Emissions Analysis from Combustion of Eco-Fuel Briquettes for Domestic Application

Jefrey Pilusa, Edison Muzenda and Robert Huberts

Abstract**—**In this study, flue gas emissions from the combustion of eco-fuel briquettes in a ceramic lined stove were investigated. The eco-fuel briquettes were made of biomass and other waste material such as spent coffee beans, mealie husks, saw dust and coal fines using a hand operated screw press. A combustion set-up consisting of digital weightometer, ceramic lined stove and a complete chimney system was used. The emissions from the combustion process were measured using a Testo 350 gas analyzer linked to the chimney system. The eco-briquettes made from a mixture of waste biomass burnt cleanly within the acceptable exposure limits as set out by Occupational Safety and Health Agency (OSHA). The measured gross calorific value was 18.9MJ/kg with a burning rate of 2g/min. These properties make eco-fuel briquettes suitable for domestic applications.

Keywords**—**Biomass Fuel, Coffee Grounds, Clean Air, Emissions, Flue Gas Quality.

I. INTRODUCTION

BRIQUETTING of biomass is a densification process which improves its handling characteristics, enhances its volumetric calorific value, reduces transportation cost and produces a uniform, clean, stable fuel or an input for further refining processes [1]. Fuel briquettes are bonded by the random alignment of fibres, generated when plant fibres and shredded waste paper are soaked in water. The process occurs at ambient temperature at a pressure of 1.5 to 3.0 MPa. To a large degree, the bonding force in the fuel briquette is mechanical, not chemical. Because of this, retaining fibre integrity and the right degree of plasticity in the mixture is crucial to the quality of the fuel briquette [2]. Due to the rising costs of electrical energy, heat energy for cooking and heating in most townships of Gauteng Province in South Africa is obtained from the combustion of paraffin, fuel wood and coal. A recent survey conducted as part of this study has indicated that, each household in these townships could use up to 200kg of coal and 20kg wood per month in addition to electricity for lighting and other applications in winter season. Combustion of these fuels contributes significantly to air pollution resulting in potential risks to human health. 1 cubic meter of fuel wood emits 61-73 kg of carbon dioxide (CO_2) equivalents as well as other toxic and greenhouse gasses over its life cycle. Prolonged exposures to these gases may cause human health complications [3].

Fuel briquettes made from corn stover, which is a major field of crop residues in the United States of America, comprised roughly of 75% of total agricultural residues with an average bulk density of 42 kg/m^3. These briquettes are produced using a hydraulic piston and cylinder press at pressures of 5-15 (MPa) [4]. Other fuel briquettes are made from palm shell and residue, and are available in 40mm, 50mm and 60mm diameters. They are also made using a hydraulic press at pressures of 5-13.5 MPa but have a higher density of 1200 kg/m^3 when compared with other briquettes [2].

Flue gas emissions from biomass combustion refer to the gas product resulting from burning of biomass solid fuel. Solid fuels are mostly burnt with ambient air as opposed to combustion with pure oxygen. Since ambient air contains about 79 volume percent nitrogen, which is essentially non-combustible, the largest part of the flue gas from most fossil fuel combustion is inert nitrogen [5]. The next largest part of the flue gas is carbon dioxide which can be as much as 10 to 15 volume percent. This is closely followed in volume by water vapor created by the combustion of the hydrogen in the fuel with atmospheric oxygen. Much of the smoke seen pouring from flue gas stacks is this water vapor forming a cloud as it contacts cool air [6]. A typical flue gas from the combustion of fossil fuels will also contain some very small amounts of nitrogen oxides (NO_x), hydrogen sulphide (H_2S), sulphur oxides (SO_x) and particulate matter. The nitrogen oxides are derived from a very small fraction of the nitrogen in the ambient air as well as from any nitrogen-containing compounds in the fossil fuel. The sulphur dioxide is derived from any sulphur-containing compounds in the fuels.

