FUNDAMENTALS OF COAL GASIFICATION TECHNOLOGY AND ITS RELEVANCE TO BOTSWANA COAL INDUSTRY.

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Coal is plentiful in many parts of the world but its combustion can create severe environmental and aesthetic problems. In the past three decades, the cost of crude oil and natural gas has been unstable and the reserves of these fuels are exhaustible. Other non-conventional energy resources, for example, solar, wind and tidal energy are only making a small contribution to the energy mix in a few countries. Consequently, coal still has an important role to play to satisfy the energy demand, especially when it can be converted before combustion to other less environmentally objectionable forms, e.g. coal gas / producer gas.

This paper describes the basic principles of coal gasification process and compares the performance of different gasifiers. The fundamentals of the raw gas cleaning methods are presented and experience to date of coal gasification in Botswana is also discussed. It seems certain that coal gasification in tandem with combined cycle power plant will be a principal technique for electricity generation in the next century. The paper recommends that Botswana takes necessary actions to gain maximum advantage from these developments.

1 INTRODUCTION

Coal was the main fuel before and during the Industrial Revolution. This resource is abundant in several parts of the world (see table 1) but its use as the chief traded fuel has been exceeded by oil. The sudden increase in the price of oil during the energy crises of the 1970s resulted in the non-availability of cheap oil. Consequently, energy production methods were then diversified and, once again, coal utilisation attained prominence. Combustion of raw coal either for domestic or industrial applications has several disadvantages, including severe environmental pollution, dirty handling mechanisms, inconvenient fuel supply methods and huge waste products.

The exhaustion of the worlds reserves of oil have been predicted by as soon as 2065 [1]. In addition to its finite life, the continued use of oil and petroleum products as a principal fuel is having serious effects in terms of global warming and environmental impact. While the earth has large reserves of natural gas this is often not available at sites where energy is required and transportation of natural gas by pipeline is expensive and vulnerable strategically. In view of this situation there has been a resurgence of interest in the possibilities of using coal in a more environmentally friendly way and a large amount of work has been done in developing so-called, 'clean coal technology' [2 - 5]. The gasification of coal for industrial purposes and power generation is a major part of this technology. Gasification of coal as part of integrated combined cycle power plants or similar technology is a prime candidate for further refinement at this time and is a likely system to be chosen for the generation of electricity and other applications in the next decade or two [2, 3, 6]

Table 1: Proved Global Hard Coal reserves [7]

Region	Total Reserves (btce)*
Africa	67
Australasia	45.3
China	62.2
Eastern Europe & FSU	135.4
North America	111.9
South & Central America	5.6
Western Europe	27.6
Other Asia	70.7

* btce = billion tons of coal equivalent

The aim of coal gasification is to convert carbon in the coal into a gaseous fuel, which is much friendlier to the environment than raw coal. When coal is burned as a fuel, the sulphur present appears as sulphur oxides that must be removed from the stack gases before they are discharged to the atmosphere. In coal gasification process, however, the sulphur in the coal is usually converted into reduced sulphur compounds, hydrogen sulphide (H_2S), and some carbonyl sulphide (COS) [6] most of which is removed before the gas is burned.

Since most of the sulphur is removed from coal gas in the clean-up process before it is burnt, it follows that the quantities of sulphur oxides to be handled in plants burning coal gas are much less than those to be removed from the stack gases of plants burning raw coal. The volume of clean coal gas is also much less than stack gases from plants burning raw coal. In addition to these factors, the technology for the removal of sulphur from coal gas is more highly developed than the removal of sulphur oxides from stack gases of coal plants [3]. These factors taken together make gasification of coal a preferred option.

