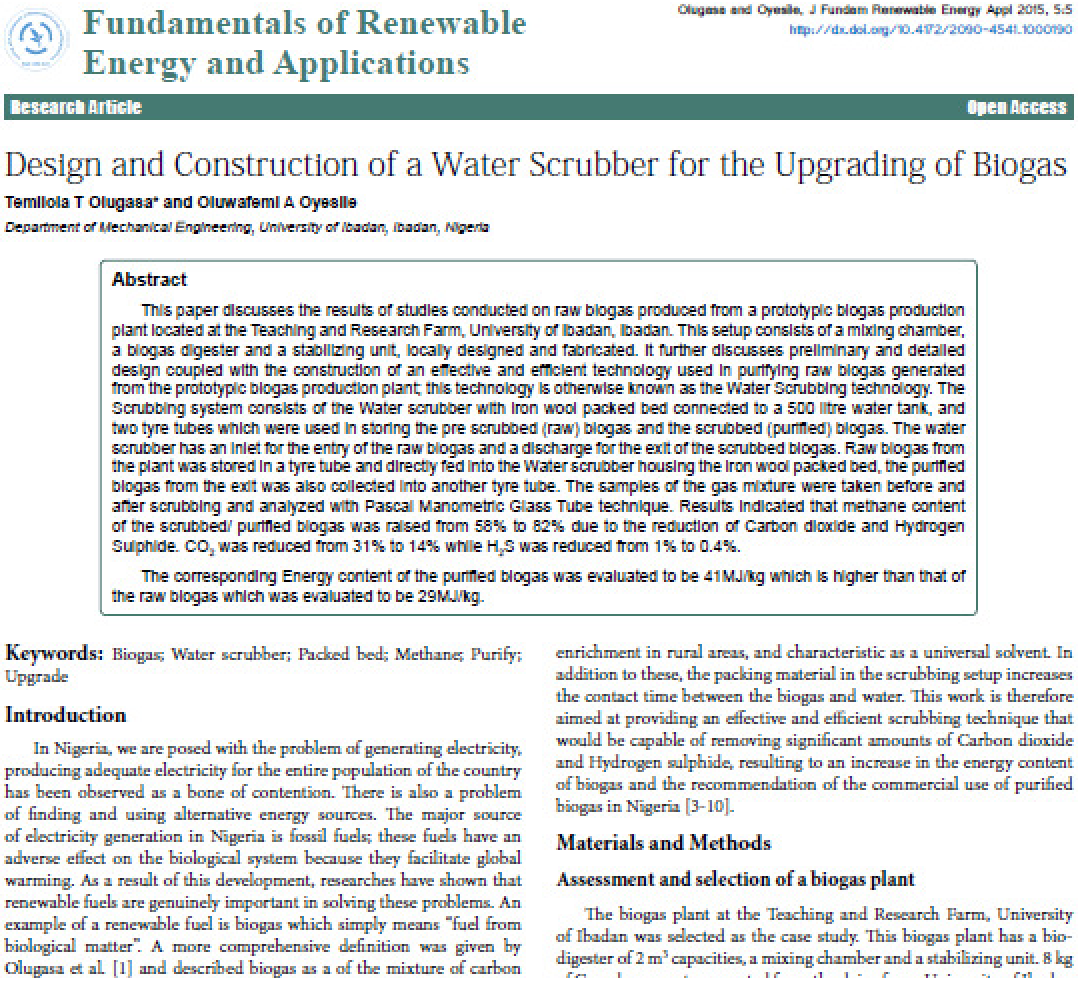
PAPER 2



Fundamentals of Renewable Energy and Applications

Olugasa and Oyesile, J Fundam Renewable Energy Appl 2015, 5:5
http://dx.doi.org/10.4172/2090-4541.1000190

