Fluidised Bed Gasification of South African Coals – Experimental Results and Process Integration

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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 at a high efficiency into clean fuel gas and/or electricity. The fuel gas can be used for process heating or for power generation using the Integrated Gasification Combined Cycle (IGCC) process.

This paper presents research on two areas – experimental work and process integration using pinch analysis.

A high-ash coal from the Waterberg coalfield was tested in a bubbling fluidised bed gasifier at the CSIR 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.

Parallel to the above experimental work, the University of Pretoria has undertaken pinch analysis to optimize the use of energy generated by IGCC power plants. The focus was on the steam path (subsystem) of IGCC power plants and no alterations were done on the syngas path of the plant. A case study on the world's largest capacity IGCC plant, the Elcogas plant, revealed that an increase in steam turbine power output from 135 MW to 145.6 MW can be achieved by applying pinch analysis. This increase in steam turbine power output results in a gross increase in efficiency from 47% to 51.6%. The new design however requires a significantly larger heat exchange area to exchange the extra energy that was not exchanged in the preliminary design. It is therefore recommended that a cost analysis should be done to determine whether the new design would be cost effective when compared to the preliminary design.

Keywords: High-ash coal, gasification, fluidised bed, oxygen enrichment, IGCC, pinch analysis.

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 currently produces 45 million tons of discards that are dumped and/or 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.

Technology employed for the utilisation of coal in South Africa 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 to meet export requirements will further reduce the quality of coal available for local use. In order to utilise these lower grade coals and minimise the impact on the environment, new coal utilisation technologies will be required in future.

FLUIDIZED BED TECHNOLOGY

Fluidized 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 $MW_{(e)}$ 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.

Fluidised Bed Gasification and IGCC

In 2006 the CSIR started 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 as compared to combustion plant. If the gasifier is operated under pressure (for example 25 bar), thermal outputs of 600 MW can potentially be obtained with a bed area of 25 m^2. It is proposed to investigate the possibility of incorporating 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 boiler tube 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 cleaning stage of an IGCC power station, CO_2 can be captured and sequestrated to underground saline aquifers.

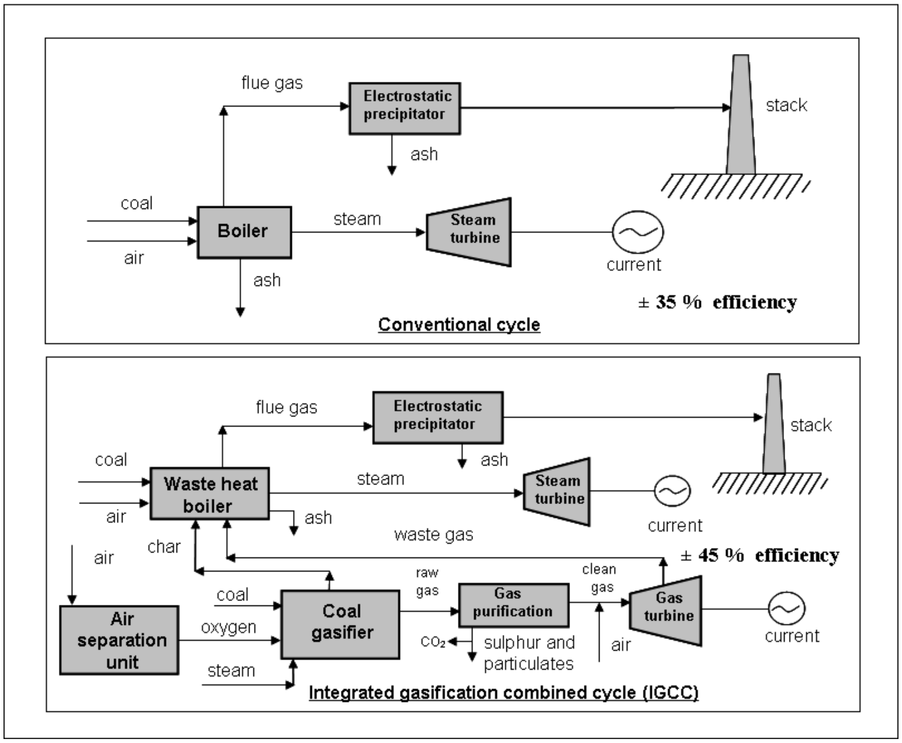

Figure 1: Conventional and IGCC power-generation cycles

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.