The potential health hazard to humans by combustion emissions is a function of the inherent toxicity of the gases and the frequency and duration of exposure. The permissible limits must not be exceeded by taking precautions [7]. The permissible limits of concentration for the long-term exposure of humans to toxic gases are set by the threshold limit value

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(TLV). This is defined as the upper permissible concentration limit of the gases believed to be safe for humans even with an exposure of 8 hours per day, 5 days per week over a period of many years [8].

Recommended TLV values are published in the hazardous substance database bank by the Occupational Safety and Health Agency (OSHA). The OSHA data base is assumed to be appropriate to be used as a benchmark for toxic gas exposure limits in the South African context. With the uncertainties involved in the designation of occupational exposure standards and the variability of the occupational environment, it would be unreasonable to interpret occupational limits as rigidly as one might interpret an engineering standard or specification [7].

II. MATERIAL AND METHOD

Fuel briquettes were made of a mixture containing 32% spent coffee grounds, 23% coal fines, 11% saw dust, 18% mealie husks, 10% waste paper and 6% paper pulp contaminated water, at moderately low pressure, of about 0.878-2.2 MPa, using hand operated screw press as shown in Fig. 1 . All briquettes had an outer diameter of 100mm, inner diameter of 35mm and were 50mm long. There was no need for a chemical binder; the material components underwent natural binding by interlocking themselves by means of partially decomposed plant fibres. This would allow the measurement and estimation of the maximum possible briquetting pressure attained by the press. Parameters such as moisture content and densities of the briquettes were measured.

Fig. 1 Production of briquettes using a screw press

The experimental apparatus comprised of a digital weightometer, POCA ceramic lined stove and extraction system complete with a chimney. The gas extraction manifold was linked to a 980mm stainless steel pipe of 90mm diameter and 2mm thickness as shown in Fig. 2. A multi-purpose gas probe was installed 50mm above the manifold for continuous gas sampling and analysis. Emissions from the eco-fuel briquettes combustion chamber were sampled directly from the chimney tunnel through the multi-purpose probe on a real time basis and measured through the Testo 350 analyzer electrochemical cells. Eco-fuel briquettes of known mass were combusted in a POCA stove and a 4 liter stainless steel pot was filled with cold water and put on the stove. The stove and pot were transferred to a weightometer in order to monitor the fuel consumption rate and heat transfer efficiencies. Data was collected over a 210 minutes period for analysis. The velocity of natural incoming air was measured using an anemometer and this together with the cross sectional area of the incoming path was used to establish the air flow rate.

The combustion behavior of the briquettes could be predicted and modified by varying the manufacturing conditions, mainly the diameter factor and the raw material. The un-burnt ash content of the fuel briquettes can be estimated using the empirical model suggested by Tabares *et al*. (2000) [6]. The model defines the ash content as a function of fixed carbon being the principal factor of the weight characteristics during combustion, The relationship function is defined by Tabares *et al*.(2000) [6] as follows:-

$$W = fc\begin{bmatrix} 2.46 - 0.036\,fc + 3.9\times10^{-4}d + 0.13d_i \\ +0.05e^{4.59-0.037t} - 0.26m - 1.2\times10^{-4}C_v \end{bmatrix} \tag{1}$$

Where,

W is the remaining weight of ash in (w/w %).
fc is fixed carbon in (w/w %)
m is the final moisture content in the briquette in (w/w %)
d_i is the briquettes diameter in (cm)
d is briquette density in (kg/m3)
t is burning time in (minutes)
C_v is the calorific value of the briquettes in (kJ/kg)