Research Article Open Access

Design and Construction of a Water Scrubber for the Upgrading of Biogas

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Abstract

This paper discusses the results of studies conducted on raw biogas produced from a prototypic biogas production plant located at the Teaching and Research Farm, University of Ibadan, Ibadan. This setup consists of a mixing chamber, a biogas digester and a stabilizing unit, locally designed and fabricated. It further discusses preliminary and detailed design coupled with the construction of an effective and efficient technology used in purifying raw biogas generated from the prototypic biogas production plant; this technology is otherwise known as the Water Scrubbing technology. The Scrubbing system consists of the Water scrubber with iron wool packed bed connected to a 500 litre water tank, and two tyre tubes which were used in storing the pre scrubbed (raw) biogas and the scrubbed (purified) biogas. The water scrubber has an inlet for the entry of the raw biogas and a discharge for the exit of the scrubbed biogas. Raw biogas from the plant was stored in a tyre tube and directly fed into the Water scrubber housing the iron wool packed bed, the purified biogas from the exit was also collected into another tyre tube. The samples of the gas mixture were taken before and after scrubbing and analyzed with Pascal Manometric Glass Tube technique. Results indicated that methane content of the scrubbed/ purified biogas was raised from 58% to 82% due to the reduction of Carbon dioxide and Hydrogen Sulphide. CO_2 was reduced from 31% to 14% while H_2S was reduced from 1% to 0.4%.

The corresponding Energy content of the purified biogas was evaluated to be 41MJ/kg which is higher than that of the raw biogas which was evaluated to be 29MJ/kg.

Keywords: Biogas; Water scrubber; Packed bed; Methane; Purify; Upgrade

Introduction

In Nigeria, we are posed with the problem of generating electricity, producing adequate electricity for the entire population of the country has been observed as a bone of contention. There is also a problem of finding and using alternative energy sources. The major source of electricity generation in Nigeria is fossil fuels; these fuels have an adverse effect on the biological system because they facilitate global warming. As a result of this development, researches have shown that renewable fuels are genuinely important in solving these problems. An example of a renewable fuel is biogas which simply means "fuel from biological matter". A more comprehensive definition was given by Olugasa et al. [1] and described biogas as a of the mixture of carbon enrichment in rural areas, and characteristic as a universal solvent. In addition to these, the packing material in the scrubbing setup increases the contact time between the biogas and water. This work is therefore aimed at providing an effective and efficient scrubbing technique that would be capable of removing significant amounts of Carbon dioxide and Hydrogen sulphide, resulting to an increase in the energy content of biogas and the recommendation of the commercial use of purified biogas in Nigeria [3-10].

Materials and Methods

Assessment and selection of a biogas plant

The biogas plant at the Teaching and Research Farm, University of Ibadan was selected as the case study. This biogas plant has a bio-digester of 2 m^3 capacities, a mixing chamber and a stabilizing unit. 8 kg

PAPER 3

International Conference of Mechanical Engineering, Energy Technology and Management, IMEETMCON 2018
September 4-7, 2018, International Conference Centre, University of Ibadan, Ibadan, Nigeria

IMEETMCON2018-054

BIOGAS PURIFICATION AND COMPRESSION FOR USE IN SPARK IGNITION ENGINES

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[1* 2 & 3] Department of Mechanical Engineering, University of Ibadan, Ibadan, Nigeria

Abstract: *Biogas is a clean and renewable fuel which is capable of replacing fossil fuels especially in Spark Ignition (SI) engines. However, the presence of non-combustible and toxic gases alongside low pressure gradients has limited its use and commercialization in Nigeria. Raw Biogas (RB) was generated in a 1.12* m^3 *digester from cow dung and water scrubbers were developed for its purification. Biogas and water were passed through single and double stage scrubbers at 0.000417* m^3/s *and 0.000833* m^3/s *to obtain Single stage Water Scrubbed Biogas (SWSB) and Double stage Water Scrubbed Biogas (DWSB), respectively. The purified gases were dried using silica gel – filled scrubber and compressed using a 1.5 hp compressor. Methane content of the purified gases were determined using Liquid Displacement Method (LDM) and the calorific value estimated using proximate analysis. SWSB and DWSB achieved a methane content of 88.57% volume and 96.67% volume, respectively. The efficiencies of first stage and second stage scrubbers were: 56.9 % and 70.9 % respectively. The calorific values of RB, SWSB and DWSB were 26.01 MJ/kg, 31.36 MJ/kg and 34.23 MJ/kg, respectively. 0.206* m^3 *of SWSB and DWSB were compressed into 0.0135* m^3 *capacity cylinders to a pressure of 375.8 kPa. This study established that Double stage Water Scrubbed Biogas had higher methane content and calorific value compared to SWSB and can be bottled to a pressure of 375.8 kPa showing that it is the more effective in the purification of biogas and is best suited for use in S.I. engines.*