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.

Description of the BFBG Pilot Plant

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

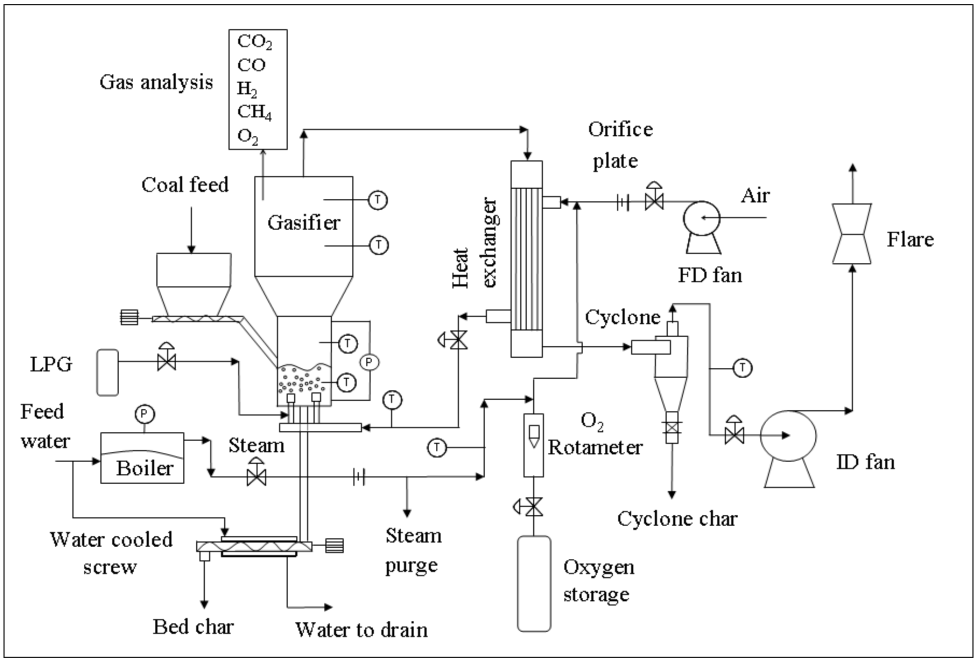

Figure 2: Pilot-scale fluidised bed gasification plant

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

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 relatively rich in oxygen.

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.

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 produced at different times.

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	20.4	21.2
Ash content (%)	34.9	33.7	32.6
Moisture (%)	1.6	2.0	1.9
Volatile matter (%)	24.9	27.0	28.8
Fixed carbon (%)	38.6	36.7	36.7
Total sulphur (%)	1.58	1.33	1.48
Ultimate analysis:			
Carbon (%)	51.96	50.47	52.60
Hydrogen (%)	3.15	3.44	3.96
Nitrogen (%)	0.99	1.03	0.86
Sulphur (%)	1.58	1.33	1.48
Oxygen (%)	5.85	8.05	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)	940	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	18.6	32.6
CH_4 (%)	1.1	2.2	4.9
CO_2 (%)	14.9	22.3	39.6
H_2S (%)	0.4	0.5	0.7
N_2 + Others[2] (%)	63.9	42.8	0.5
Calorific value (MJ/kg)	3.05	5.09	9.05
CO_2 “free”[3] calorific value (MJ/kg)	3.58	6.55	14.97
Fixed carbon conversion	67.1	52.38	67.64
Gas flow (Nm^3/h)	59.40	42.35	32.28
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 calorific value of the gas vs degree of oxygen enrichment 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.