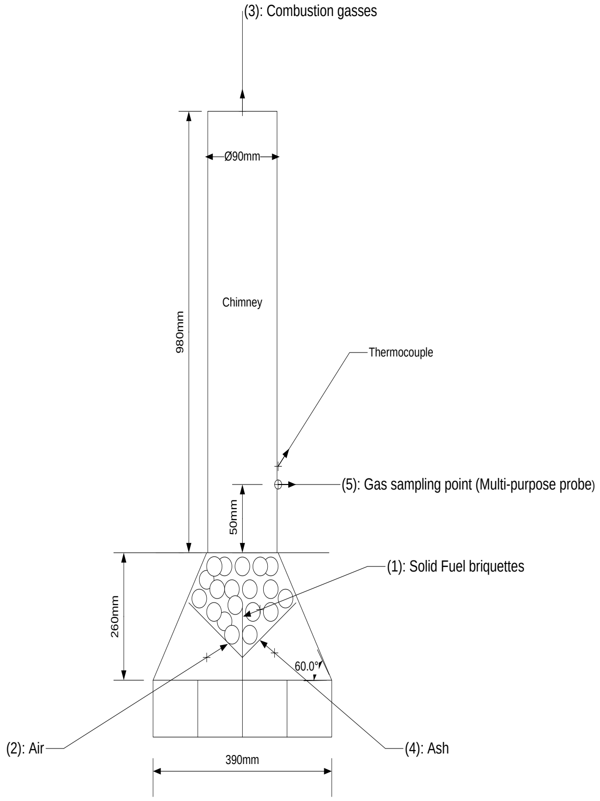

Fig. 1 Schematic diagram of the combustion system used

III. RESULTS AND DISCUSSION

A. Properties of Eco-Fuel Briquettes

Ultimate and proximate analysis of dry eco-fuel briquettes were conducted using ICP-Optima model 2100DV. Eco-fuel briquettes contain 26.30% fixed carbon, 39.34% volatile matter, 10.9% moisture and 10.46% ash as per proximate analysis. The ultimate analysis show 36.65% carbon, 4.60% hydrogen, 36.3% oxygen, 0.75% nitrogen and 0.34% sulphur in the briquettes. The bomb calorimeter tests have shown the briquettes yielding a gross calorific value of 18.9MJ/kg. The dry bulk density was measured as 721kg/m^3. It was noticed that Tebares *et al*. (2000) [6] correlation defined by Eq. 1 does not give an accurate ash content estimation for eco-fuel briquettes. This could be as a result of the geometry of the eco-fuel briquettes being hollowed cylindrical shape as opposed to solid cylindrical briquettes used to derive the Tabares *et al*. (2000) [6] empirical correlation. Table I shows the comparison between flue gas generated from combustion of coal and eco-fuel briquettes, this comparison indicates that coal is still a better fuel in terms of its higher calorific value (25.92MJ/kg), carbon content (61.2%) and lower ash content of 12% compared to the eco-fuel briquettes which have calorific value, carbon content and ash content of 18.9MJ/kg, 22.5% and 28.4% respectively. However, the eco-fuel briquettes are made of organic waste material with a lower sulphur content of 0.002% compared to 3.9% in coal.

TABLE I
COMPARISON OF COAL AND FUEL BRIQUETTES PROPERTIES

Combustion Gas Properties	Eco-fuel Briquette	Coal
Gross Calorific values	18.9	25.92
Specific Gravity	0.503	0.860
Carbon w/w%	22.5	61.2
Hydrogen w/w%	0.71	4.3
Oxygen w/w%	43.8	7.4
Sulphur w/w%	0.002	3.9
Nitrogen w/w%	0.001	1.2
Ash w/w%	28.40	12
Water w/w%	2.98	10
Combustion gas Molar mass (g/mol)	29.88	30.7
Carbon dioxide: volume%	19.68	15
Oxygen: volume %	13.37	3.7
% Excess air	12.8	20
Nm^3/GJ:8MJ/1.14m^3	142.5	293.6

B. Eco-Fuel Briquettes Combustion

Variation of flame temperature with the concentration of oxygen in the combustion gases is shown in Fig. 3. The oxygen concentration drops below 8.31% at the maximum combustion rate at a flame temperature of 197^{o}C. As the flue gas temperature drops, the oxygen concentration in the flue gasses increases, meaning that less oxygen is consumed when the combustion process slows down. The final oxygen concentration of 20.57% is attained when the flue gas temperature is equal to the ambient temperature, providing evidence that the combustion process stopped and oxygen was no longer consumed. The air to fuel ratio of 1.44:1 was obtained which shows that 60% of air was consumed for every 40% of fuel combusted.

