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Quantitative devolatilization of Botswana coal in a pilot scale plant*

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***Abstract*— Coal gasification is a new and clean coal conversion technology that converts coal to liquids and synthetic gas to be used in power generation and chemical products. Botswana coal was studied in a pilot plant to produce synthetic gas which can be used for power generation and chemical products (dyes, detergents, plastic, synthetic fibers, fuels). Pilot plant provides information on the amount of gas produced per mass of feed, and the amount of synthetic gas produced per variation of parameters (temperature and pressure). Every kilogram of coal produces about 95 liters of raw synthetic gas per day.**

Keywords: Botswana coal gasification, new coal technology, synthetic gas

I. INTRODUCTION

Coal is considered a non-renewable energy source as it was formed hundreds of millions of years ago from plants and ferns that died and buried in swamps. The reserves that exist now cannot realistically be replaced. Coal makes one of the greatest energy sources getting its energy from the buried plant remains.

Botswana has 212 Billion tonnes of coal resources which is covering about 70 percent of its geographical strata (Paya, 2010). It is in the region of what is called the Karoo Supergroup which is the most widespread stratigraphic area in Africa south of the Sahara desert (Johnson M. R., 1996). These reserves have been found to have high ash, medium calorific value, and low-medium quality bituminous coal (Grynberg, 2012). With all these reserves, Botswana has only one coal fired power plant (combustion) that generates and supplies electricity to the whole country. This is only able to meet 30 percent of the demand in the country. Botswana is developing at a high rate with a lot of infrastructure being erected which calls for more power supply.

In 2012, Botswana demand for electricity was 530 MW, of this power 70 percent was supplied by Eskom in South Africa (Abi, 2011) and the rest by Morupule Power Plant using a coal fired power generator to produce only 132 MW from four 33 MW coal fired units (Mawson, 2006) with coal supplied from adjacent Morupule Coal Mine. The demand has been increasing with an average of 10 percent a year (Mawson, 2006) due to developments in the country putting the country on deficit and worsening after Eskom has cut its supply. Despite the failed plans to build more power stations in the country (Benza, 2014), the current process is harmful to the environment and less efficient, therefore calls for new coal conversion technologies.

Coal gasification includes two distinct processes; devolatilization followed by char gasification. Devolatilization normally occurs at temperatures above 400 C in the absence of oxygen to give away moisture and volatiles (Basu, 2006). This process allows coal structure to be changed to produce tar (a gas mixture of heavy molecular weight hydrocarbons at high temperatures and condensible at room temperature), solid char, condensible liquids and light gases. The process of char gasification depends mainly on gasification medium (inert gas/ hydrogen).

Coal gasification is the process in which coal is partially combusted. It involves the reaction of solid coal with air and steam to yield gaseous products that are able to be used as fuel gas, chemical feedstock and other products (Sha, 1995). The three processes that occur in a typical gasifier being drying and pyrolysis, combustion then gasification. In drying and pyrolysis, water that is fed with coal and moisture with the coal is driven off by heat introduced. Then the weak bonds in coal start breaking producing gases, tar and char. Oxygen supplied to the reactor reacts with combustible substances in the system forming carbon dioxide and water. These two products then undergo reduction when they get in contact with char to produce carbon monoxide and hydrogen. The system goes through a series of endothermic and exothermic reactions which need to be balanced otherwise there will be a low carbon conversion in the gasifier.

Gasification is cleaner than combustion in terms of the amount of pollutants produced. Combustion converts N and S containing compounds to SOx and NOx while gasification converts them to H2S and NH3 that are cleaner. In terms of energy efficiency, syngas produced from gasification contains heating value as a chemical energy which can be liberated at a later stage in contrast with CO2 from combustion which only contains energy as a hot gas and limited to use in steam turbines (Yun and Chung, 2006).

Other coal based power plants utilize only 30 percent of the energy produced from coal for power generation. A coal gasification plant however utilizes most of the gases it produces. Firstly, the gases are cleaned of any pollutants to put them in a state very close to natural gas. The hot exhaust of the gas turbine, and some of the heat generated in the gasification process are then used to generate steam for use in a steam turbine generator (US Department of Energy, 2016). Coal gasification produces heat that is used to turn gas turbines and produce electricity. Gasification is a component of a complete system called Integrated Gasification Combined Cycle (IGCC) that feeds row coal that is dirty.IGCC is much more efficient than the coal fired power plants to due to the heat recovery feature it has.