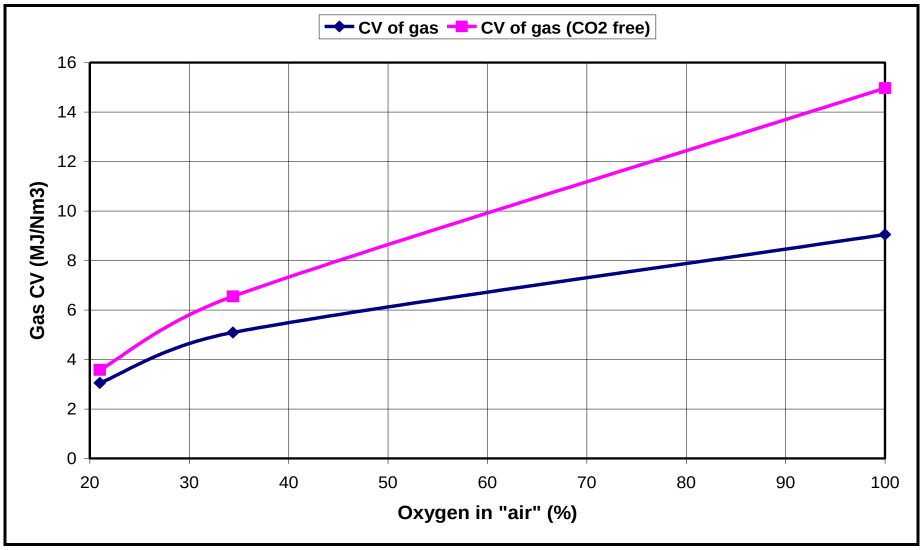

Figure 3: Calorific value of the gas as a function of oxygen enrichment

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.

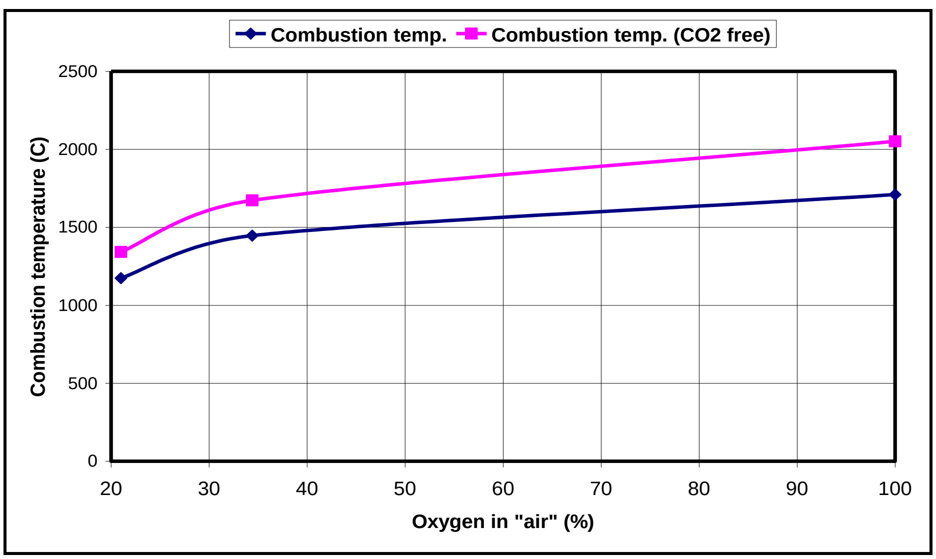

Figure 4: Gas combustion temperature as a function of oxygen enrichment

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.