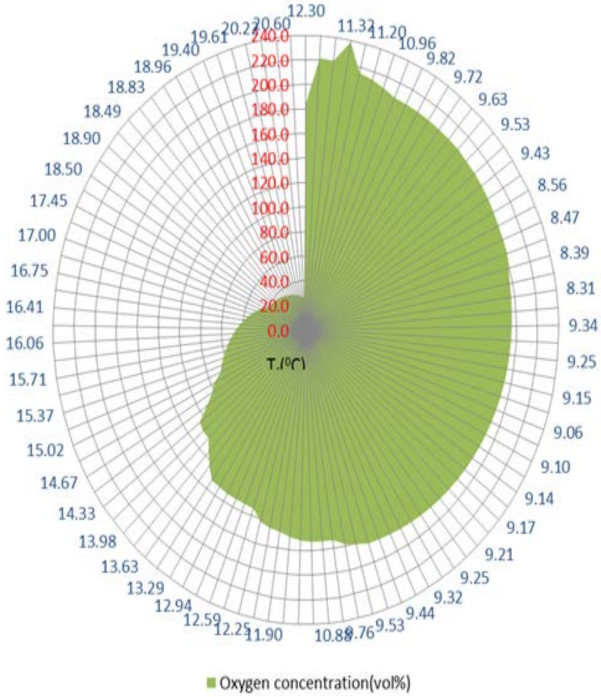

Fig. 2 Flue gas temperatures with oxygen concentrations

C. *Eco-Fuel Briquettes Emissions*

Table II shows a comparison between the actual gas emissions from fuel briquettes and maximum human exposure limit over 8 hours. The table clearly indicates that the gas emission produced by the fuel briquettes conforms by 83.3 % to the Occupational Safety and Health Agency (OSHA) occupational exposure standards. The carbon dioxide concentration is 46 times above the human exposure limit over the 8 hour exposure time. The safe exposure time for this high carbon dioxide concentration was estimated to be 11.25 minutes and this is sufficient to enable ventilation and control of flue gasses.

TABLE II

8 HOURS MAXIMUM EXPOSURE LIMITS FOR SELECTED EMISSIONS FROM ECO - FUEL BRIQUETTES

Emission	**Flue gas conc.(actual)**	**OSHA Limit**
Carbon dioxide	213, 329 ppm	5,000 ppm
Carbon monoxide	74 ppm	200 ppm
Hydrogen sulphide	4.3 ppm	20 ppm
Sulphur dioxide	3.7 ppm	5 ppm
Nitrogen oxide	1.3 ppm	25 ppm
Nitrogen dioxide	2.7 ppm	5 ppm

Although the other gases are in low concentrations as shown in Fig.4, the maximum safe exposure time to the combustion gasses produced by the fuel briquettes is 11.25 minutes due to the high carbon dioxide concentration. In principle the fuel briquette is deemed to be a clean fuel compared to other fossil fuels. The carbon dioxide produced is 2892 times the carbon monoxide, which indicates complete combustion. Furthermore, carbon dioxide is less toxic than carbon monoxide; therefore combustion of fuel briquettes is even more suitable for well ventilated indoor applications.

