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Making the most of South Africa's low-quality coal: Converting high-ash coal to fuel gas using bubbling fluidised bed gasifiers

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Abstract

South Africa has abundant resources of high-ash and other low-quality coals. The aim of this work is to investigate the possibility of using fluidised bed gasification technology to convert these coals into clean fuel gas. The fuel gas can be used for process heating or for power generation using the IGCC (Integrated Gasification Combined Cycle) process.

A high-ash coal from the Waterberg coalfield was tested in a bubbling fluidised bed gasifier using various gasification agents and operating conditions. The results of the tests show that when air and steam are used as the gasification agents, the calorific value of the gas is too low (2.9 MJ/Nm^3) for efficient power generation using the IGCC process. The calorific value of the gas can be increased to 4.85 MJ/Nm^3 if oxygen-enriched air (34% oxygen) and steam are used as the gasification agents. Calculations show that combustion of this gas using air can produce flue gas temperatures of up to 1 500 °C, which would result in high IGCC plant efficiencies.

The effect of temperature and residence time on the conversion efficiency of coal in the gasifier using oxygen-enriched air was also investigated. The results show that the coal conversion increases by increasing the temperature and residence time of coal char in the gasifier.

The results of the pilot-plant tests are being used to calibrate a simulation model that can be used to determine the optimum temperature, residence time and oxygen-enrichment levels for large-scale fluidised bed gasifiers using Grootegeluk coal from the Waterberg coalfield.

Keywords: High-ash coal, gasification, fluidised bed, oxygen enrichment, combined cycle, simulation

1 Introduction

South Africa has estimated coal reserves amounting to 35 billion tons [1] which has contributed to establishing the country as the leading economy in Africa and as a major world coal exporter. Annually 285 million tons of coal are mined from 72 mines that are situated in 19 coalfields in South Africa [2]. Domestic consumption of coal amounts to 171 million tons, and 69 million tons are exported. In order to produce coal for the domestic and export markets a significant amount of the mined coal requires beneficiation (washing) which produces 45 million tons of discards that are dumped and pumped to slimes dams.

Domestically, coal is consumed mainly for the generation of electricity by Eskom (110 million tons) and the production of synthetic fuels and chemicals by Sasol (40 million tons). The remaining 21 million tons are consumed mainly in boilers and furnaces for industrial and domestic heat production. The 171 million tons per annum of coal that are consumed domestically represent 74% of South Africa's total primary energy production. The balance of the primary energy is supplied by oil (12%), nuclear power (4.2%), gas (2.3%) and renewables (7.5%).

Technology for the utilisation of domestic coal consists mainly of pulverised coal combustion (Eskom and Sasol), fixed-bed coal gasification (Sasol) and grate-fired boilers (industry). The quality of coal available to the domestic market is expected to decrease in future since lower grade coal (high-ash) seams are being mined and coal washing is being scaled down as a result of environmental legislation. In order to utilise these lower grade coals and minimise the impact on the environment, new coal utilisation technologies will be required in future.

2 Fluidised bed technology

2.1 Fluidised bed combustion technology

In 1983 a research project was launched by the former National Institute for Coal Research of the CSIR to develop fluidised bed combustion technology to utilise low-grade coals in South Africa. The research demonstrated that due to the good heat and mass transfer properties of fluidised beds, coal with ash contents up to 70% can be utilised. The CSIR's research and development work resulted in the installation of five bubbling fluidised bed combustors (BFBCs) between 1989 and 1999. Other companies, such as Babcock and Scientific Design, also installed a number of BFBC plants during this time. It was realised during the development of BFBC technology that due to the low lateral dispersion coefficient of coal, the maximum bed area of these plants is about 60 m^2, which limits their thermal output to less than 40 MW. For large power station such as those built by Eskom, unit capacities of 600 MW are required. Internationally, this resulted in the development of circulating fluidised bed (CFB) technology. Higher thermal outputs are possible with CFB boilers since they operate at a higher fluidising velocity, which improves coal dispersion and mixing. The CSIR did not embark on the development of CFB technology since many large international companies, such as Alstom and Foster Wheeler, that supply boilers to the electrical utility market were active in the development of CFB technology.

2.2 Fluidised bed gasification and IGCC

In 2006 the CSIR launched a project to assess the feasibility of Bubbling Fluidised Bed Gasification (BFBG) technology for the gasification of high-ash-content fine coals. Fluidised bed gasifiers operate under reducing conditions (no excess air) and therefore have a much higher thermal output per square metre of bed area. If the gasifier is operated under pressure (25 bar), thermal outputs of 600 MW can potentially be obtained with a bed area of 25 m^2. It is proposed to incorporate BFBGs into integrated gasification combined cycle (IGCC) plants.

The flow sheets for conventional and IGCC power generation cycles are given in Figure 1. In a conventional cycle, all the energy in the coal is used to generate steam which is then exhausted through a steam turbine to generate electricity. The exhaust steam has to be recondensed and recycled to the boiler. Due to large energy losses during condensation, the overall efficiency (coal to electrical power) of a conventional power station is between 33 and 38% [3]. This can be raised to 45–47% by increasing the temperature and pressure of the steam [4]. New high-strength materials are being developed to achieve this target.