The focus of this paper will be on the first process of devolatilization at 500 degrees Celsius. Gas and differ-

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ent density liquids collected will be measured in different measuring cylinders. Botswana coal produced relatively satisfactory amount of gas by mass of coal fed into the reactor. Subbituminous coals have been determined as the best suitable coals for coal gasification due to high volatility and content of volatile matter.

Another subbituminous coal from Indonesia yielded 55 and 67 liters of gas from the two runs that were carried out in a pilot gasifier. The feed contained a lot of moisture that was visible through the bubbler and the last condenser measuring cylinder. Indonesia produces high quality synthetic gas from subbituminous coal through the process of gasification. Except for too much moisture, Indonesian coal portrays the same characteristics as Botswana coal.

II. Experimental

A. Coal samples

Five samples were used in these experiments; four of which came from Morupule colliery mine, and one from Indonesia and were all ranked as subbituminous. The samples allow a comparison between Botswana coal and coal from Indonesia in terms of quantity of gas produced during pyrolysis/ gasification. Samples were of size range 1-20 mm and stored in lid sealed containers until used. Table 1 shows proximate and ultimate analysis done on Botswana coal.

B. Sample preparation

A representative sample that will be enough to fit into the gasifier is taken from the whole sample. The total mass of the sample is measured and recorded. Voidage of the sample is determined by the ratio between volume of water in an empty bucket take out volume of water with coal filled in and using the formula below;

$$\epsilon = Volume(sand)/Totalvolume(bucket) \tag{1}$$

C. Loading the reactor and start-up

A batch type dry feeding laboratory scale plant that is located in Gaborone, Botswana and can treat coal of 1.2 kg/ day with feed size range 20 mm to 100 mm. The facility of 4 by 5 by 1.5 m is located in a 8 by 7 by 5 m room shown in figure 1.

The system is initially purged using nitrogen to create inert atmosphere before coal can be fed into the plant. System is flushed with acetone to wash away any condensed liquids from previous runs. Gasometer is primed by filling it up with water so that there is zero liters left for the gas produced to fill up.

Coal is fed into a mesh cylinder that is placed into a reactor. Mesh gives allowance between the walls of the reactor and coal for uniform burning of coal. Reactor lid is then bolted and properly sealed. Insulation is provided around reactor to avoid too much heat loss. An electrical heater is used in heating the gasifier, no preheating is done. There are three condensers operating at 150, 100 and room temperatures for heavy oils, light oils and clear liquid respectively. A bubbler is used to check for any gas produced in he system. It gets filled with water of 200 mL and a bubbler pipe with two holes inserted. The top hole indicates a low gas flow rate while the bottom hole signifies high gas flow rate. The gas is then passed to a gasometer to be measured with an application of the Bernoulli's principle. The gas kinetic energy increases as more gas is produced which causes water to be displaced due to difference in pressure.

Fig. 1. Overview of the pyrolysis plant at Pyro carbon energy laboratory

Gasometer is connected to a u-tube. Left end of the u-tube is connected to the reactor and receives gas at 95 kPa pressure, while the right end is connected to a water tank for drainage. Right side is closed to a water tank therefore vapour pressure is acting on the right side of the u-tube. Vapour pressure was calculated as 2.5 kPa considering room temperature of 25 degrees Celsius using Antoine's formula below;

$$\log P = A - B \div (C + T) \tag{2}$$

where A = 8.07, B = 1730.63 and C = 233.43 (AJ Design software, 2011)

Temperature is calculated in degrees Celsius and Pressure in mmHg with the above constants.

There is a valve at the bottom where water that is displaced by gas is drained out.

Normal operation consists of leak test, purging, transient operation, devolatilization and shutdown process.

The feed coal was Morupule Colliery Mine (MCM) ROM coal and conventional analysis was done on it with results presented in Table 1. Coal was air dried to about 1 percent moisture content before feeding into a reactor. Ash content in Morupule coal is around 28 percent ash.

In a pilot scale dry feeding plant, nitrogen used for purging is present during the pyrolysis process therefore reaction atmosphere can be considered as nitrogen atmosphere.