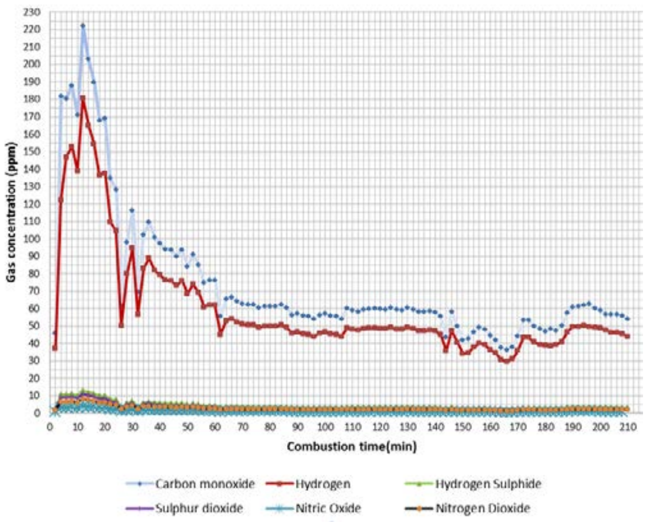

Fig 3 Low concentration emissions in the flue gas

Table III summarizes the flue gas compositions for fuel oil, coal and eco-fuel briquettes. From this summary, it is evident that eco-fuel briquettes flue gas is cleaner than other fossil fuels. A theoretical air requirement for combustion of the fuel briquettes was estimated as 2.57m^3 of air for every kg of fuel combusted. The experimental dry air consumed during combustion was measured as 752.65g at absolute pressure of 82.96 kPa. The average volumetric flow rate of the flue gas was measured as 0.4m^3/h over a period of 210 minutes and absolute pressure of 82.96 kPa, which is equivalent to 3.20m^3 of flue gas production per kilogram of eco-fuel combusted.

TABLE III

FLUE GAS QUALITY COMPARISON ON VARIOUS FUELS

Pollutant	**OSHA Limit**	**Fuel Oil**	**Coal**	**Eco-Fuel Briquettes**
Nitrogen	-	80vol.%	80vol.%	60.3 vol.%
Carbon dioxide	5,000 ppm	14 vol.%	11 vol.%	21.3 vol.%
Oxygen	-	6 vol.%	7 vol.%	12.8vol. %
Carbon monoxide	200 ppm	3,200ppm	5,571ppm	74 ppm
Nitrogen dioxide	5 ppm		1vol.%	2.7 ppm
Nitrogen Oxide	25ppm		1vol.%	1.3 ppm
Ammonia	50 ppm			
Sulphur dioxide	5 ppm		2,500ppm	3.7 ppm
Hydrocarbons	-			
Hydrogen sulphide	20 ppm			4.3 ppm
Mecury	-	-		
Ash	-	0	12w/w%	10.46w.w%

Note: 1vol.% =10,000 ppm

IV. CONCLUSIONS

Combustion of fuel briquettes in a laboratory-scale POCA ceramic stove was investigated to evaluate its combustion characteristics and gas emission quality. The results show that high combustion efficiencies could be achieved by choosing appropriate operating conditions. The efficiencies were between 91-95% for carbon utilization efficiency and over 99.47% for CO combustion efficiency at an estimated air-to-fuel ratio of 1.44:1. The average burning rate of 2g/min was obtained from the test work, meaning that 1kg of eco-fuel briquettes can burn for 7 hours which makes it ideal for domestic applications. The standard enthalpy of formation was found t be -1619.3kJ/mol. The flue gas produced from this reaction consisted of 21.3 vol.% CO_2, 74 ppm CO, 4.32 ppm H_2S, 1.34 ppm NO, 3.67 ppm SO_2, 5.5 vol.% water vapor (H_2O), 59.8 ppm hydrogen (H_2), 60.3 vol.% nitrogen (N_2) and 12.8 vol.% oxygen (O_2). The gas was mostly dominated by inert atmospheric nitrogen, oxygen, carbon dioxide and water vapor. The test results have shown that Eco- fuel briquettes are the cleanest solid fossil fuels. The effects of operating parameters on fuel briquettes combustion, such as gas velocity and excess air, and preheated air temperature and velocity may need to be investigated in detail in order to model the combustion efficiency of the briquettes under given conditions. The empirical correlation suggested by Tabares *et al. 2000* [6] for estimating the ash content of the eco-fuel briquettes may need to be studied for various briquettes geometry. Although eco-fuel briquettes burn cleanly within the acceptable OSHA emission exposure limits, consumers need to be educated of the health hazards associated with the exposure of combustion gasses over prolonged periods, without sufficient ventilation. In addition, combustion of eco-fuel briquettes using uncertified stove may cause excessive emissions due to air-fuel ratio imbalances.

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