DESIGN AND DEVELOPMENT OF A THROATLESS DOWNDRAFT GASIFIER FOR THE GASIFICATION OF HYBRID WASTE

Original Paper.

ABSTRACT

Muffle furnace, Isoperibolic calorimeter, microanalyser and macroanalyser were used to subject three fuel samples (sawdust, coconut shells and thermoplastics) to proximate and ultimate analysis to determine their suitability as gasification fuels. A throatless downdraft gasifier was designed, developed and tested. The design was implemented using a combination of empirical relations, experimental data and computational methods. Proximate analysis results showed sawdust have calorific value and fixed carbon content of 18.9167% and 18.40% respectively while coconut shells have 19.928% and 24.60% respectively and plastics have 19.5968% and 20.33%. The percentage fixed carbon and calorific values of these fuels signifies they are promising fuels for gasification. Ultimate analysis results showed sawdust, coconut shells and plastics with carbon and hydrogen contents of (43.7528%, 5.3216%), (44.8767%, 5.2590%) and (49.0044%, 5.97%) respectively. The composition of these major combustible constituents of the fuels shows the fuels are excellent for gasification. Gasifier design results show reactor diameter of 374mm, height of 787mm, Fuel Consumption Rate (FCR) of 10.56 kg/hr, Air Flow Rate (AFR) of 18.27m^3/hr and reactor/gasifier minimum wall thickness of 3.74mm. Test results showed that the hybrid fuel had higher reduction zone temperature T_1 of 967˚C, combustion zone temperature T_2 of 800˚C and pyrolysis zone temperature T_3 of 540˚C compared to gasification with individual fuels. Gasification with individual fuels and with the hybrid fuel produced stable flame but the hybrid fuel produced flame with greater flame length and width. This shows that more yield of combustible syngas was obtained during gasification with the hybrid fuel.

KEYWORDS: Gasification, Proximate, Ultimate, Design, Syngas.

INTRODUCTION

Access to clean energy is an enormous challenge facing the African continent because energy is fundamental for socioeconomic development and poverty eradication. For decades, Nigeria has been faced with several formidable energy crises that have not only undermined her economic growth but also deprived over 200 million populations the privilege of sustainable and reliable access to LPG (Liquefied Petroleum Gas) and electricity. For instance, LPG (cooking gas) is increasingly the major source of fuel for domestic use by households, schools, hotels and other related consumers in the Nigerian urban areas. In 2020, the consumption of this product hit a record 1 million metric tonnes. However, in the rural areas, it is currently estimated that less than 30% of Nigerian population use LPG as a cooking energy while the remaining 40% use Kerosene and 30% use firewood owing to reasons such as the relative high cost of cylinders, access to LPG (Ozoh et al. 2018). In addition, the Nigeria power sector had witnessed a substantial decline in energy production, which forced many households and businesses to rely on the fossil fuel-based generators to meet the energy demand. Currently, the available generation capacity is constantly hovering between 3,500MW and 5,000 MW while the demand is between 9, 051MW and 20, 00MW for a population of about 200 million people. More worrisome is the fact that about 80% of the Nigerian rural dwellers do not have access to electricity. This is an indication that there is a wide gap between the demand and supply of energy (Salau, 2020).

Given this scenario, it has become pertinent to explore all available sources of energy to abate this crisis and to give Nigerian households a mix of energy sources to cushion the effects of the growing energy paucity occasioned by internal forces of population increase and external forces of global energy politics. The sudden shift by Nigerians from the challenge of using dirty fuel such as kerosene, firewood and charcoal to a cleaner and more environmentally friendly source of energy, which is the Liquefied Petroleum Gas (LPG) popularly called cooking gas, opened a new vista of opportunities for the design of alternative source of hybrid Fuel. Gasification is brought forward in this research as a possible solution to this growing concern.

Gasification is the thermo-chemical energy conversion technology, which has attracted immense interest because it offers highest thermal efficiency, and most usable energy, as compared to direct combustion (Sokhansanj et al. 2013; Zhou et al. 2013). In addition to reducing dependence on petroleum, gasification has been seen in recent times as a value-added process for handling some byproducts. Byproducts that would normally have been disposed of by land filling, incineration, or microbial decomposition could be gasified as an alternative process to the traditional disposal methods, which are sometimes unavailable, expensive, or cumbersome (Bowser *et al*., 2015). In Nigeria, with the abundance/availability of agricultural waste such as corn stocks, coconut shells, palm kernel shells etc., gasification provides invaluable means of turning these and other wastes to wealth.

