SASOL'S UNIQUE POSITION IN SYNGAS PRODUCTION FROM SOUTH AFRICAN COAL SOURCES USING SASOL-LURGI FIXED BED DRY BOTTOM GASIFIERS

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Abstract
Sasol has been operating the Sasol-Lurgi fixed bed coal gasification process for more than fifty years, and with ninety seven units in operation still remains the world's largest commercial application of this technology. The combined operational and engineering expertise vested in Sasol represents a formidable capability in the field of coal and gasification science. Coal is a crucial feedstock for South Africa's unique synfuels and petrochemicals industry, and is used by Sasol as a feedstock to produce synthesis gas (CO and H_2) via the **Sasol-Lurgi fixed bed dry bottom gasification** process.

South Africa, as well as many other countries in the world, will for many years to come rely on its abundant coal resources for energy and specifically for the production of petrochemical products. Synthesis gas production through gasification is growing at a rate of approximately 10% per annum [1], indicating that gasification is definitely not a dying technology. The Sasol plants located in Secunda and Sasolburg (South Africa) gasify >30 million tons per annum of bituminous coal to synthesis gas, which is converted to fuels and chemicals via the Fischer-Tropsch process. The production of chemicals is currently the dominant application for synthesis gas, followed by power generation, Fischer-Tropsch synthesis and gaseous fuels.

Sasol-Lurgi gasifiers are extremely robust devices, and coal from sources with widely varying properties (e.g. ash content <10% to as high as 35% or "brown coal" with moisture content of approximately 30%) can be gasified provided that certain operational changes are implemented. Other properties, like high caking propensity for example, require blending to acceptable levels and /or mechanical modifications. Interpretation of coal characterization data gives an indication of expected gasifier performance and the suitability of a specific coal source for Sasol-Lurgi Fixed Bed Gasification process. It is therefore critically important to gain an accurate and fundamental understanding of the properties and expected behavior of the targeted coal feedstock in order to (1) prepare a suitable conceptual flow scheme and (2) to maximize the eventual probability of success in any proposed gasification venture and (3) to optimize the operation and profitability of existing plants and (4) effectively address the environmental aspects.

It is the view of the authors that fixed bed gasification technology has a bright future in the areas mentioned above and that Sasol has a unique role in the future application and commercialization of gasification technology globally. The unique skills of Sasol could however be complementary to those of other parties who share our view on the future of gasification and related technologies.

Keywords: Sasol-Lurgi FBDB gasification, syngas (CO+H_2) to chemicals, coal characteristics, experience.

1. INTRODUCTION

Sasol has been operating the Sasol-Lurgi fixed bed coal gasification process for more than fifty years, and with ninety seven units in operation still remains the world's largest commercial application of this technology. The Sasol-Lurgi Technology Company (SLTC), a joint venture between Sasol Technology (PTY) LTD. and Lurgi South Africa, is the sole licensor of the Sasol-Lurgi fixed bed dry bottom gasification process, as well as a host of

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related process technologies including (amongst other) coal distribution and co-product processing schemes. The combined operational and engineering expertise vested in the Sasol-Lurgi Technology Company represents a formidable capability in the field of coal and gasification science.

Coal is used as main feedstock for South Africa's unique synfuels and petrochemicals industry and it is used by Sasol as a feedstock to produce synthesis gas ($CO + H_2$) via the Sasol-Lurgi fixed bed gasification process. South Africa, as well as many other countries in the world, will for many years to come rely on its abundant coal resources for energy and specifically for the production of petrochemical products.

Gasification is a fairly simple and commercially proven process for the conversion of solid and liquid carbonaceous feedstocks to synthesis gas. In the past gasification was viewed by many as a "dirty" technology with great adverse environmental impacts associated with the technology. This view is steadily changing, since gasification technology has over the past decade managed to demonstrate its versatility and efficiency in many areas. The technology is ideally suited to treat wastes and byproducts from other processes, as well as natural or renewable feedstocks like biomass, agricultural and municipal waste. The increasing concerns over environmental issues are viewed as strong drivers for the future growth of gasification technology, despite the fact that solid byproduct is produced which has to be disposed of in an environmentally acceptable manner. Gasification produces valuable synthesis gas, consisting mainly of H_2 and CO, due to the stoichiometric shortage of oxygen and the presence of steam.