In view of the requirement to drastically reduce CO_2 emissions, clean burning of coal will almost certainly

In view of the requirement to drastically reduce CO_2 emissions, clean burning of coal will almost certainly become mandatory and coal gasification processes will attain a high level of importance. By integrating coal gasification with highly efficient combined cycle power generation technology, low environmental impact can be achieved. The integrated gasification combined cycle (IGCC) and pressurised fluidised bed combustion (PFBC) are two main coal-based power generation technologies under development that may dominate the conventional energy sector in the 21st century. In particular, IGCC has minimum emissions of Nox, SOx, CO_2, trace elements and particulates in comparison to conventional and emerging coal-based power production systems [5, 8, 9]

2 THE COAL GASIFICATION PROCESS

2.1 Gasification Chemistry

The purpose of a gasification process is the conversion of a solid fuel, e.g. coal, biomass or solid wastes, to a gaseous fuel, namely, coal / producer gas. This is achieved with the help of a gasifying medium. Depending on the grade of coal and producer gas quality requirements, the gasification process includes all or part of the following stages: coal preparation and pre-treatment, gasification, producer gas cleanup, shift conversion, particulate matter and acid gas removal, and methanation. Figure 1 shows a schematic layout of a typical plant. Thus, the basic system configuration may comprise a coal crusher and mill, coal pre-treatment unit, gasifier, air separation unit (ASU), producer gas cooler with waste heat utilisation, and gas cleanup [3, 8].

In all current commercial coal gasification units, heat for the endothermic reaction is released by the oxidation of a small portion of coal that is inside the gasifier using pure oxygen, or oxygen contained in air or steam. The steam, oxygen or air is referred to as the gasifying agent or medium. The gasification process can be represented as follows:

$$\text{Coal (carbon)} + \text{Gasifying medium} \xrightarrow{Heat} \text{Producer gas} + \text{Residue (slag, ash)} \quad (1)$$

The following fundamental reactions of both complete and partial oxidation of carbon with oxygen take place in the gasifier:

$$C + O_2 \rightarrow CO_2 \ (\Delta H_r = -406 \text{ kJ/mol}) \quad (2)$$

$$C + \tfrac{1}{2} O_2 \rightarrow CO \ (\Delta H_r = -123 \text{ kJ/mol}) \quad (3)$$

The initial stage of the gasification process includes the introduction of crushed coal into the gasifier, coal preheating, drying and devolatilization at low to moderate temperatures followed by coal pyrolysis at high temperatures. During this stage, a gaseous product containing some tar vapour is produced from the volatile matter of the coal and the solid residue is char or coke. The gaseous product contains carbon monoxide, hydrogen, methane, other hydrocarbons C_nH_m, carbon dioxide, nitrogen, and water vapour in various proportions [9, 10]. The gas produced by pyrolysis and its composition depend on the coal quality and the process conditions, for example, temperature.

Pyrolysis, i.e. the heating of coal in the absence of oxygen may be achieved in the conventional carbonisation process or by a modern technique based on fluidisation that enhances gas-solid mixing with high thermal performance. The process can be represented as follows:

$$Coal \xrightarrow{Heat} Char + \text{Gaseous product } (CO_2, CO, H_2, H_2O, C_nH_m) + Tar_v \quad (4)$$

In the next stage of the process, a gasifying medium is introduced into the gasifier and the products of pyrolysis are converted to producer gas. Steam is normally used as the gasifying medium together with pure oxygen or air to achieve partial oxidation of the coal.

In the gasification process, both heterogeneous reactions (between solids, liquids and gases) and homogeneous reactions (between species within gaseous phase) occur. For example, the heterogeneous water-gas and Boudouard (gas-gas)