In an IGCC power station, a coal gasifier is incorporated into the flowsheet. During gasification, coal is reacted with oxygen, air and steam to produce a combustible gas (syngas). This gas stream has a low volume compared with the flue gas resulting from conventional coal combustion, and therefore gas clean-up systems can be reduced in size. The cleaned gas is combusted in a gas turbine which produces electrical power, while heat is recovered from the turbine exhaust gas by means of a conventional steam cycle. This configuration (IGCC) can produce higher efficiencies (45–55%) and lower emissions than conventional power stations [5]. In the gas purification stage of a IGCC power station, CO_2 can be captured and sequestrated to underground saline aquifers.

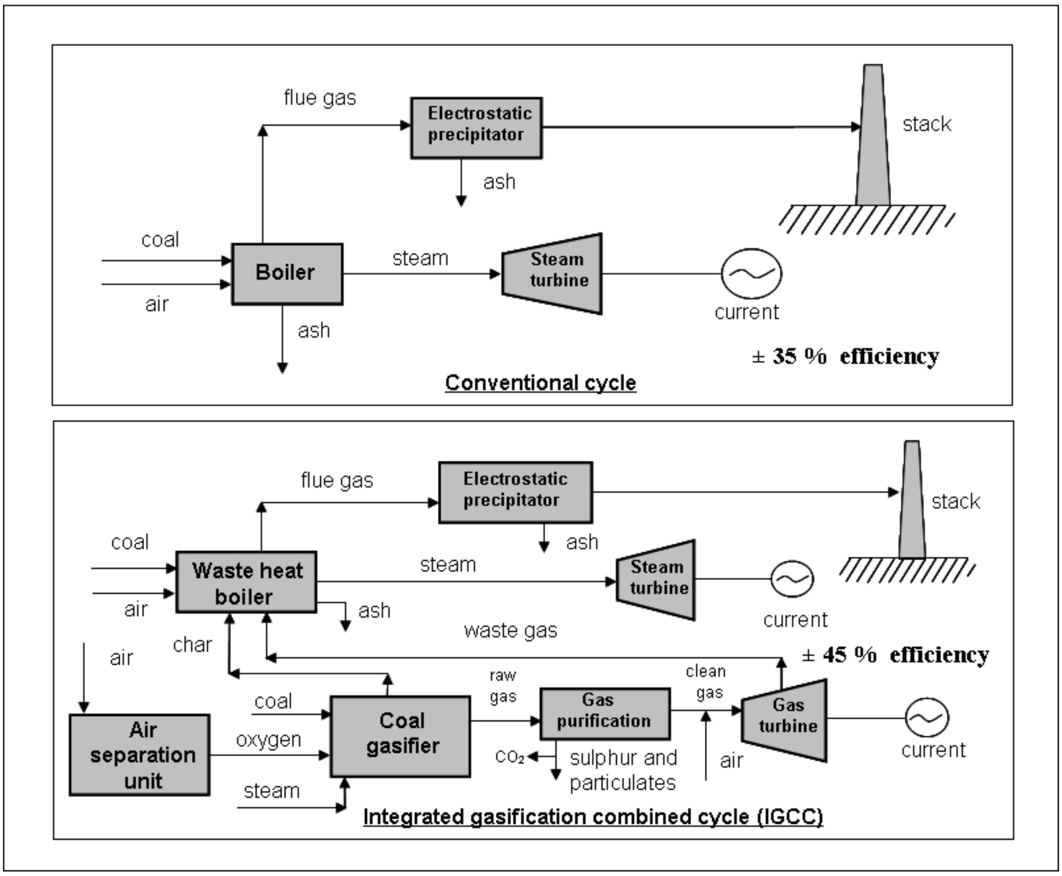

Figure 1: Conventional and IGCC power-generation cycles

The IGCC concept originated from the natural gas (CH_4) combined cycle (NGCC) power plants that have been operating since the early 1970s. An NGCC plant does not have a gasification stage since the natural gas produced from gas wells and oil refineries is fired directly into the gas turbine. Most NGCC power plants recover the heat in the turbine exhaust gas using a conventional steam cycle, as shown in Figure 1.

In NGCC power stations, efficiencies (gas to electrical power) of up to 60% can be achieved since the heat losses associated with the gasification stage are avoided. An NGCC plant produces less CO_2 per MW of electricity generated due to its higher thermal efficiency and because the combustion of 1 mol of CH_4 results in the release of 1 mol of CO_2 and 2 moles of H_2O.

NGCC power stations produce 25% of the electricity energy requirements of the USA. In 2001, 95% of the new electrical generation capacity added (22.5 MW) in the USA consisted of NGCC power plants.

3 Bubbling fluidised bed gasification tests

In order to assess the suitability of BFBGs for incorporation into future IGCC power stations in South Africa a pilot-scale bubbling fluidised bed combustion (BFBC) plant at the CSIR was converted into a BFBG.

3.1 Description of pilot plant

A flow diagram and the specifications of the pilot-scale BFBG are given in Figure 2 and Table 1.