Synthesis gas production through gasification is growing at a rate of approximately 10% per annum [1], indicating that gasification is definitely not a dying technology. The Sasol plants located in Secunda and Sasolburg (South Africa) gasify >30 million tons per annum of bituminous coal to synthesis gas, which is converted to fuels and chemicals via the Fischer-Tropsch process. A total of 97 fixed bed dry bottom gasifiers, 17 at Sasolburg and 80 at Secunda, have a combined production capacity of $>5.1 \times 10^6$ m^3_n/h dry crude gas, which is equivalent to $>3.6 \times 10^6$ m^3_n/h pure synthesis gas (pure gas is defined as 56% hydrogen, 32% carbon monoxide and 11% methane). These production rates are well in excess of the design capacity and are achieved by continuous debottlenecking and optimization.

2. HISTORY AND DRIVERS OF GASIFICATION AT SASOL

SASOL was established on 26 September 1950 with the prime objective to convert low grade coal into petroleum products and chemical feedstocks. Sasol One was built in Sasolburg and produced its first liquid product in 1955. In 1969 the Natref crude oil refinery was commissioned and in 1980 and 1982 Sasol Two and Sasol Three respectively began production in Secunda. Today, more than 50 years after the initial start-up, Sasol produces the equivalent of *150 000 barrels* per day of fuels and petrochemicals from coal via its indirect liquefaction process. The process produces in excess of 40% of South Africa's liquid fuels requirements. The company is listed on the Johannesburg and New York Stock Exchange. Sasol manufactures more than 200 fuel and chemical products in Sasolburg and Secunda in South Africa, as well as at several global locations. Its products are exported to more than 70 countries around the world. The history of Sasol revolves around the Group's impressive track record in innovating new or improved products and processes. Notable breakthroughs have been achieved in the fields of geology, mining production systems, coal preparation and gasification systems, mining explosives, fertilizers, biotechnology, environmental engineering and gas to liquids technology [3].

During the past ten years the syngas production of the 97 gasifiers used by Sasol has increased by almost 15%. The factors that contributed to the increased production can be put into 4 broad categories [10]

- 60% due to increased gasifier throughput
- 20% due to the reduction of CO_2 produced during gasification
- 10% due to the recovery of coal lock off gas
- 10% due to increased gasifier availability

Sasol One was originally equipped with ten Mark III gasifiers with an internal diameter of 3,66 m. Three gasifiers of similar design were added in 1966. In 1978 three Mark IV gasifiers, scaled up 55% above original design, were installed and a Mark V (114% scaled up above original). Pure gas production in Sasolburg has grown 11.7% over the last decade. Pure gas production in Secunda has grown by 13.3% over the last decade. The unit cost of pure gas has decreased by almost 14% from 1998 to 2003.

According to a recent survey by the Gasification Technologies Council [1], there are 161 existing and planned commercial scale gasification plants worldwide. This represents a total of 414 gasifiers with a total synthesis gas production of 446 million m^3_n/day of synthesis gas, which is equivalent to approximately 61 000 $MW_{thermal}$ or 800 000 barrels of oil per day. Coal and petrochemical byproducts (e.g. refinery residue, petroleum coke, naphtha, etc) are the two predominant feedstocks. The worldwide synthesis gas production capacities from these two sources are approximately equal, with biomass-based applications producing only a very small volume of synthesis gas. The Sasol plants in South Africa are the largest consumers of coal for gasification purposes (approximately 30 million tons per annum), the other coal-based gasification units being DGC – Dakota Gas Company in the U.S. and a few IGCC demonstration plants. The estimated growth in synthesis gas production from coal-based gasification is expected to exceed petroleum-based gasification. Gasification of biomass and renewable feedstocks are expected to grow, especially in Japan and Europe where governments offer tax incentives for these developments. Unfortunately economy of scale is difficult to achieve with biomass and renewable sources due to logistical problems and limited feedstock volumes.