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TABLE I
TABLE 1: ANALYSIS DATA OF COAL FEED

	Item	MCM ROM
Proximate analysis	Moisture (air-dried)	1.1
	Ash content (air-dried)	27.9
	Ash content (dry basis)	28.2
	volatile matter (air-dried)	13.5
	volatile matter (dry basis	13.7
	fixed carbon (by calculation)	57.5
	total sulphur	1.32
	gross calorific value (MJ/kg)	22.42
Ultimate analysis	Carbon content (air-dried)	59.09
	Hydrogen content (air-dried)	2.43
	Nitrogen content (air-dried)	1.48
	Oxygen content (by calculation)	6.68

D. Devolatilization reactions

When coal is gasified under practical conditions the following coal gasification processes take place;

- Syngas is produced from the first stage of coal gasification which is devolatilization.
- The process that follows is char gasification. There are secondary processes observed during gasification.
- Coal molecules break down at weak aliphatic and ether bonds in the process of pyrolysis during which volatile matter is released [all gases, tar(liquid hydrocarbons), light gaseous hydrocarbons].

$$coal \longrightarrow char(C) + coalvolatiles(VM) - \Delta H \quad (3)$$

- Pyrolysis is then followed by hydrocracking which is the addition of hydrogen to the tar molecules present in the volatile matter. This process produces methane.

$$VM + H2 \longrightarrow CH4 - \Delta H \quad (4)$$

- Tar then undergoes gasification process producing carbon monoxide and hydrogen

$$VM + H2 \longrightarrow CO + H2 + \Delta H \quad (5)$$

III. RESULTS AND DISCUSSION

The gasifier pressure was controlled at 95 kPa while gasifier temperature was maintained at 500 degrees Celsius that was enough for devolatilization of coal.

The parameters are required for devolatilization and liberation of gases contained in coal. Temperature shown in the Table II was average temperature in the gasifier. There are 7 points (TT-03 to TT-09) where temperature is measured throughout the gasifier (Figure 3), an average of the middle 3 temperatures was taken to represent coal temperature as it was assumed to be a point where coal was.

Each experiment ran for about 3 hours in which run 1 produced 55 liters of gas while run 2 measured 67 liters. Bubbler was used to estimate end of reaction by observation when bubbles were no longer produced. Gasifier operating parameters with corresponding gas produced are illustrated in Table II. Data was arranged in order of increasing sample mass. With increasing sample mass it was observed that gas volume increased proportionally with around the same operating temperature and pressure.

Besides gas produced, gasifier has liquid products (heavy oils, light oils and clear liquids), three cylinders hanging from right to left in Figure 2.

Syngas produced was measured in a gasometer which is proportional to the mass of the coal sample fed into the reactor. The more the sample the more gas it produces. The tests only focused on the quantity of gas produced.

TABLE II
TABLE OF COMPARISON OF OPERATING PARAMETERS TO PRODUCT GAS

Operation time time (2017)	Sample mass mass (kg)	Gasifier pressure (kPa)	Gasifier temperature (C)	Gas volume (L)
20-Mar	0.5	93.0	570	55
21-Mar	1.0	93.0	520	123
22-Mar	1.5	96.7	570	125
23-Mar	2.2	95.0	530	194

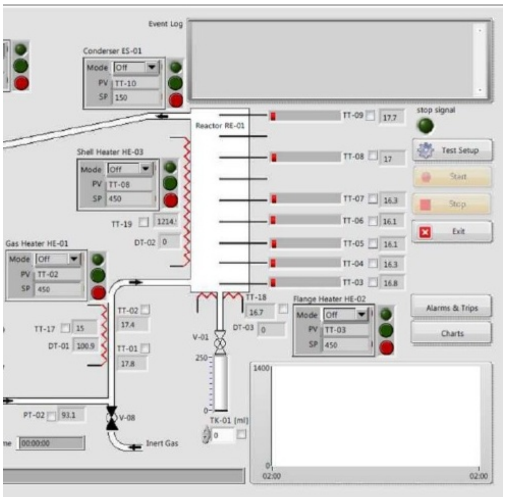

Fig. 2. SCADA screenshot showing gasifier temperature transmitter points

IV. CONCLUSIONS

Botswana coal is promising to have enough synthetic gas that can be used for power generation and chemical products. This was observed in comparison with Indonesian subbituminous coal that yielded similar amount of gas and liquids as Botswana coal. 1.0 kg of coal produced an average of 95 liters of gas. Botswana coal is subbituminous as Indonesian coal. Indonesian coal synthetic gas content is 36-38 percent CO, 14-16 percent H2, and 5-8 percent CO2 concentrations on dry basis.

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Fig. 3. liquids products, from right to left; heavy oils, light oils, clear liquid. On the counter is a bubbler

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