Coal, air, oxygen and steam are the input streams to the process which produce the output streams: gas and char (ash). Coal is fed to the gasifier by means of a screw conveyor at a height of 1.5 m above the distributor. Steam is generated in an electrode boiler and is mixed with air and oxygen at the inlet to a shell-and-tube heat exchanger. The preheated steam, air and oxygen stream is injected into the gasifier via a nozzle-type distributor. Char (bed char) is removed from the bed by means of a water-cooled screw conveyor and from the gas (cyclone char) by means of a cyclone which is placed after the gas cooler. The de-dusted gas is combusted (flared) before it is vented to atmosphere.

Coal particles that enter the furnace via the coal feed chute drop into the fluidised bed section and start conversion to gas and char. The char particles move rapidly up and down between the gasification and combustion zones in the bed. The combustion zone is limited to the lower 10–15% of the bed above the distributor and is rich in oxygen.

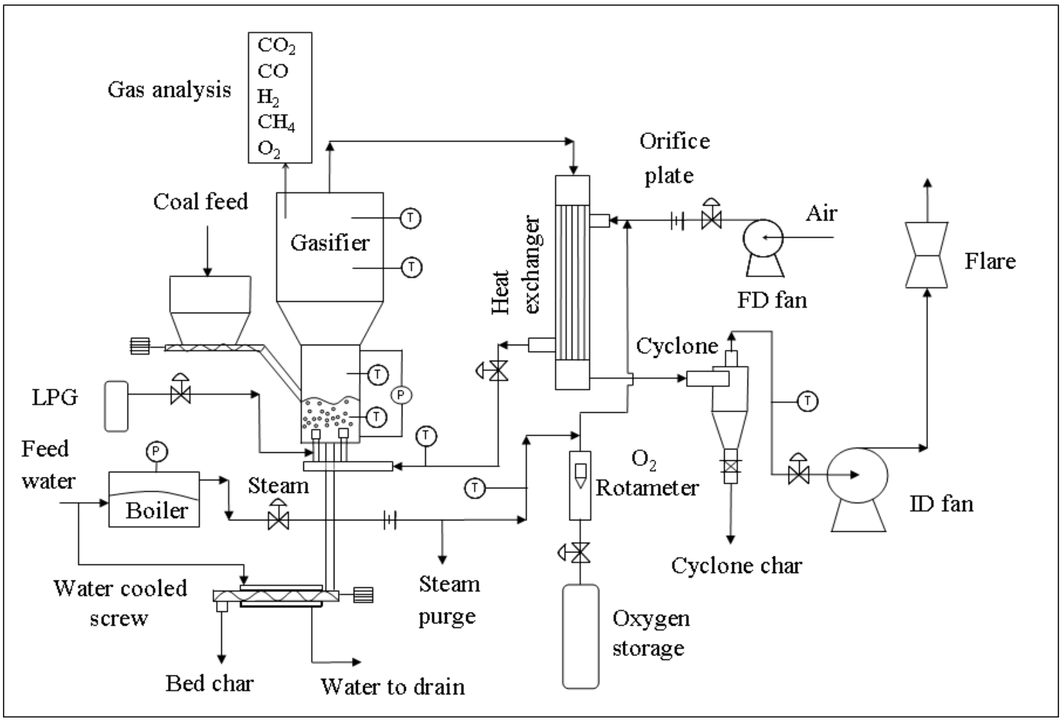

Figure 2: Pilot-scale fluidised bed gasification plant

Due to the fluidising action of the bed, the char particles experience attrition and break down into smaller particles. When the particles are small enough, they are entrained into the freeboard section (upper part) of the furnace. Due to the expanded nature of the freeboard, the gas velocity decreases and the particles fall back to the bed, resulting in internal circulation of particles between the bed and the freeboard. Further breakdown of the char particles results in their terminal falling velocity (U_t) being lower than the freeboard velocity and they are elutriated from the furnace. A significant proportion of the char particles (40–60%) are not elutriated from the furnace and these are drained from the bottom of the bed in order to maintain a constant fluidised bed height.

Table 1: Specifications of the BFBG pilot plant

Operating pressure	Atmospheric
Bed dimensions (m)	0.2 × 0.2 (square)
Freeboard dimensions (m)	0.40 × 0.40 (square)
Furnace height (m)	4 (2 m bed & 2 m freeboard)
Fluidised bed height (m)	< 0.6
Coal feed rate (kg/h)	18–30
Coal particle size (mm) (d_{50})	1.2–1.9
Coal CV (MJ/kg)	> 10
Air flow rate (Nm^3/h)	15–60
Oxygen flow rate (kg/h)	4–16
Steam flow rate (kg/h)	5–35
Bed temperature (°C)	860–980
Air, steam and oxygen temperature (°C)	155–300
Fluidising velocity (m/s)	1.2–2.2

3.2 BFBG start-up and control

The BFBG is started up by adding 15 kg of silica sand (0.4–0.85 mm) to the furnace. The silica sand is fluidised by starting the forced-draught (FD) and induced-draught (ID) fans. LPG is injected into the fluidised silica sand bed via the distributor nozzles. The LPG is ignited by means of a pilot flame which is inserted through the furnace door and directed down toward the bed. When the temperature reaches 850 °C, the pilot flame (lance) is removed and the furnace door is closed. The temperature is further increased to 930 °C by increasing the LPG flow. The furnace is operated with LPG at 930 °C for 6 h to allow thermal soaking of the refractories and heating of the freeboard. After 6 h, coal, steam and oxygen are added to the furnace and the temperature of the bed is controlled at the required set-point by varying the oxygen flow. The furnace is operated for a further 6 h to allow the bed carbon content and freeboard temperature to stabilise. Once stable conditions have been achieved, operating data are recorded and samples are collected for a period of 3 to 4 h.