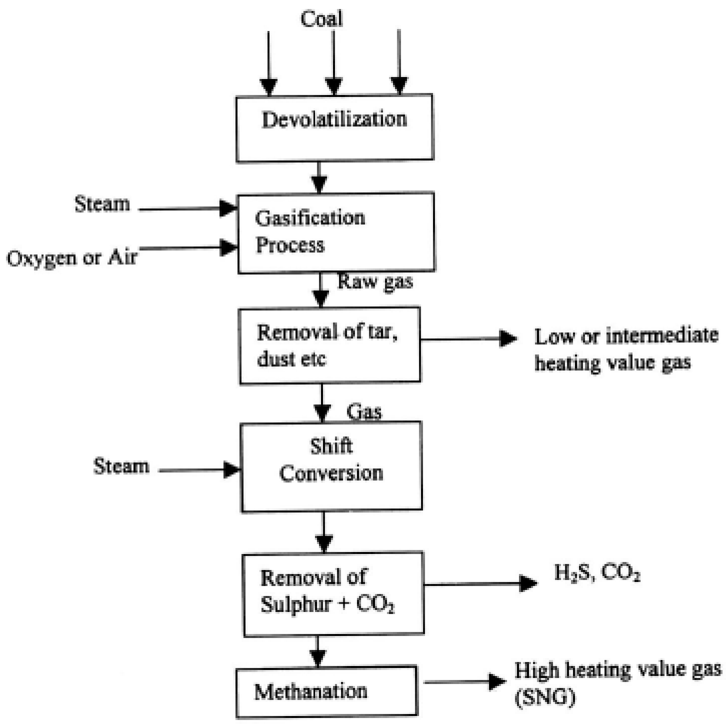

Fig 1: Layout of a simple coal gasification plant.

reactions are represented respectively by:

$$C + H_2O \rightarrow CO + H_2 \; (\Delta H_r = +\,119 \text{ kJ/mol}) \quad (5)$$

and

$$C + CO_2 \rightarrow 2CO \; (\Delta H_r = +\,162 \text{ kJ/mol}) \quad (6)$$

Also, the homogeneous water-gas /water-gas and methanation reactions are respectively given by:

$$CO + H_2O \rightarrow H_2 + CO_2 \; (\Delta H_r = -\,42 \text{ kJ/mol}) \quad (7)$$

and

$$CO + 3\,H_2 \rightarrow CH_4 + H_2O \; (\Delta H_r = -\,206 \text{ kJ/mol}) \quad (8)$$

2.2 Producer Gas Composition and Heating Value

The reactions of the gasification process described by equations 1-8 above take place in differing proportions depending on the particular gasification technology, coal grade, gasifying medium, and gasification temperature and pressure. Thus the composition and heating value of the resulting producer gas vary accordingly. The combustible constituents of the producer gas are carbon monoxide, hydrogen, and a small proportion of methane. Some carbon dioxide is usually present as an inert component. In air-blown gasifiers, nitrogen from the air is another inert component, whereas the producer gas from oxygen-blown gasifiers contains little or no nitrogen. Producer gases can be classified according to their heating values as depicted in table 2.

Table 2: Heating value of producer gases [3]

Type of gas	Heating value (MJ/m^3)
High heating value	35 - 39
Intermediate (medium) heating	11 – 17
Low heating	< 7.5

Based on the lower heating values, LHV_i, of the major combustible constituents of the producer gas and their molar fractions r_i, the lower heating value of the producer gas is given by:

$$LHV_g = \sum r_i \, LHV_i \tag{9}$$

The LHV_i for methane, hydrogen and carbon monoxide are respectively 37 MJ/m^3, 12MJ/m^3 and 12 MJ/m^3. Thus, if coal gas with a high heating value has to be produced, a large proportion of methane is required in the final composition.

Usually, the intermediate heating value gases contain only 5 to 15% of CH_4, 65 to 70% CO, H_2 in various proportions and the remainder is mostly CO_2. However, such a gas can be upgraded to the synthetic or substitute natural gas (SNG) having a high heating value. The conversion occurs in a succession of water-gas shift reactions followed by a methanation process according to equations (7) and (8). As the worlds' supply of crude petroleum oil is diminishing very rapidly, a replacement can be obtained from gasification process. For example, SNG can be used directly or for the production of hydrogen, methanol and liquid hydrocarbon fuels (gasoline).