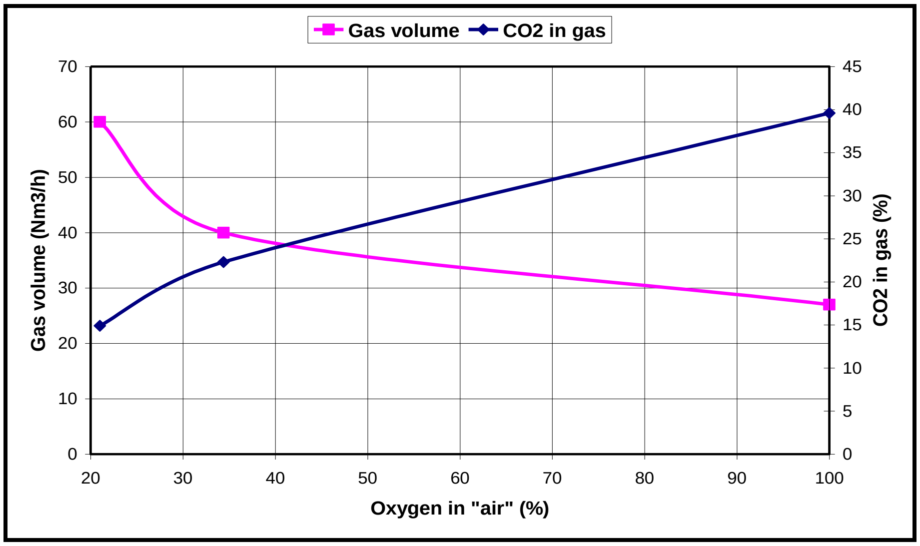

Figure 5: Gas volume and CO_2 concentration as a function of oxygen enrichment

The cost of capturing CO_2 from the gas stream produced by oxygen-enriched air gasification would be significantly 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.

PINCH ANALYSIS AND PROCESS INTEGRATION

Process integration techniques based on pinch analysis have become a powerful tool to optimize process designs. These techniques allow the engineer to track the energy flows in manufacturing processes to reduce energy consumption and yield results superior to those achieved using conventional methods.

The integrated gasification combined cycle (IGCC) is one of the cleanest available technologies for coal based electric power generation [9]. The problem encountered in IGCC plants is that most of the energy available in the system is not utilized.

The objective of this facet of the research was to increase the efficiency of an existing IGCC power plant (Elcogas power plant) by applying process integration techniques (pinch analysis) to maximize the use of the energy available in the system. A further objective was to improve the design of the process used by the plant such that it incorporates the integration. This review is based on a case study on the Elcogas plant located in Spain. The learning gained through this research will be applied to the results of the experimental gasification results in future studies.

The Elcogas power plant

Figure 6 is the process flow sheet of the Elcogas power plant. The process followed by this plant (and other IGCC plants) can be viewed as a two path process made out of the syngas path and the steam path.

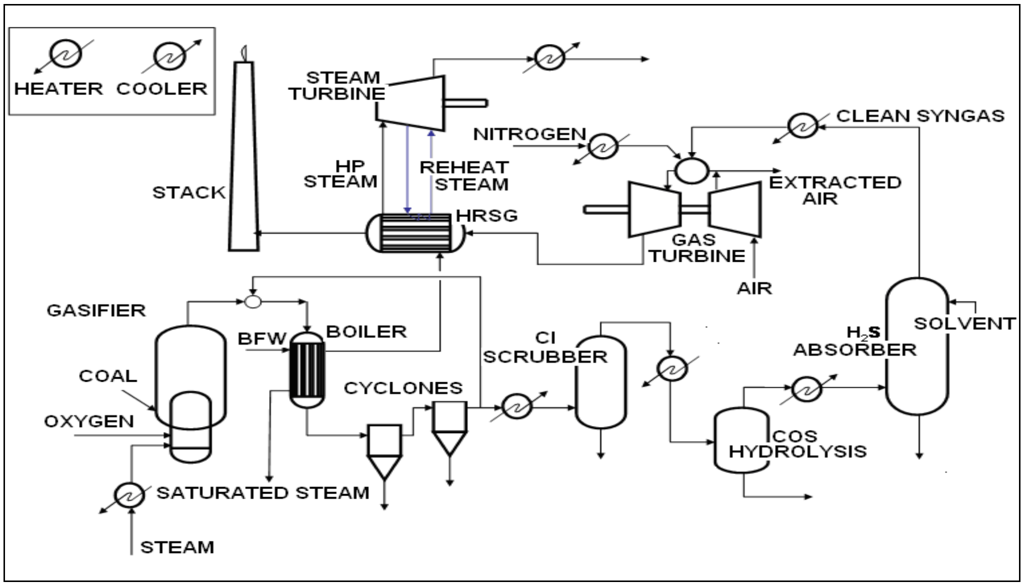

Figure 6: Simplified flowsheet of the Elcogas plant

The syngas path starts from the gasifier's exit stream, goes through the boiler and cleaning section (cyclones, Cl srubber, COS hydrolysis and H_2S absorber) then through the gas turbine and ends up in the stack. The steam path commences at the boiler as boiler feed water (BFW), goes through the Heat Recovery Steam Generator (HRSG) then finally through the steam turbine. Both the boiler and the HRSG are at a pressure of 127 bar. This plant has a net capacity of 335 MW_{ISO} and a gross efficiency of 47% [10]. The power output of the gas turbine (W_{GT}) is 200 MW while steam turbine power output (W_{ST}) is 135 MW.