3.3 Fluidised bed gasification tests

In order to assess the suitability of BFBG for incorporation into future IGCC plants in South Africa, tests were carried out using air + steam, oxygen + steam and air + oxygen + steam mixtures as the gasification agents. The coal selected for the tests is from the Grootegeluk mine which is situated in the Waterberg coalfield. This coalfield is situated in the north-eastern part of Limpopo province and has estimated reserves of 6.5 billion tons of high-ash coal [2]. Most of the coal mined at the Grootegeluk mine is transported to the nearby Matimba power station (Eskom) which consumes 15 million tons per annum of coal and produces 3.6 GW of electrical power. Before being transported to the Matimba power station, the coal is washed in order to reduce the ash content from ± 50% (as mined) to ± 33%. Discards with an ash content of ± 75% are produced during the washing process.

The analysis of the coal used for the three tests on Grootegeluk coal is given in Table 2. It can be seen that the coal analyses used for the three tests differ slightly. This is because the tests shown in Table 2 are from different test campaigns using different batches of coal.

Table 2: Analysis of coal product samples from Grootegeluk mine

	Gasification agents		
	Air + steam	**Air + oxygen + steam**	**Oxygen + steam**
Calorific value (MJ/kg)	19.8	21.4	21.2
Ash content (%)	34.9	31.7	32.6
Moisture (%)	1.6	1.9	1.9
Volatile matter (%)	24.9	28.3	28.8
Fixed carbon (%)	38.6	38.1	36.7
Total sulphur (%)	1.58	1.17	1.48
Ultimate analysis:			
Carbon (%)	51.96	52.93	52.60
Hydrogen (%)	3.15	4.11	3.96
Nitrogen (%)	0.99	1.19	0.86
Sulphur (%)	1.58	1.17	1.48
Oxygen (%)	5.85	7.00	6.00
Reflectance analysis:			
Vitrinite random reflectance (%)	0.68	0.71	0.72

The results of the tests using three different gasification agent mixtures are given in Table 3.

Table 3: Results of gasification tests using Grootegeluk coal

	Gasification agents		
	Air + steam	**Air + oxygen + steam**	**Oxygen + steam**
Coal feed rate (kg/h)	23.0	23.0	22.8
Airflow (Nm^3/h)	47.8	22.7	0
Steam flow (kg/h)	10.0	20.0	36.3
Oxygen flow (kg/h)	0	6.6	15.3
Oxygen in "air" (%)	21.0	34.40	100
Mid bed temp (°C)	950	943	918
Residence time (min)[1]	45.0	36.2	50.0
Bed velocity (m/s)	2.1	1.7	1.9
Gas analysis :			
CO (%)	10.2	13.6	21.7
H_2 (%)	9.5	16.8	27.9
CH_4 (%)	1.1	2.2	4.9
CO_2 (%)	14.9	22.3	39.6
H_2S (%)	0.50	0.46	0.92
N_2 + Others[2] (%)	63.80	44.64	4.98
Calorific value (MJ/kg)	2.94	4.85	8.46
CO_2 "free"[3] calorific value (MJ/kg)	3.58	6.25	14.04
Fixed carbon conversion	67.0	57.4	66.7
Gas flow (Nm^3/h)	60.0	40.0	27.0
Gas combustion temperature (°C)[4]	1 174	1 447	1 710
CO_2 "free" gas combustion temperature (°C)	1 342	1 673	2 051

[1] Calculated average residence time based on the bed pressure drop and coal feed rate.
[2] Others are < 0.1% and include NH_3, HCN and C_2^+.
[3] The calorific value calculated after removal of CO_2 from the gas.
[4] Calculated assuming 15% excess air and a combustion air preheat temperature of 250 °C.

The increase in the calorific value of the gas is given in Table 3 and Figure 3. It can be seen that when the air is enriched to 34% oxygen (13% enrichment), the calorific value of the gas increases from 2.94 to 4.85 MJ/Nm^3 which is an increase of 65%. When 100% oxygen and steam is used as the gasification agents (79% enrichment), the calorific value of the gas increases to 8.46 MJ/kg, which is a 187% increase.