Coal gas having a low heating value is usually produced in air-blown gasifiers and contains a high proportion of ballast gases especially nitrogen. In spite of its low heating value, such a gas can still be used to power a high efficiency gas turbine in an advanced combined-cycle power plant located at the gas production site.

2.3 Performance Criteria for Gasification Processes

The performance of the new generation of advanced gasifiers can be measured in terms of the gasification efficiency, carbon conversion, gasification thermal efficiency and throughput.

Gasification Efficiency: The gasification efficiency, η_g, is defined as the ratio of the chemically bound energy of the producer gas to that of the coal and it is expressed as:

$$\eta_g = \frac{V_g LHV_g}{LHV_c} \tag{10}$$

where the terms are defined in the nomenclature.

Carbon Conversion Efficiency: The carbon conversion efficiency, η_C, is defined as the ratio of the carbon content in the producer gas to that of the coal. Thus,

$$\eta_C = \frac{V_g C_g}{C} \tag{11}$$

Gasification Thermal Efficiency: The thermal efficiency, $\eta_{g,th}$, of the gasification process is defined as the ratio of the total energy, i.e. the sum of the chemically bound energy and sensible heat, of the producer gas to the sum of the chemically bound energy of coal and latent heat of steam within the gasifying medium. Thus,

$$\eta_{g,th} = \frac{V_g (LHV_g + c_{pg} t_g)}{(LHV_c + m_s h_s)} \tag{12}$$

3 COAL GASIFICATION PROCESSES AND GASIFIERS

Current gasification technology is based on fixed/moving bed, fluidised bed, and entrained flow coal gasification processes and gasifiers. Common commercial gasification processes are: Lurgi dry ash and British Gas/Lurgi (BGL) slagging fixed/moving bed processes, Koppers-Totzek, Prenflo (**P**ressurised **En**trained **Flo**w), Dow, Shell and Texaco entrained flow processes, Winkler and Kellogg-Rust-Westinghouse (KRW) fluidised bed processes [2,3,11]. The Lurgi technology is a high pressure process so that the produced raw gas can easily be transported without a boosting device but the process is slow. The Koppers-Totzek gasification technique is rapid because it operates at elevated temperature and it is flexible as it can handle a range of solid fuels. However, it produces low-pressure gas. Other major characteristics and performance data of these processes are presented in Tables 3 - 6. It is pertinent to mention here that considerable experience has been gained in South Africa in design, research and extended operation of coal gasification reactors over the last 50 years. SASOL (South Africa) is renowned for major innovations in proprietary technologies and developments for the production of high-quality synthetic fuels [12].

4 ENVIRONMENTAL IMPACT OF COAL GASIFICATION

The gas produced from coal contains environmentally harmful components such as sulphur compounds (hydrogen sulphide, sulphur dioxide and carbon oxysulphide), ammonia, hydrogen cyanide and chlorine as well as some traces of alkali metals (sodium and potassium) all of which are derived from coal. The quantity of each compound released depends on the quality of coal, gasification technology, and operating conditions (i.e. gasifying medium, temperature, and pressure). The harmful compounds or elements must be removed from the gas to reduce the adverse environmental impact of the gasification plant. In addition, the particulates containing alkali metals must be removed before the gas is burned in a gas turbine of an IGCC plant to protect the blades against high-temperature corrosion. Part of the trace metals in the coal may be retained in the ash and must be considered when choosing the ash disposal method. Brief descriptions of two methods for cleaning coal gas are presented below but further details of the environmental impact of gasification processes are discussed in Newby and Bannister [4] and Norman et al [13].

Cold and Hot Gas Cleanup: Two methods can be employed for raw gas cleaning, namely, cold gas cleanup (CGCU) and hot gas cleanup (HGCU). The current commercial CGCU controls all kinds of emissions efficiently including alkali metals. However, large quantities of sensible heat are rejected and therefore the overall efficiency of the gasification process is reduced. Consequently, the HGCU is currently being developed. It will be carried out at temperatures at or above 550°C and the overall efficiency will be much higher due to lower sensible heat losses. The HGCU is a vital component required for successful integration of the gasification process into thermal power plants.

