Journal of Analytical and Applied Pyrolysis 126 (2017) 158–168

Contents lists available at ScienceDirect

Journal of Analytical and Applied Pyrolysis

journal homepage: www.elsevier.com/locate/jaap

Coal-derived low smoke fuel assessment through coal stove combustion testing

Thys Kühn[a], John R. Bunt[a,*], Hein W.J.P. Neomagus[a], Stuart J. Piketh[b], Raymond C. Everson[a], Sansha Coetzee[a]

[a] Coal Research Group, Unit for Energy and Technology Systems, School of Chemical and Minerals Engineering, North West-University, Potchefstroom 2520, South Africa
[b] Chemical Resource Beneficiation, North-West University, Potchefstroom 2520, South Africa

ARTICLE INFO

Keywords:
Pyrolysis
Low smoke fuel
Coal
Tar
Combustion
Environmental
Air pollution

ABSTRACT

A study was undertaken to investigate the production of low smoke fuel from coal currently used in low-income households in South Africa. Pyrolysis of large coal lumps was studied as a possible production method, and an optimum production temperature (550 °C) was found to yield a viable alternative fuel. Combustion tests of the low smoke fuel in well instrumented coal stove experiments showed that the benefits thereof included: reductions of approximately 80%, 90% and 35% less particulate matter, volatile organic compounds (VOC's) and sulfur dioxide emissions, respectively, when compared to raw medium rank C bituminous coal. Further research is required to develop this low smoke fuel with the end goal of large-scale production and performance trials in low-income households, in collaboration with the end users, as well as industry.

1. Introduction

In South Africa, an estimated 1 Mt of coal is uitilised annually as primary energy source for heating and cooking purposes in low-income households (commonly known as township households) [1–3]. This relates to an estimated national total coal consumption of 3% and 7%, for cooking and space heating, respectively [3]. Coal is the preferred source of energy for cooking and heating in low-income households, due to its abundance, availability and relatively low cost in comparison to other available energy sources [2,3]. Statistics South Africa indicated that 63% of low-income households in the Vaal Triangle region in Gauteng are reliant on coal as energy source [4]. A major source of urban air pollution in South Africa is caused by domestic combustion of coal, where its contribution is approximated to be about 20% of the total air pollution related to coal usage [5]. Studies conducted in the Gauteng Province concluded that 65% of the total ambient air pollution, and 48% of the quantifiable particulate emissions, are caused by inefficient coal combustion in rural areas [6,7].

When coal burns in the presence of oxygen it releases volatile gases which are harmful to the environment and living beings. These pollutants include carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), methane (CH_4), nitrous oxide (N_2O) and sulphur dioxide (SO_2). The emitted volatile gases also include particulate matter (PM) consisting of PM_{10} and $PM_{2.5}$, and volatile organic compounds (VOC's), each with their respective health risks [4,8]. Volatile organic compounds include any compound of carbon (excluding CO, CO_2, carbonic acid, metallic carbides or carbonates, and ammonium carbonate) that participates in atmospheric photochemical reactions [9]. Clearly, a need exists for a cleaner fuel or mitigation technology for low-income household usage. Research to date has focused on (1) the development of low smoke fuel, and (2) the development of new clean coal stove design technology.

A low-smoke fuel is defined as the solid product formed during pyrolysis at temperatures ranging between 400 and 900 °C [10]. This solid residue is referred to as char or semi/char, and degree of pyrolysis is dependent on the final pyrolysis temperature. Le Roux et al. [11] developed a test method for validating low-smoke fuels, which includes the determination of calorific value, ignition time, boiling time for 1L of water, and total solid emissions in comparison to the parent coal. Factors such as the fuel ratio (FC/VM) and the "Time to Cooking", defined as the time progression since the fire has been lit until cooking can commence, are also important to consider [11]. Mangena [12] developed a briquetting process which can convert ultrafine coal discards into a valuable low smoke fuel, according to the criteria

Abbreviations: a.d.b., air-dried basis; CSN, crucible swelling number; d.a.f., dry, ash free basis; d.m.m.f., dry, mineral matter free basis; FC, fixed carbon; FR, fuel ratio; GC, gas chromatography; m.m.f., mineral matter free basis; PM, particulate matter; TGA, thermogravimetric analyser; TSP, total suspended particulate matter; VM, volatile matter; VOC, volatile organic compounds; XRD, X-ray powder diffraction; XRF, X-ray fluorescence spectroscopy

* Corresponding author.
E-mail address: john.bunt@nwu.ac.za (J.R. Bunt).

http://dx.doi.org/10.1016/j.jaap.2017.06.012
Received 13 February 2017; Received in revised form 5 June 2017; Accepted 12 June 2017
Available online 15 June 2017
0165-2370/

developed by Le Roux et al.[11], for application in South Africa's domestic coal market. The investigation evaluated D-grade coal, low volatile coal, and anthracite. It was found that the briquettes took the longest time to boil 1L of water, but outperformed the other fuel sources in terms of particulate emission reduction.

The implementation of a clean coal stove design may also assist in reducing harmful emissions during household coal combustion. Household burning of coal in South African townships is predominantly performed via a traditional coal stove [5], where incomplete combustion of coal in traditional coal stoves result in the production of air pollutants which are released into the atmosphere [4,5,8]. A feasible solution previously proposed is the "BasaNjengoMagogo" (BNM) or "Top Down" method of ignition, in which the coal is ignited from the top and combusts downwards. This method is economical, can be fitted to existing appliances, burns less coal, and reduces the evolution of harmful emissions [5]. Alternatively, the use of Vesto stoves which use biomass (such as wood and charcoal) can be considered, as well as solar cookers [5,13].