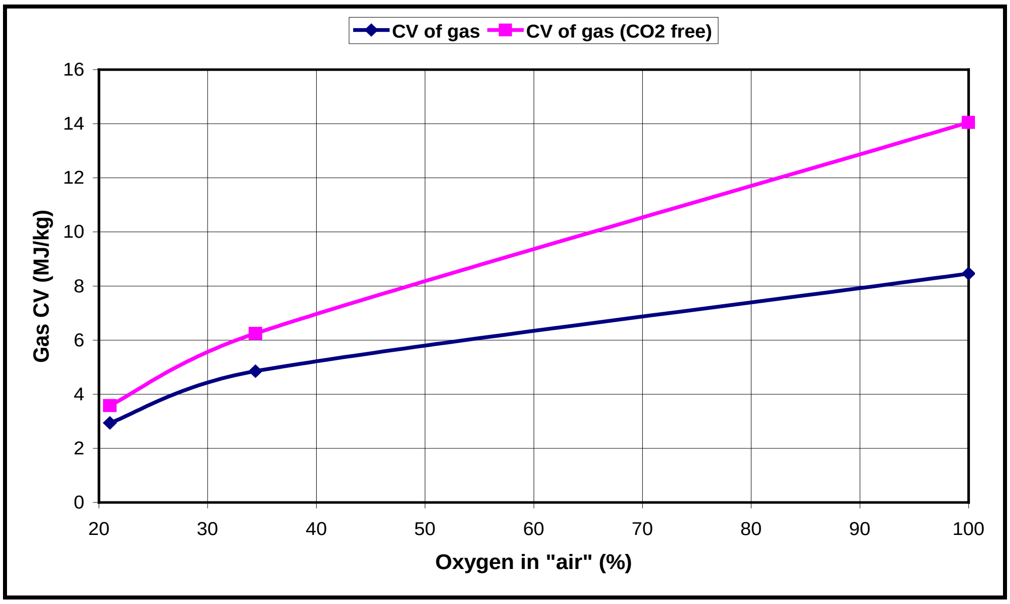

Figure 3: Calorific value of the gas as a function of oxygen enrichment

If the gas produced is combusted with 15% excess air, the resulting calculated adiabatic flame temperatures are given in Table 3 and Figure 4. State-of-the-art gas turbines are designed to accept gas inlet temperatures of up to 1 500 °C [6]. It can be seen that with air + steam gasification, the combustion temperature of the gas is too low for efficient utilisation in a gas turbine. With 13% enrichment of the gasification air, a gas with a calorific value of 4.85 MJ/Nm^3 is produced which, when combusted with 15% excess air, produces a temperature high enough for utilisation in a gas turbine. In the case where oxygen and steam are used as gasification agents, the gas combustion temperature is too high and additional excess air will be required at the turbine inlet to maintain the gas turbine inlet temperature at 1 500 °C.

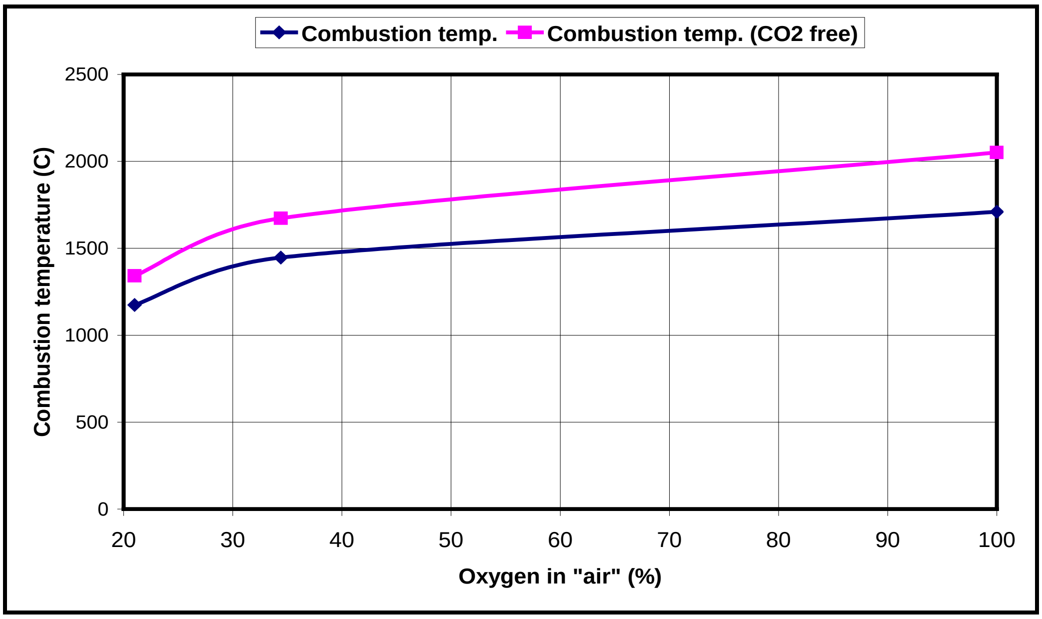

Figure 4: Gas combustion temperature as a function of oxygen enrichment

Table 3 shows that when oxygen and steam are used for gasification, the oxygen and steam requirement is much higher than when oxygen-enriched air is used. Oxygen-enriched air with oxygen concentrations between 25% and 40% can be produced using commercially available membranes [7] and could be a cheaper option that cryogenic air separation which produces 100% oxygen. The above suggests that there is a strong case for using oxygen-enriched air and steam as gasification agents when fluidised bed gasifiers are integrated into IGCC plants in South Africa.