Removal of Hydrogen Sulphide: The two-stage Claus process oxidises H_2S with oxygen of the air. In the first stage, the producer gas mixed with the air is fed into a furnace at a temperature of 600°C. Thereby, the major portion of H_2S in the gas is oxidised with O_2 to produce sulphur and water, both in vapour forms according to the following reaction:

$$2\,H_2S + O_2 \rightarrow 2\,H_2O + S \qquad (13)$$

By subsequent cooling, the sulphur vapour is condensed. The gas is then reheated to about 250°C, and any remaining H_2S is oxidised in this second catalytic stage where the sulphur vapour is condensed and solid elemental sulphur is the end product. Small amounts of carbon oxysulphide COS and carbon disulphide CS_2, together with residual H_2S and SO_2, can be removed by further treatment.

Table 3. Summary of the Major Characteristics of Coal Gasification Processes [3, 14, 15].

Gasification technology	Fixed/moving bed	Fluidised bed	Entrained flow
Process	BGL	Winkler KRW	Koppers-Totzek Texaco, Prenflo
Coal type	Bituminous, Anthracite	Lignite	Bituminous, Lignite
Coal particle size, mm	≤ 30	≤ 10	≤ 0.1
Gasifying medium	Steam + O_2	Steam + Air or O_2	Steam + O_2
Operating conditions:			
Temperature, °C	800-1200	≈1000	1300-1800
Pressure, MPa	0.1 - 10	0.1 - 3	0.1 - 4
Steam / O_2 ratio	4 - 8	2	0.5
Coal-Gas flow scheme	Counterflow	Parallel flow	Parallel flow
Residence time	30-60 min	1-10 min	≤ 0.1 s

Table 4. Comparison of Producer Gas Yield in Commercial Gasification Processes

Rate (kg/kg of coal)	Fixed bed process	Fluidised bed process	Entrained flow process
Coal gas output	2.1	5.3	2.2
Steam consumption	0.5	0.6	0.15
Oxygen consumption	0.7	-	1.1
Air consumption	-	3.75	-

Table 5. Comparison of the Composition and Thermal Characteristics of Dry Producer Gas in Commercial Gasification Processes [3, 14, 15].

Dry gas composition (% by vol.)	Fixed bed process	Fluidised bed process	Entrained flow process
Carbon monoxide	60	19	55
Hydrogen	28	20	34
Methane	9	1	-
Carbon dioxide	2	10	10
Nitrogen	1	50	1
Heating value, MJ/kg of coal	15.4	5.5	11.4

Table 6: Comparison of the Performance of Commercial Gasification processes [3].

Performance Criteria (%)	Fixed bed process	Fluidised bed process	Entrained flow process
Gasification efficiency, η_g	89	73	79
Carbon conversion efficiency, η_C	99	95	99
Gasification thermal efficiency, $\eta_{g,th}$	94	92	95

5 EXPERIENCE WITH COAL GASIFICATION IN BOTSWANA

Oil and natural gas currently provide the bulk of world wide energy consumption. Although the cost of these fuels has fallen drastically ($10/barrel, 1998 price), it is certain that the resources are exhaustible and other sources of energy are desired. Nuclear power is objectionable in many countries, especially in the developing nations because of the operational risks and environmental hazards associated with it. Although renewable energy sources such as solar, wind, geothermal and tidal waves are gradually coming on stream, their cost for power generation is still prohibitive for many economies.

For these reasons, coal will continue to play a major role in the energy mix of those countries that have the resource in abundance. The main issue that will significantly affect its use is mitigation of environmental pollution. This is where coal gasification becomes attractive. The research and development of the various conversion processes for the production of synthetic fuels from coal seem well established and should become more adopted in the next century. The use of coal gasification process in tandem with a combined cycle power plant can significantly increase the thermal efficiency beyond that of a gas turbine or a steam power plant operating individually.