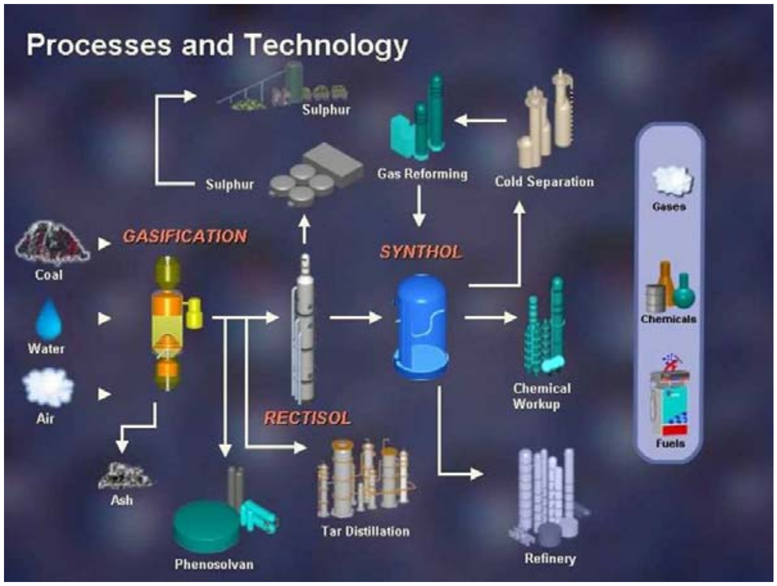
The production of chemicals is currently the dominant application for synthesis gas, followed by power generation, Fischer-Tropsch synthesis and gaseous fuels. The distinction between syngas for chemicals and syngas for Fischer-Tropsch products is not very clear, since a host of extremely valuable chemicals can be produced via the Fischer-Tropsch process, e.g. alpha olefins, alcohols, acids, solvents, etc. As mentioned before, power generation is the fastest growing application [1] for gasification derived gas. Power can also be co-generated from synthetic fuel or chemical plants using, for example un-converted tail gas.

3. THE SASOL PROCESS

The Sasol process starts with the Gasification plant where coal is converted to crude gas under pressure and at high temperature in the presence of steam and oxygen. Condensates from subsequent cooling of the gas yield co-products such as tar and oils. Other co-products such as nitrogenous compounds, sulphur and phenolic compounds are recovered as ammonia, sulphur, cresols and phenols respectively [3].

The purified synthesis feed gas is made available for conversion into long chain hydrocarbons with the Sasol Advanced Synthol (SAS) or Sasol Slurry Phase Fischer Tropsch proprietary technologies (Figure 1) [3].

FIGURE 1
THE SASOL PROCESS



3.1 High-temperature Fischer-Tropsch conversion [3]

After purification, synthesis feed gas is sent to the SAS reactors where hydrogen and carbon monoxide react under pressure in the presence of a fluidized, iron-based catalyst at moderate temperature to yield a broad spectrum of hydrocarbons in the C_1 – C_{15} range. This process is primarily used to produce liquid fuels, although Sasol extracts a number of valuable chemicals, for example alpha olefins, from the crude synthetic oil.

Oxygenates in the aqueous stream from the SAS process are separated and purified in the chemical work-up plant to produce alcohols, acetic acid and ketones including acetone, methyl ethyl ketone (MEK) and methyl iso butyl ketone (MIBK).

3.2 Low-temperature Fischer-Tropsch conversion [3]

An alternative use for the synthesis feed gas from gasification or reformed natural gas, is the low-temperature Sasol Slurry Phase Fischer Tropsch technology, which was developed by Sasol Technology (PTY) LTD. In this process, which Sasol uses at the Sasolburg site in South Africa, the synthesis feed gas is reacted at a lower temperature than is the case in the SAS reactors. Linear-chained hydrocarbon waxes and paraffins are produced. Apart from hard wax, candle wax and specialty Fischer Tropsch (FT) waxes, high-quality diesel can also be produced in this process. The wax can be hydrocracked to a high quality sulphur free diesel product.