The disadvantage of using oxygen-enriched air and steam compared with using oxygen and steam for gasification is that the cost of capturing CO_2 from the gas steam will be higher since the gas volume is higher and the CO_2 concentration is lower, as can be seen from Table 3 and Figure 5.

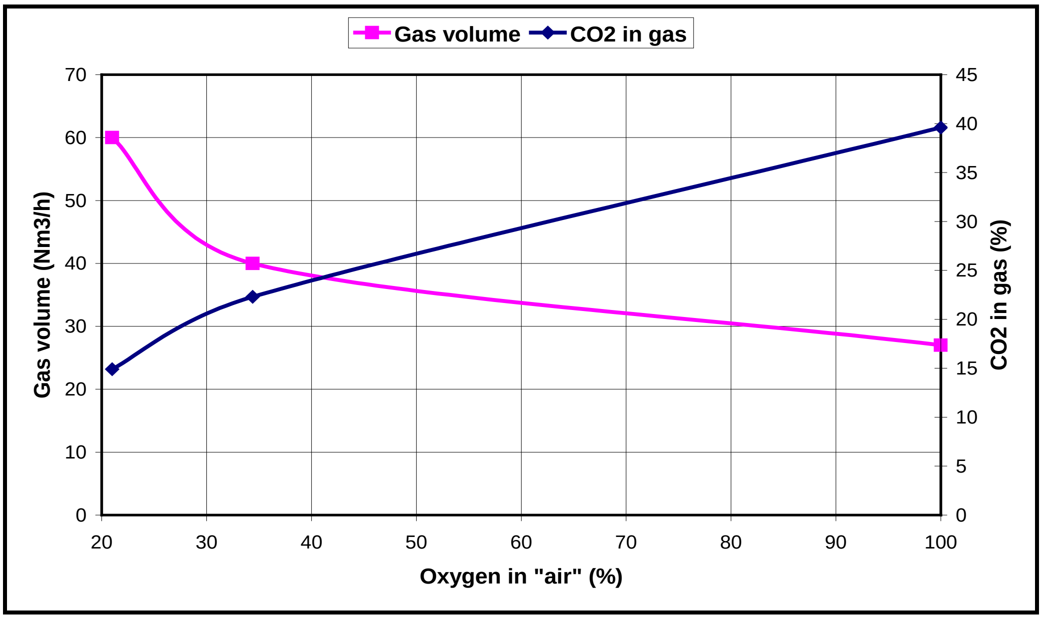

Figure 5: Gas volume and CO_2 concentration as a function of oxygen enrichment

The cost of capturing CO_2 from the gas stream produced by oxygen-enriched air gasification would be many orders of magnitude lower than capturing CO_2 from the flue gas of a conventional power station based on coal combustion. The utilisation of 23 kg/h of Grootegeluk coal in a conventional power station would produce ± 200 Nm^3/h of flue gas having a CO_2 concentration of ±13%. From Table 3 and Figure 5 it can be seen that the gas volume produced during oxygen-enriched air gasification of 23 kg/h of Grootegeluk coal is 40 Nm^3/h, with a CO_2 concentration of 22.3%. Commercial fluidised bed gasifiers operate under pressures of up to 28 bar which would result in a significant further reduction in the gas volume and an increase in CO_2 partial pressure, thereby lowering the CO_2 capture cost even further.

4 Modelling and optimisation

For the oxygen-enriched air case, five additional tests were carried out at different residence times and temperatures in order to find the optimum operating conditions. The results will be used to calibrate a simulation model (CSFMB) that has been developed for the fluidised bed gasification process. The comprehensive simulation of fluidised and moving beds (CSFMB) was acquired from the University of Campinas in Brazil [8].

The results of the five additional tests, including more detailed results on the oxygen enrichment test given in Table 3, are given in Table 4 (test 5).

Table 4: Results of six oxygen enrichment tests using Grootegeluk coal

Test number	**1**	**2**	**3**	**4**	**5**	**6**
Mid-bed temperature (ºC)	979	982	976	945	943	876
Char residence time (min)	54.1	46.0	36.1	54.5	36.2	38.5
Coal feed rate (kg/h)	16.0	19.6	23.0	16.0	23.0	23.0
Airflow (Nm^3/h)	15.9	20.9	22.1	18.5	22.72	24.5
Steam flow (kg/h)	11.5	15.0	18.3	15.0	20.0	17.8
Oxygen flow (kg/h)	6.0	7.0	8.3	6.0	6.6	4.5
Oxygen in enriched air (%)[1]	37.5	36.1	37.5	35.6	34.4	30.0
Oxygen in total inlet flow (%)[2]	21.9	20.9	20.6	19.5	18.0	16.7
Total inlet flow temperature (ºC)	247.7	273.8	293.9	247	287.4	255.7
Oxygen:carbon molar ratio	0.50	0.59	0.46	0.48	0.41	0.36