Method

The focus of this project was on the steam path of the IGCC plant and no improvements or alterations were done on the syngas path of the plant. The idea behind using the pinch analysis was to determine the maximum flowrate of steam ($\dot{m}$) that could be generated using most of the energy available from the IGCC plant. This amount of steam would then be used to determine the maximum power the steam turbine can generate given its thermodynamic efficiency. The plant efficiency calculated using this maximum power output of the steam turbine would definitely be higher than the current efficiency of the plant.

Case study

A case study on the world's largest capacity integrated gasification combined cycle, the Elcogas plant, was done. Figure 7 shows the 8 streams that were extracted from the process accompanied by their data in Table 4. The dotted and dashed lines in Figure 7 represent hot and cold streams respectively. The mass flowrate of steam for the plant is 85.6 kg/s.

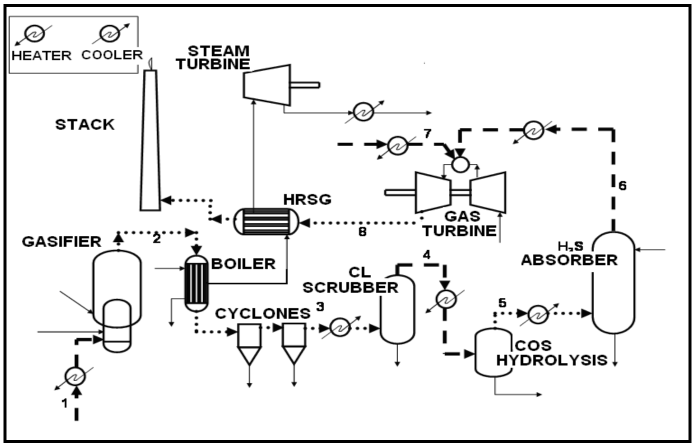

Figure 7: Streams extracted from the plant

Results and Discussion of Process Integration Studies

Figure 8 shows the grand composite curve (GCC) constructed from the results of the problem table algorithm. It is evident from Figure 3 that 390 MW of energy (Q) is available in the plant after process-process heat exchange. This amount of energy leads to a maximum steam flowrate of 120.5 kg/s which in-turn gives a maximum steam turbine power output of 145.6 MW. The gross power output is increased to 345.6 MW giving a gross plant efficiency of 51.6%.

Table 4: Stream data

Stream No.	Stream name	Stream type	Supply T (ºC)	Target T (ºC)	CP (MW/ ºC)	ΔH (MW)
1	Steam Generated	Cold	25	240	0.197	42.4
2	Raw Syngas	Hot	800	235	0.081	45.8
3	Particulate Free	Hot	235	35	0.060	12
4	COS Rich	Cold	35	130	0.053	5
5	COS Free	Hot	140	35	0.057	6
6	Sweet Syngas	Cold	35	350	0.054	17
7	Nitrogen	Cold	180	480	0.070	21
8	GT Exhaust	Hot	650	90	0.736	412

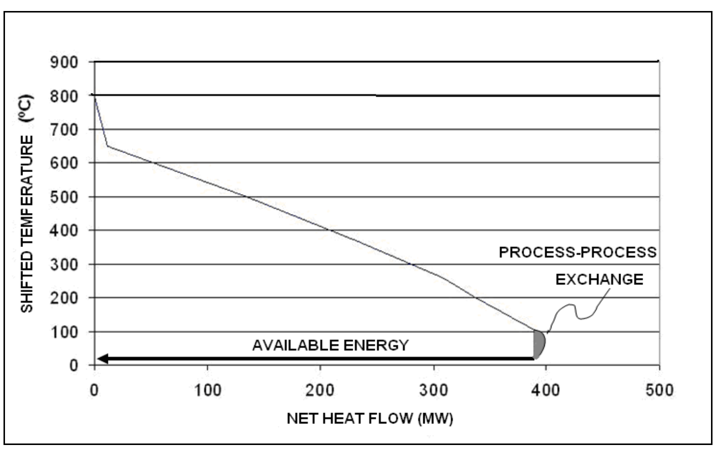

Figure 8: The grand composite curve for the Elcogas plant (excluding the steam path)