Botswana has considerable coal reserves, estimated in excess of 200×10^9 tonnes [16]. Despite Government efforts over the past fifteen years to increase usage of coal, less than one million tonnes is mined and used each year, (766,000 in 1997) [17].

5.1 The Nature of Botswana Coal

Botswana coal is a bituminous/semi-bituminous coal. In its run-of-mine (ROM) condition it contains varying amounts of shale and stone and is friable, i.e. breaks down easily to fines. The gross heating value of the coal is 24.2 MJ/kg and its other characteristics are presented in Table 7.

Table 7: Analysis and Properties of ROM Botswana Coal [18].

Proximate Analysis	% as Received
Moisture	5.70
Volatile Matter	23.2
Fixed Carbon	52.9
Ash	18.2
Total Sulphur	1.46
Ultimate Analysis	**% as Received**
Carbon	61.41
Hydrogen	3.40
Nitrogen	1.36
Sulphur	1.46
Oxygen	8.47
Ash fusion Temperature	**Reducing °C**
Initial Deformation (softening)	1310
Hemispherical (melting)	1370
Fluid	1380

Local coal is not attractive for domestic and small industrial applications due to its poor burning qualities in the ROM condition and due to the high cost incurred in transportation from the mine to user. These users cannot burn fines (< 25 mm) and it should be noted that in handling and transportation, up to 25% by mass can be lost during on and off loading. A further loss is experienced if the coal becomes wet (some users have reported up to 40% by mass as being unusable on delivery [19]). These losses increase the price per tonne to the consumer. Industrial consumers also have difficulties burning such coal, unless it is modified and usually expensive equipment is required. The price per tonne of ROM coal from the pit-head at the colliery, is P49.50. By the time the coal is transported to depots approximately 250 km from the mine, the price rises to P168.75/tonne, while imported higher-grade coal from South Africa is only P135. (May 1998 prices).

It is this high cost and the condition in which coal is received that are critical factors affecting its adoption for several purposes. Most users, unless they have specially modified equipment, prefer to use coal-imported from South Africa. It would not appear viable to introduce beneficiation of Botswana coal at present, and for the foreseeable future, because of the low level of consumption [20]. In view of the forgoing, it is necessary to determine whether more sophisticated methods such as Coal Gasification can overcome some of the problems experienced in using local coal.

It should be pointed out that when it comes to such applications as electrical power generation, where pulverised coal is required, Botswana coal in its ROM condition is very satisfactory. In Botswana the sole power station is less than two kilometres from the colliery so that transportation of coal is not a problem and is achieved by belt conveyor. In addition the characteristics of the coal are well suited to the application and superior to those of coal burnt in many countries for this purpose. For example, the sulphur content of Botswana coal is currently lower than 1.46% [18]. Consequently it has not been necessary to install Flue Gas Desulphurisation (FGD) equipment at the Morupule Power Station to be able to stay within (and better) the laid down limits for SO_x in flue gases.

5.2 Feasibility Studies for a Coal Gasification Plant in Botswana.

Experience at Lobatse Clay Works (LCW) in using ROM Morupule coal for the firing of brick kilns resulted in several technical problems. For example, high ash were deposited on pallets and kiln brickwork and this led to quality problems with brick and clay products. It also led to the need for expensive cleaning devices and to environmental degradation of the surrounding area. [18].

A Pre-Feasibility Study for the installation of a small coal gasification plant was carried out in 1995 [18]. The study concluded that it would be feasible to build and operate an air blown fixed bed gasifier based on Wellman-Galusha technology at LCW. This was to consist of a two-phase programme. Phase 1 would supply clean desulphurized fuel gas from local coal for LCW and serve as a source of fuel for new industries to be established in the area. The second phase would consist of expanding the gasification facility and installing two dual fuel (diesel/gas) engine/generator sets to produce electrical power that could be sold to the national grid system. The project, if successful, could be a prototype scheme to supply power to small isolated villages, industrial areas and off-grid rural areas.