Steam: carbon molar ratio	0.90	0.96	1.0	1.18	1.09	0.97
Coal particle size (mm)[3]	1.7	1.4	1.4	1.4	1.7	1.7
Fluidising velocity (m/s)	1.2	1.5	1.8	1.4	1.8	1.6
Lower bed temperature (ºC)	998.3	1003.0	998.7	959	958	908.3
Gasifier exit temperature (ºC)	752.3	973.0	808.3	746	810	747.0
Dry gas composition						
CO (%)	16.6	17.0	16.1	15.0	13.6	9.6
H_2 (%)	18.9	17.7	18.6	18.3	16.8	12.3
CH_4 (%)	1.5	1.4	1.7	2.2	2.2	2.9
CO_2 (%)	22.8	20.0	21.2	27.4	22.3	20.5
N_2 + others[4] (%)[5]	40.1	43.8	42.4	37.1	45.1	54.7
O_2 (%)	0.1	0.1	0.0	0.0	0.0	0.0
Gas calorific value (MJ/Nm^3)	5.21	5.07	5.20	5.19	4.85	4.04
Bed pressure drop (Pa)	1816	1816	1816	1816	1816	1964
Char extracted from bed (kg/h)	3.27	3.10	5.05	3.52	5.90	8.85
Carbon in bed char (%)	4.50	10.80	21.71	16.4	28.24	38.64
Bed char particle size (mm)	0.52	0.70	0.88	1.05	1.05	1.35
Char elutriated to cyclone (kg/h)	2.90	5.0	5.30	3.42	5.150	3.70
Carbon in cyclone char (%)	32.4	30.7	35.51	37.3	40.10	49.0
Cycl. char particle size (µm)	67	67	70	72	72	70
Char entrained to cyclone (%)	47.0	61.60	51.22	49.38	46.62	29.48
Fixed carbon conversion (%)	82.16	74.96	65.42	69.55	57.44	40.32
Total carbon conversion (%)	87.20	82.03	75.19	78.15	69.46	57.15
Gasification efficiency (%)[6]	64.3	62.9	61.4	68.10	57.69	44.70

[1] Oxygen concentration of combined air and oxygen stream

[2] Total inlet flow consists of air, steam and oxygen

[3] d_{50} – 50% of the coal mass is less than the d_{50} size

[4] Others are < 0.4% and include H_2S, NH_3, HCN and C_2^+

[5] (N_2 + others) by difference

[6] Chemical and sensible heat in the gas as a percentage of the heat in the coal

The effect of temperature on the fixed carbon conversion is shown in Figure 6. These tests (Tests 3, 5 and 6) were carried out using a constant residence time of ± 36 min.

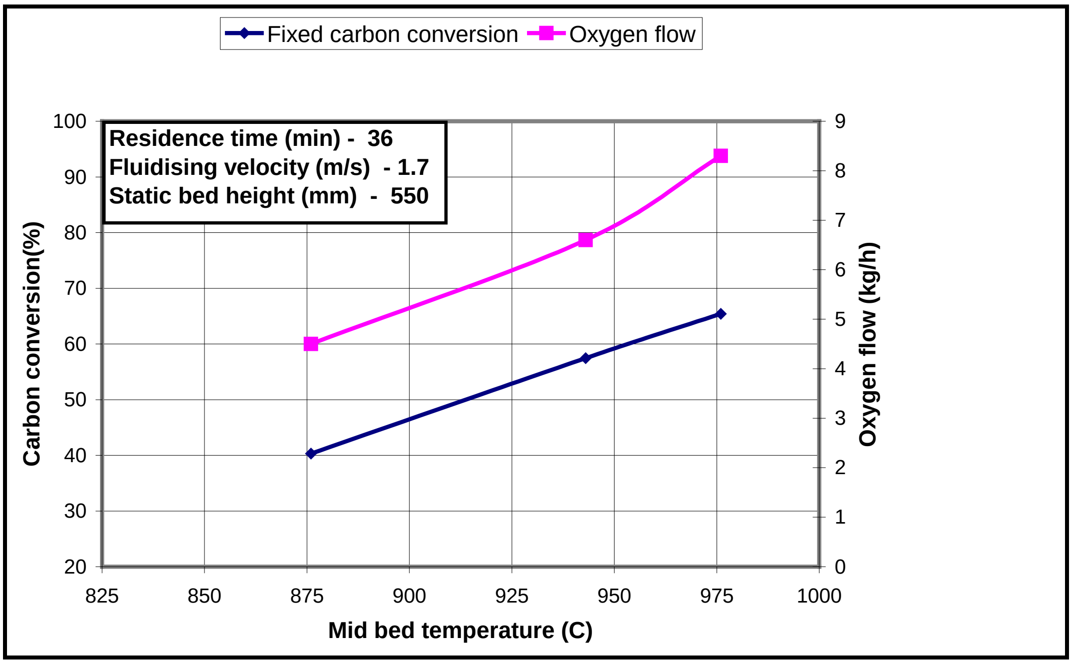

Figure 6: Effect of temperature on fixed carbon conversion

Figure 6 shows that temperature has a significant effect on the fixed carbon conversion. The fixed carbon conversion increased by 26% with a temperature increase of 100 °C. Figure 6 also shows that in order to increase the fixed carbon conversion additional oxygen is required, which would increase the operating cost of the process.