It is upon this backdrop that this study aims at designing and developing a mini throatless Downdraft Gasifier for the Gasification of Hybrid Fuel to tackle the energy crisis faced by urban/rural dwellers in Nigeria.

MATERIALS AND METHODS

Material Preparation

Biomass (sawdust and coconut shells) were obtained from Katako saw mill and market respectively in Jos metropolis. Waste thermoplastics were equally sorted from municipal waste. Three samples of these fuels were prepared and stored in appropriately labelled airtight containers to retain their as-received conditions.

The biomass samples (saw dust and coconut shells) were individually crushed and prepared using the American Society for Testing and Materials code ASTM E1757-19 to give a representative sample of each. A hammer mill was used for this operation, reducing the sample sizes from a top size of about 3cm to a suitable size of 2mm. A manual sieve was used to sieve the samples to this desired size distribution.

The plastic material was prepared using ASTM E1131 code to give a representative sample. An electric motor driven plastic shredder was used for this operation

Proximate Analysis

1g of each sample (sawdust, coconut shell and plastic) passing through a 2mm test sieve was used for proximate analysis. Moisture, ash, volatile matter and fixed carbon were analysed using a CRN-48 muffle furnace with maximum temperature of 125^{o}C based on ISO 1171:1997. The calorific values were determined using an isoperibolic calorimeter model PARR 6400 based on ISO 16559:2014.

Ultimate Analysis

1g of each sample passing through a 2mm sieve was use for ultimate analysis. The ultimate analysis of the representative samples was carried out using Thermo Flash 1112 microanalyser. The elemental composition was done using LECO CHNS 628 series macroanalyser based on ISO 12902:2001. The sample preparation, proximate analysis and ultimate analysis were done at the National Geosciences Research Laboratory (NGRL), Kaduna.

Figure 1. Samples of sawdust(A), coconut shells (B) and thermoplastics (C)

Gasifier Design

A combination of empirical relations, experimental data and computational methods were applied to design the gasifier. The thermal capacity of the gasifier was set, calorific values of the fuels were determined experimentally while sizing was achieved through computations and experimental data.

Table 1. Basic Assumptions

Type of Gasifier	Stratified throatless downdraft Gasifier
Type of fuel	Hybrid (Coconut shells, sawdust and plastics)
Gasification efficiency	70%
Equivalence ratio	0.3
Thermal Power output (Q_{net})	40kW
Specific gasification rate	100 kg/m^2-hr
Air velocity (v)	10m/s
Working pressure	P = 180 MPa

Gasifier diameter

The fuel Consumption Rate (FCR) is given by (Ojolo and Orisaleye, 2010) as:

$$\text{FCR} = \frac{Q_{net}}{CV_{fuel} \times \eta} = 10.56 \text{ kg/hr}$$

Reactor area/ grate area is given by (Ojolo and Orisaleye, 2010) as:

$$A = \frac{FCR}{SGR} = 0.1056 \text{ m}^2$$

Diameter of reactor, D_R is given by (Ojolo and Orisaleye, 2010) as:

$$D_R = \sqrt{\frac{4 \times FCR}{SGR \times \pi}} \quad D_R = 0.374\text{m}$$

Gasifier height

Volume required to store 10.56kg of fuel blend of average density 635kg/m^3 for 5 hours of gasifier operation per batch is V= $\frac{10.56 \times 5}{635}$ = 0.0831m^3

Height of the reactor (top to grate), H_R is given by $H_R = \frac{volume\ of\ reactor}{area\ of\ reactor} = \frac{0.0831}{0.1056}$ = 0.787m

Stoichiometric air (SA) requirement

The stoichiometric air requirement for gasification is computed using the ultimate analysis results similar to the work of (Akhator et al. 2019) as:

***Carbon*:**

$C + O_2 \rightarrow CO_2$

By mass: 12kg C + 32kg O_2 → 44kg CO_2

1kg C + $\frac{32}{12}$kg O_2 → $\frac{44}{12}$kg CO_2

Sawdust = 0.437528 × $\frac{32}{12}$ = 1.167kg

Coconut Shell = 0.448767 × $\frac{32}{12}$ = 1.197kg

Plastic = 0.49 × $\frac{32}{12}$ = 1.307

Hydrogen:

$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

By mass: 2kg H_2 + 16kg O_2 → 18kg H_2O

1kg H_2 + 8kg O_2 → 9kg H_2O

Sawdust = 0.053216 × 8 = 0.426

Coconut Shell = 0.05259 × 8 = 0.421

Plastic = 0.0597 × 8 = 0.478

Sulphur:

$S + O_2 \rightarrow SO_2$

By mass: 32kg S + 32kg $O_2 \rightarrow$ 64kg SO_2

1kg S + 1kg $O_2 \rightarrow$ 2kg SO_2

Sawdust = 0.002kg

Coconut Shell = 0.01kg

Plastic = 0.03kg

Air is assumed to contain 23.3% oxygen by mass

Sawdust = $\frac{1.167+0.426+0.002}{0.233}$ = 6.845 kg of air/ kg of sawdust

Coconut Shell = $\frac{1.197+0.421+0.01}{0.233}$ = 6.987 kg of air/ kg coconut shell

Plastic = $\frac{1.307+0.478+0.03}{0.233}$ = 7.79 kg of air/ kg plastic

Therefore, the **SA** for the fuel blend = $\frac{6.845+6.987+7.79}{3}$ = **7.21** kg of air/ kg of fuel blend.

Air flow rate (AFR)

Air flow rate (AFR)= $\frac{ER \times FCR \times SA}{\rho_{air}}$

Density of air is 1.25 kg/m^3

AFR = $\frac{0.3 \times 10.56 \times 7.21}{1.25}$ = 18.27 m^3/hr

Diameter of air tuyeres

To avoid interference, odd air nozzle arrangement was chosen, (Basu et al. 2010) and the assumed air velocity (Reed et al. 1988) used to compute for tuyere diameter. The tuyere diameter D_t is given by (Susastriawan et al. 2017) as:

$$D_t = \sqrt{\frac{4 \times AFR}{\pi \times v \times number\ of\ tuyeres}} \qquad D_t = 0.011m = 11mm$$

Gasifier Wall Thickness

Minimum gasifier wall thickness is given from Hoop stress formula as:

$$t = \frac{P_h Di}{(200\ x\ 0.8x\ J\ xRe) - P_h}$$

Where (J) is joint efficiency = 0.9 (Standard for non-radiographical weld joints)

Yield strength of material (Re) = 215Mpa

Diameter of cylinder, D = 374mm

P = 180 MPa

t = 2.19mm

Considering additional thickness requirements such as:

Corrosion allowance = 0.2mm; and

Temperature allowance = 0.1mm

Total gasifier wall thickness is:

t = 2.19 + 0.2 + 0.1 = 2.49

Using a factor of safety of 1.5:

t = 2.49 x 1.5 = 3.74mm

The computed minimum wall thickness is 3.74mm, thus 4mm mild steel sheets were used.

Gasifier Development

Table 2. Materials used for the fabrication and testing of the gasifier.

Material/ Tool/ Equipment	Function
4mm Mild steel sheets	Gasifier Lining
Mild steel propane tanks	Intermediate Lining
Rock wool	Insulation material
2mm mild steel sheets	Outer shell
Pressure gauge	Pressure measurement
Vernier caliper	Measurement
Measuring tape	Measurement
Cutting and filing machine and cutting discs	Cutting and filing
Electric arc welding machine and electrodes	Welding
Rolling machine	Rolling
Nipples and caps	Temperature measurement
Thread tape	Thread sealing
Body filler	Smoothing
Gasket	Preventing leakages
Oil paint	Body finishing
2mm mild steel square pipes	Fabrication of the skid/ stand for the gasifier
2mm mild steel round pipes	Gas inlet and outlet
Valves	Gas inlet and outlet

Engineering drawings of all the components of the gasifier derived from design calculations were developed and they formed the basis for the fabrication/development of the gasifier. The gasifier was fabricated using a 4mm thick and 343mm wide propane tank. The propane tank housed the reduction zone, choke mantle, choke plate, air jacket, pyrolysis ring, and the condensate liner. The gasifier vessel was cut using a cutting disc attached to a cutting machine. Sheet metals were cut and folded to form an external shell of 365mm. The seam of the metal sheet was welded using AC and DC Kaierda model 2 X EI-400 arc welding machine with the aid of electrodes and filler metals. Rockwool refractory materials were stocked into the void created by the difference in diameter of the two sheets forming an insulation thickness of 11mm. Electric power grinding machine was used to grind and finish the welded metal sheets. Each component of the gasifier was similarly fabricated with the welding machine, cutting and grinding discs and then assembled as shown in figure 3. The assembled gasifier was then finished using body filler consisting of polyester resin and a cream hardener. Upon drying, a fine abrasive paper attached to the grinding machine was used to smoothen the gasifier body.