However, another study undertaken in 1996, [21] did not support this gasification project because generation of power from the plant would not be economically competitive with cheap electricity from the Southern African Power Pool. At the time of the study, Botswana Power Corporation (BPC) was generating electricity at 2.23t/kWh (0.787 US cents/kWh). Imported power from South Africa was 4.33t/kW (1.528 cents/kWh) and this was approximately one third of the price estimated for electricity from the proposed 10 MW coal gasification installation at Lobatse. It should be emphasised that the 1996 study rejected the idea of the gasification project on the grounds of cost. The high cost estimated for generation of coal gas and electricity were largely based on using American built gasification equipment, technology and two very expensive dual fuel engines. However, since technology of generating low heating value gas from coal is well established and extensively used in South Africa, it would be convenient and probably cheaper to use facilities and technology from that country and to consider alternative systems for generating electricity.

Botswana has been considering building a super-exporting power station for several years now [16]. This is predicted to be required as early as 2010, but almost certainly by 2015. Naturally such a station will incorporate the most appropriate and efficient technology available at that time. It is therefore appropriate that steps should be taken now to keep up with developments and that specialised training is given to at least some indigenous engineers to acquire expertise in gasification technology.

As new energy technologies emerge, the cost and performance of coal gasification plants will become more competitive with the conventional applications of coal. It is certain that gasification will be cheaper as the scale of plant increases (11) so that the huge reserve of coal in Botswana that are not exportable can be gasified to provide a wide range of products for industrial development.

6 CONCLUSION

This paper discussed the fundamentals of coal gasification technology including gasifier types, gasification conditions (i.e. temperature and pressure), and coal gas composition. Depending on the process conditions, coal gas with intermediate or low heating value can be produced. Intermediate heating value coal gas can be readily upgraded to yield synthetic natural gas and many other useful by-products. In addition, the paper presented the characteristics and performance data of major commercial gasifiers. The most efficient application of coal gasification is in integrated gas combined cycle (IGCC) power plants. To reduce environmental impact of gasification processes and to ensure efficient and durable operation of gas turbines in IGCC power plants, a hot gas cleanup unit is required.

Coal gasification technology seems to be technically attractive in Botswana. The expertise for both the technology and the equipment exists on Botswana's doorstep, and would probably prove to be cheaper and more cost effective than using American expertise or equipment. The viability of small gasification plants operating in Botswana is still a topic for further consideration. It is likely however that these would only be viable when built close to a supply of cheap coal.

NOMENCLATURE

- C mass fraction of carbon in coal;
- C_g carbon content of producer gas [kg C per m^3 gas];
- c_{pg} isobaric specific heat of the producer gas [kJ/m^3K];
- H mass fraction of hydrogen in coal;
- h_s specific enthalpy of steam [MJ/kg];
- LHV_c lower heating value of the coal, MJ/kg;
- LHV_g lower heating value of producer gas [MJ/m^3];
- LHV_i lower heating value of the i-th component of the producer gas;
- m_s steam requirements [kg steam per kg coal];
- O mass fraction of oxygen in coal;
- N mass fraction of nitrogen in coal;
- r_i molar fraction of the i-th component of the producer gas;
- S mass fraction of sulfur in coal;
- t_g producer gas temperature [°C];
- V_g producer gas yield [m^3 per kg coal];

Greek Symbols

- ΔH_r reaction enthalpy [MJ/mol] at 1 bar and 298 K;
- η_C carbon conversion efficiency;
- $\eta_{g,th}$ thermal efficiency of the gasification process;
- η_g gasification efficiency.

Subscripts

- c coal;
- i the i-th component of the producer gas;
- v vapour

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