The effect of residence time on fixed carbon conversion at a constant temperature is shown in Figure 7. These tests (Tests 1, 2 and 3) were carried out at a temperature of ± 980 °C.

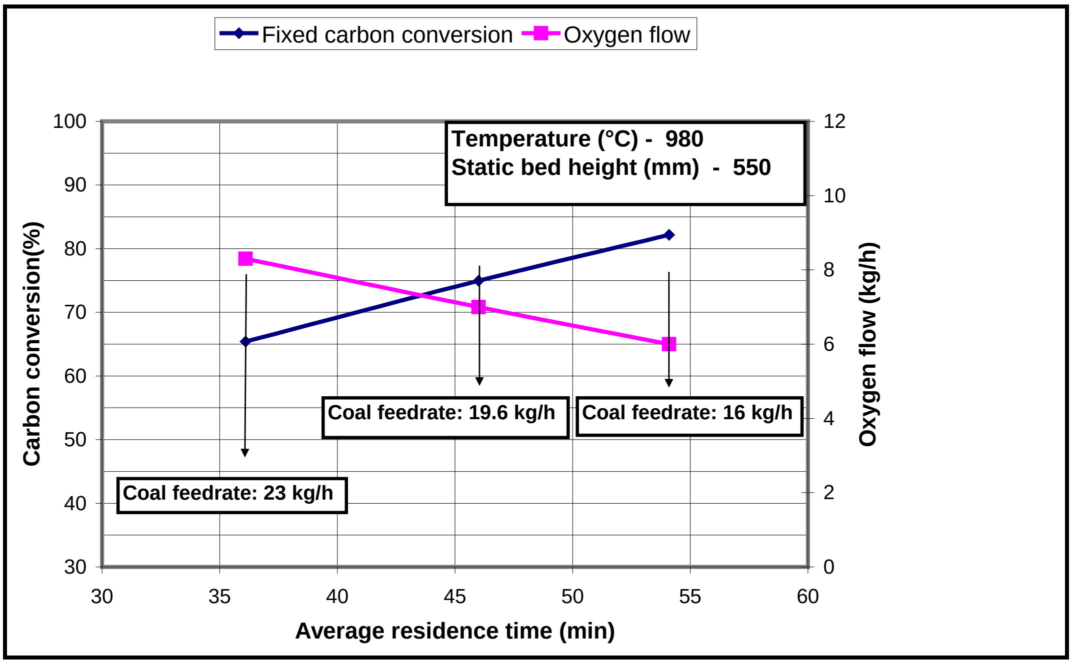

Figure 7: Effect of residence time on fixed carbon conversion

In order to increase the residence time of char in the gasifier, the coal feed rate was decreased from 23 to 16 kg/h while maintaining a constant bed height (bed pressure drop). Figure 7 shows that the fixed carbon conversion increases from 65.4% to 82.2% when the residence time is increased from

36 min to 54 min. This is, however, achieved at the expense of gasifier thermal output since the coal feed rate was decreased in order to increase the residence time.

The optimum temperature, residence time and oxygen flow for a bubbling fluidised bed gasifier integrated into an IGCC power plant would be the values required to:

- Maximise the gasification efficiency and thermal output of the gasifier
- Minimise the capital and operating costs of the gasifier
- Maintain the calorific value of the gas at ± 5 MJ/Nm^3 (dry gas without CO_2 removal).

The results of the tests given in Table 4 will be used to calibrate the CSFMB process simulator. The simulator has adjustable parameters which are associated with the rates of the chemical reactions taking place in the gasifier. The most important reactions are:

$C + 3/2O_2 \rightarrow 1/2CO_2 + 1/2CO$
$C + CO_2 \rightarrow 2CO$
$C + H_2O \rightarrow CO + H_2$
$CO + H_2O \rightarrow CO_2 + H_2$
$C + 2H_2 \rightarrow CH_4$

The parameters are adjusted in order to minimise the difference between the results given in Table 4 and the results predicted by the simulator. Once the simulator has been calibrated in this way, it can be used for the design, optimisation and scale-up of fluidised bed gasifiers using Grootegeluk coal.

5 Conclusions and recommendations

The following conclusions are drawn and recommendation given as a result of this investigation:

- The ash content of coal available for domestic consumption in South Africa is expected to increase in the future.

- In order to utilise these lower grade coals in the future new coal utilisation technologies will be required.

- In order to utilise Grootegeluk coal in fluidised bed gasifiers that are integrated into IGCC power stations, oxygen enrichment of the gasification air is required. The optimum level of oxygen enrichment is estimated to be between 30% and 40% oxygen in the enriched “air”

- The fixed carbon conversion in a fluidised bed gasifier using oxygen-enriched air and steam as the gasification agents increases when the temperature in the gasifier and the residence time of char in the gasifier are increased

- In order to determine the optimum temperature, residence time and oxygen enrichment levels required in large-scale fluidised bed gasifiers, a simulation model is required that has been calibrated using pilot-plant results related to the specific coal to be utilised in a commercial gasifier.

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