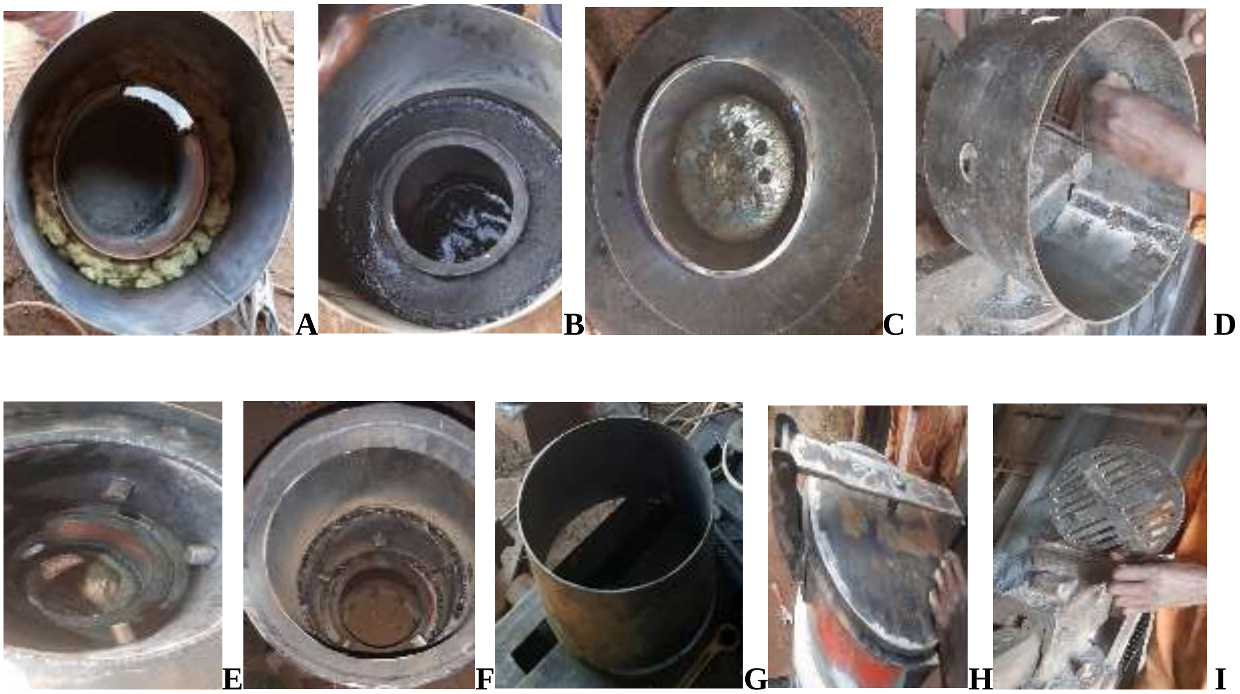

Figure 2. Components of the gasifier: Gasifier internal shell (A), choke mantle(B), choke plate (C), air jacket (D&E), pyrolysis ring (F), condensate liner(G), gasifier cover and grate assembly (I).

Figure 3. Assembled gasifier

Experimental Procedure

The fabricated gasifier was tested using forced convection from a centrifugal blower that delivers air to the gasifier to ignite and sustain gasification. Red hot charcoal was used for pre-ignition. The experimental procedure was conducted using the three fuels (sawdust, coconut shells and thermoplastics) separately and then a blend of the three fuels also known as hybrid fuel was also gasified. Four kilograms (4kg) of each fuel was charged separately into the gasifier and gasified for 60 minutes. Temperature readings were taken for each of the fuels at three points in the gasifier representing the pyrolysis, combustion and reduction zones and recorded. Flame type was equally observed for both individual fuels and the hybrid fuel.

RESULTS AND DISCUSSION

Proximate Analysis

Results of proximate analysis of three samples A, B, and C representing sawdust, coconut shells and thermoplastics respectively are shown in table 3.

Table 3: Results of proximate analysis of three fuel samples.

Properties	**Sawdust Sample A**	**Coconut Shells Sample B**	**Plastic (PET) Sample C**
Moisture Content	9.30	8.00	0.40
Ash Content	1.90	3.20	0.00
Volatile Matter	70.40	64.19	79.24
Fixed Carbon	18.40	24.60	20.33
Sulphur	0.002	0.01	0.03
Calorific Value (MJ/kg)	18.9167	19.9280	19.5968