Figure 9 shows the new process design constructed from the heat exchange network diagram obtained from the Super Target 6.0 software package. It is evident from Figure 9 that in order to use up all (practically most) of the energy available, a larger heat exchange area is required. The darkened heat exchangers in Figure 9 are the heat exchangers that form part of the steam path (substituting the boiler and HRSG from the preliminary design) with the dashed lines indicating the steam path.

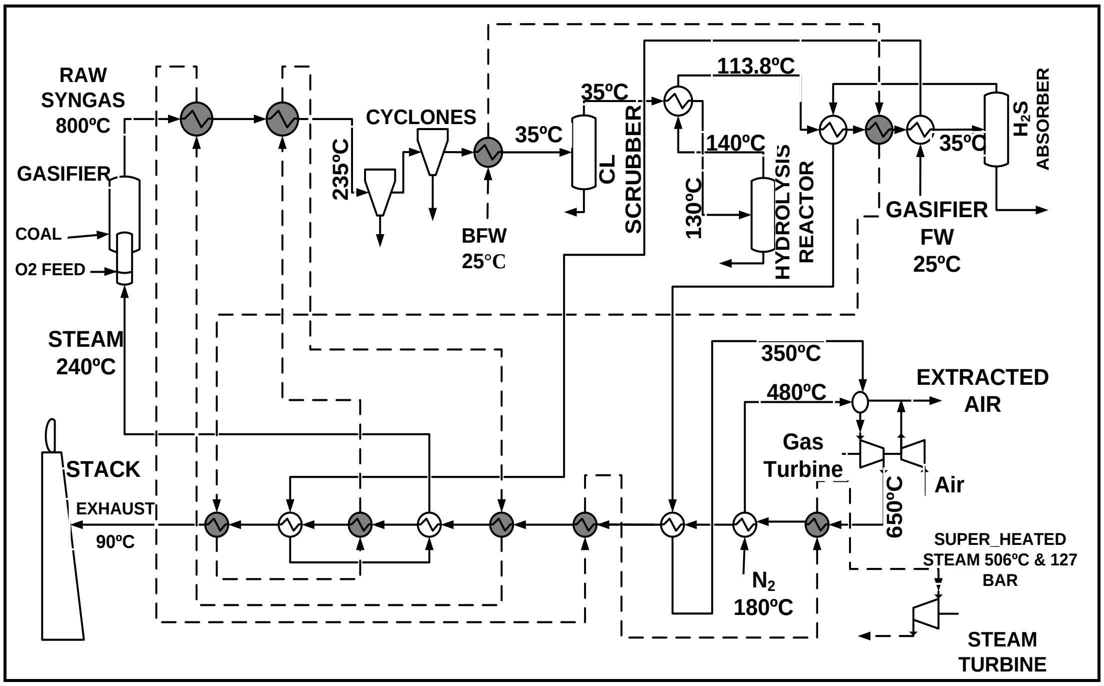

Figure 9: The proposed new design of the Elcogas plant

Conclusions and Recommendations

The following conclusions are drawn and recommendation given as a result of these investigations:

- 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.

- A maximum steam turbine power output of 145.6 MWISO (compared to 134 MWISO for the preliminary process) that increases the Elcogas plant's gross efficiency from 47% to 51.6% can be achieved. This increase in plant efficiency comes with a penalty of increased heat exchange area for the new design to exchange the extra energy that was not exchanged in the preliminary design. It is therefore recommended that a cost analysis on the new process design should be done to check whether the new process will be cost effective when compared to the preliminary process.

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