To date, none of the above initiatives have been implemented due to cost, performance constraints, etc. In all of the previous work no quantifiable measurement of the gaseous and solid emissions occurring during combustion has been investigated. Moreover, none of the previous work has considered the gaseous and solid emissions occurring during combustion testing of the low-smoke fuel in a coal stove oven, which is the prevailing equipment used for cooking and space heating in low income households in South Africa. This investigation focused on the production of a technically viable low-smoke fuel (char), via pyrolysis of large coal particles obtained in Kwadela Township, near Secunda, South Africa. The economic and technical potential of the pyrolysis by-products, consisting of tar and gas components, was also determined, with the intent to possibly increase the feasibility of the low-smoke fuel implementation.

2. Experimental

2.1. Coal sample and preparation

The coal sample used for investigation was a typical Highveld coal from the Kwadela Township, situated approximately 55 km east of Secunda, South Africa. Particle size fractions of +19–26 mm, +26.5–37.5 mm, and +37.5–53 mm were obtained from the air-dried 300 kg bulk sample, and will consequently be referred to as 20, 30, and 40 mm particles, respectively. Single particles were selected based on density, and mercury submersion was used to ensure that the particles were within a density range of 1400–1700 kg/m^3 [14,15]. The coal was characterised using conventional methods (proximate and ultimate analysis), as well as other advanced techniques (XRF, XRD, and petrographic analysis).

2.2. Thermogravimetric analysis (TGA)

Thermogravimetric analysis was conducted with the purpose of ascertaining the temperatures at which the bulk char preparation would be conducted. The TGA experiments were conducted prior to combustion testing of the raw coal, and prepared chars.

The experimental TGA set-up is illustrated in Fig. 1, and has been described in detail previously [16]. A vertical tube furnace (supplied by Lenton Ltd.), with an inner diameter of 50 mm, was used for the TGA experiments. A 1 mm, K-type thermocouple was used to measure the temperature of the reaction zone within the work tube of the furnace. The furnace has a maximum operating temperature of 1500 °C, and a maximum heating rate of 25 °C/min. Nitrogen (N_2, 2 NL/min) was used as inert gas during pyrolysis, and was controlled with a Brooks model 0254 mass flow controller. The coal sample was placed in a sample holder consisting of an aluminium tripod and quartz stand, and the sample weight was continuously measured via a Radwag PS 750/C/2 precision balance.

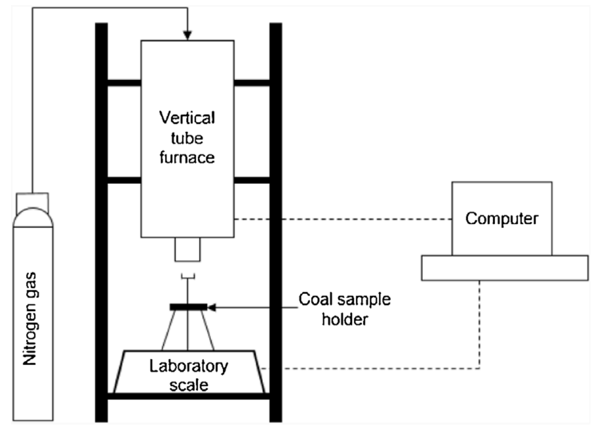

Fig. 1. Experimental TGA set-up.

Particles sizes of 20, 30, and 40 mm were selected for the TGA experiments, as the furnace is equipped to accommodate particles up to 40 mm in diameter. Pyrolysis experiments were conducted in order to obtain mass loss data for three different particle sizes up to 900 °C. The selection of 900 °C was motivated by a previous devolatilisation study that employed temperatures within a similar range [17,18]. Sample mass and the reaction zone temperature were recorded as pyrolysis experiments progressed from ambient temperature to 900 °C. During experimentation, N_2 gas was first injected into the furnace, after which the recording of the mass and temperature was initiated. Once the furnace had reached a temperature of 900 °C, the temperature was kept constant at this point for 30 min, after which the furnace was allowed to cool down.

2.3. Production of low-smoke fuel

Low-smoke fuels are produced from coal during the process of pyrolysis or devolatilisation, between temperatures of 400 °C and 900 °C [10]. Per definition, low-smoke fuel is a fuel that emits fewer pollutants during combustion, resulting in a cleaner atmospheric environment [10,19].

The low-smoke fuel was prepared at temperatures of 450 °C, 550 °C, 650 °C and 750 °C, using a Lenton Pyrolysis tube furnace. The horizontal tube furnace (18.7 kW, 400 V) operates according to a pre-programmed heating curve, which was set prior to conducting the experiments. A 300 mm long stainless steel loading boat (into which the coal sample was loaded) was manufactured according to the length of the heating zone of the furnace. Two different work tubes were used for the pyrolysis experiments. A Mullite tube was used for the lower temperature experiments at 450 °C and 550 °C, while a more robust Kanthal metal tube was used at the two higher temperatures of 650 °C and 750 °C. N_2 gas (ultra-high purity grade, 99.999%) as supplied by African Oxygen (AFROX), was used as inert atmosphere to prevent combustion of the coal. The method of devolatilisation necessitated that the coal samples be prepared according to the particle size distribution (PSD) of the coal as obtained from the Kwadela Township, Mpumalanga, South Africa. The top size fraction of the particles (+75 mm) was not used for the experiments, since the laboratory scale equipment could not accommodate this particle size. The −9.5 mm coal fraction was also omitted due it being too small to be retained on the combustion stove ash grate. Table 1 shows the original and normalised size fractions of the coal sample.

Numerous 1 kg representative batches of the normalised coal fraction (Table 1) were used to generate the low-smoke fuels for combustion performance assessment. The tube furnace was purged with 3 L/min N_2 flow for 5 min prior to pyrolysis, where after a constant N_2 flow rate of 3NL/min was maintained throughout the duration of the