Keywords: *Biogas, Water scrubbing, Purification, calorific value, Methane content*

1. INTRODUCTION

Global warming is a phenomenon which poses a threat to lives and property as seen in the increase in occurrences of floods where lives and property are destroyed, heat waves in the eastern countries and different kinds of diseases surfacing as a result of climate change. In order to forestall global warming, many developed countries are shifting focus to renewable energy which is clean and reduces green house gas emissions. Nigeria, though a developing country, has a National energy policy which has provision for the use of environmentally friendly and renewable energy especially in rural areas and isolated power systems [6]. Nigeria has the capacity of producing an estimate of 15.319 million tonnes of agro waste and municipal solid waste which can be used for generating biogas [15]. However, solar photovoltaics, hydro power and Wind power are the only renewable sources of energy being used for generating electricity in Nigeria [15]. Biogas technology has not been commercialized in Nigeria because of overdependence on fossil fuels, the low energy content per unit volume of biogas and difficulty associated with its liquefaction. For biogas to effectively replace fossil fuels in Nigeria, its application must go beyond its use for cooking and lighting on farms and must be used widely for running internal combustion engines either in vehicles or in generating sets for the generation of electricity [12].

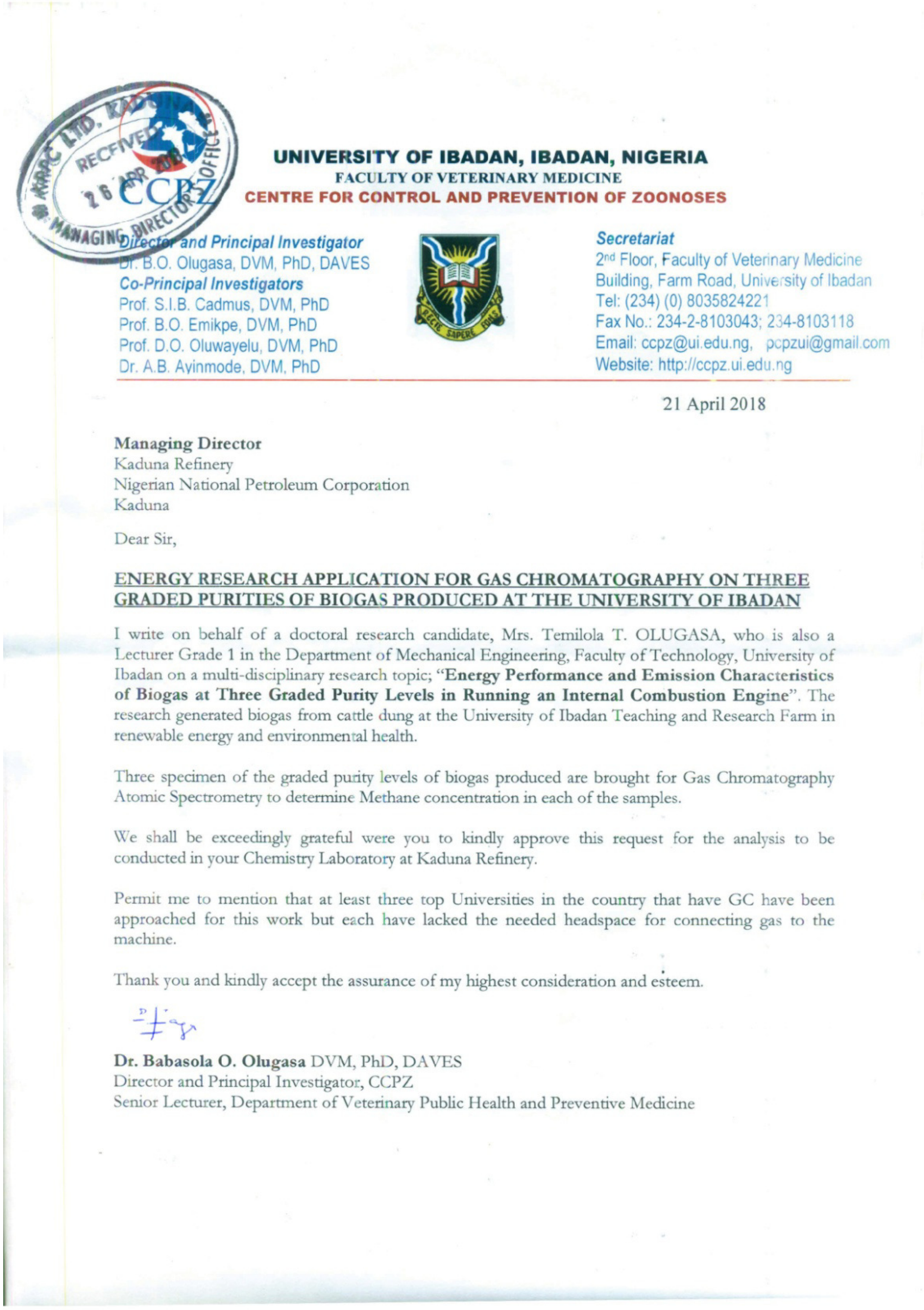
Biogas is a mixture of Methane CH_4, Carbon dioxide (CO_2), hydrogen sulphide (H_2S) and small portions of ammonia, water vapour e.t.c .The percentage composition of the constituent gases is dependent on the substrate digested. The purification of biogas is essential in order to remove the incombustible and toxic gases present thereby upgrading the gas by increasing its methane content and consequently its calorific value in the process. Biogas has to be upgraded to a methane content of at least 90 % vol. and made portable by compressing it to high pressures [1] for it to be suitable for use in use in internal combustion engines (ICE) among which is the S.I engine.