The parameters investigated under proximate analysis for the three samples are moisture content, ash content, volatile matter, fixed carbon, Sulphur and calorific value (energy content). The moisture content for sample A(sawdust) 9.3% supersedes that of sample B (coconut shells) 8% and that of sample C(plastics) 0.4%. The ash content of sample B is the highest with a value of 3.2% followed by the ash content of sample A with sample C having no ash content. The percentage of volatile matter for sample C is highest with a value of 79.24% followed by that of sample A with a value of 70.44% while that of sample B is 64.19%. For fixed carbon, sample B has the highest composition of 24.6% while that of plastic is 20.33% and sawdust 18.4%. High fixed carbon content in fuels is essential for the production of high quality syngas. Sulphur is undesirable in gasification and the relative low Sulphur content is a is a sign that the fuel is good for gasification. The calorific value or energy content of a fuel is one of the most critical properties in the selection of fuels for gasification. This is because it forms the bulk part of thermal efficiency, cold and hot gas efficiencies of the gasification process. Coconut shells had 19.928 MJ/kg followed by plastics with19.5968MJ/kg and then sawdust with 18.9167MJ/kg.

Ultimate Analysis

The parameters or fuel properties investigated in the ultimate analysis are carbon content, hydrogen content, oxygen content, nitrogen content and Sulphur. Carbon and nitrogen are the major combustible constituents of the fuel samples and both have appreciable values.

Table 4: Results of ultimate analysis of three fuel samples.

Properties	Sawdust Sample A	Coconut Shell Sample B	Plastic (PET) Sample C
Carbon	43.7528	44.8767	49.0044
Hydrogen	5.3216	5.2590	5.9700
Oxygen	39.1040	38.0328	43.8987
Nitrogen	0.6920	0.8162	0.5152
Sulphur	0.002	0.01	0.03

The higher the carbon content, the better the quality of fuel for gasification. A value of 49.0044% which represent the highest was obtained for plastics (sample C) followed by coconut shells (sample B) with 44.8767% and sawdust (sample A) with 43.7528%. Oxygen is essential for hydrogasification as it combines with hydrogen to form water gas during gasification. Plastics had the highest oxygen content of 43.8987% followed by sawdust with 39.104% and coconut shells with 38.0328%.

The syngas produced in the gasifier was flare and the flame observed during the gasification is shown in figure 4. The flame produced in each case was observed to be reddish brown but that of the hybrid fuel had wider flame width and longer flame length. This implies that more syngas was produced when a blend of the three fuels (hybrid fuel) was used for gasification.

Figure 4: Production and flaring of syngas during gasification.

Results of temperature measurements during experimental procedure are shown in table 5

Table 5: Results of temperature measurements during gasification

Fuel	Reduction zone Temperature T_1 (°C)	Combustion zone Temperature T_2 (°C)	Pyrolysis zone Temperature T_3 (°C)
Coconut shells	680	520	450
Sawdust	550	400	390
Thermoplastics	620	490	430
Hybrid fuel	967	800	540

From the measured temperatures, it can be seen that the highest temperatures were recorded at the reduction zone followed by the combustion zone and then the pyrolysis zone. The hybrid fuel generated the overall highest temperature of 967 °C at the reduction zone while the combustion zone temperature was 800 °C and 540 °C was recorded at the pyrolysis zone. This means that there was higher yield of synthesis gas during gasification with the hybrid fuel.

CONCLUSION

Results of proximate analysis of three fuels for gasification showed that sawdust has a calorific value of 18.9167% and fixed carbon content of18.40%. Coconut shells has calorific value of 19.928% and fixed carbon content of 24.6% while thermoplastics had calorific value of 19.5968% and fixed carbon content of 20.33%. These properties are crucial in the selection of fuels for gasification and the values obtained were sufficient for gasification fuel. Results of ultimate analysis of three fuel samples showed sawdust had carbon content 43.7528% and hydrogen content of 5.3216% while coconut shells had carbon content of 44.8767% and hydrogen content of 5.2590%. Thermoplastics had carbon content of 49.0044% and hydrogen content of 5.97%. These values are significant and show that these fuels are good for gasification based on ASTM D6316-17 code and the work of (Datta et al. 2016). The gasifier was designed and design results showed reactor diameter of 374mm, height of 787mm, fuel consumption rate of 10.56kg/hr, air flow rate of 18.27m^3/hr and reactor minimum wall thickness of 3.74mm. The gasifier was tested, temperatures measured and the syngas flared. Results of test show reduction zone temperature T_1 of 967˚C, combustion zone temperature T_2 of 800˚C and pyrolysis zone temperature T_3 of 540˚ for gasification with hybrid fuel. There was generally more yield of synthesis gas when hybrid fuel was used for gasification compared with when the individual fuels were gasified. The syngas is useful for direct combustion (cooking) and for generation of electricity.

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