1.1 Methods of Purifying Biogas

A number of methods are adopted for purifying biogas, for the removal of water, H_2S and CO_2 namely:

APPENDIX VIII

LETTER OF APPROVAL FOR GC ANALYSIS AT NNPC, KADUNA



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FACULTY OF VETERINARY MEDICINE
CENTRE FOR CONTROL AND PREVENTION OF ZOONOSES

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21 April 2018

Managing Director
Kaduna Refinery
Nigerian National Petroleum Corporation
Kaduna

Dear Sir,

ENERGY RESEARCH APPLICATION FOR GAS CHROMATOGRAPHY ON THREE GRADED PURITIES OF BIOGAS PRODUCED AT THE UNIVERSITY OF IBADAN

I write on behalf of a doctoral research candidate, Mrs. Temilola T. OLUGASA, who is also a Lecturer Grade 1 in the Department of Mechanical Engineering, Faculty of Technology, University of Ibadan on a multi-disciplinary research topic; "**Energy Performance and Emission Characteristics of Biogas at Three Graded Purity Levels in Running an Internal Combustion Engine**". The research generated biogas from cattle dung at the University of Ibadan Teaching and Research Farm in renewable energy and environmental health.

Three specimen of the graded purity levels of biogas produced are brought for Gas Chromatography Atomic Spectrometry to determine Methane concentration in each of the samples.

We shall be exceedingly grateful were you to kindly approve this request for the analysis to be conducted in your Chemistry Laboratory at Kaduna Refinery.

Permit me to mention that at least three top Universities in the country that have GC have been approached for this work but each have lacked the needed headspace for connecting gas to the machine.

Thank you and kindly accept the assurance of my highest consideration and esteem.

Dr. Babasola O. Olugasa DVM, PhD, DAVES
Director and Principal Investigator, CCPZ
Senior Lecturer, Department of Veterinary Public Health and Preventive Medicine