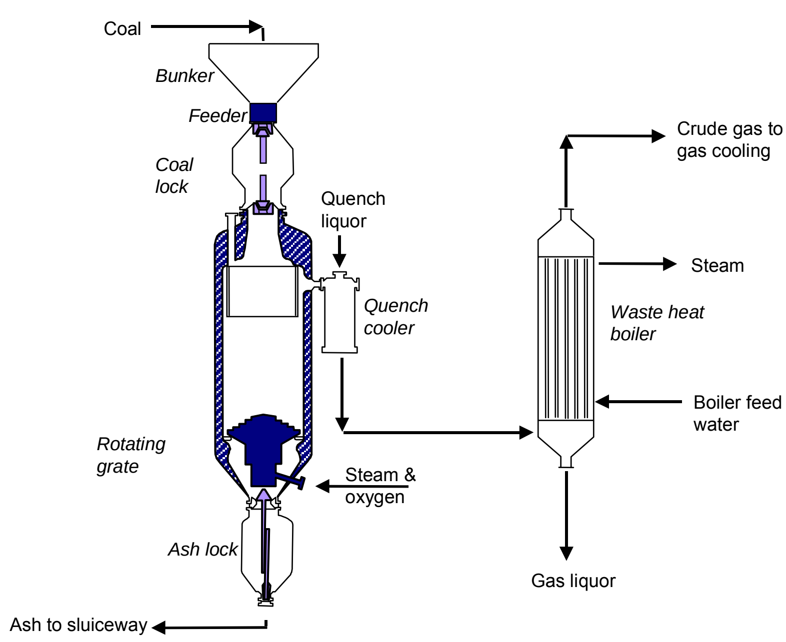
Lighter hydrocarbons are hydro-treated to produce pure kerosene or paraffin fractions. Ammonia is also produced and is sold as such or is utilized downstream to produce explosives and fertilizers.

4. SASOL-LURGI FIXED BED DRY BOTTOM GASIFICATION

The Sasol-Lurgi process is a medium temperature and pressure process suitable for a large variety of coal feedstock. Coal as primary feedstock is gasified at a typical pressure of 30 bar in the presence of steam and oxygen as gasification agents to produce a gas suitable for a variety of applications ranging from (1) the production of Town Gas, typically employed in urban and industrial heating networks; (2) the production of Substitute Natural Gas (SNG) used to supplement low natural gas supplies and (3) the generation of electricity by means of an Integrated Gasification Combined Cycle (IGCC). At Sasol's Secunda operations the synthetic gas produced from coal is processed by means of a High Temperature Fischer-Tropsch (HTFT) process utilizing the Sasol Advanced Synthol proprietary technology, to produce fuel in the petrol and diesel range for automotive use, as well as chemicals.

This gasifiers are sometimes also referred to as fixed bed gasifiers, although moving bed is probably more correct since the coal bed moves downwards under gravity. Two modes of operation are possible, i.e. the ash can be removed in a dry state or as a molten slag. The Sasol-Lurgi fixed bed dry bottom gasifiers are commercially proven for pressurised application, and these gasifiers are known to be very reliable and tolerant to changes in feedstock quality. The Sasol plants in South Africa produce a total volume of 3.2 million m^3_n/hr of pure synthesis gas from a total number of 97 gasifiers. DGC – Dakota Gas Company in the U.S. operates 14 similar gasifiers, and there is a small plant in the Czech Republic owned by SUV/EGT. At the Schwarze Pumpe site in the former East Germany, 7 fixed bed Lurgi gasifiers are utilized for treatment of solid wastes, such as plastics, sewage sludge, rubber, contaminated wood, paint residues household wastes [2]. There are also 7 Sasol-Lurgi gasifiers operated in China (Shanxi and Yima). The Sasol-Lurgi gasifier technology produces approximately 28% of the total amount of synthesis gas produced worldwide [1]. Figure 2 shows a typical Lurgi fixed bed gasifier.

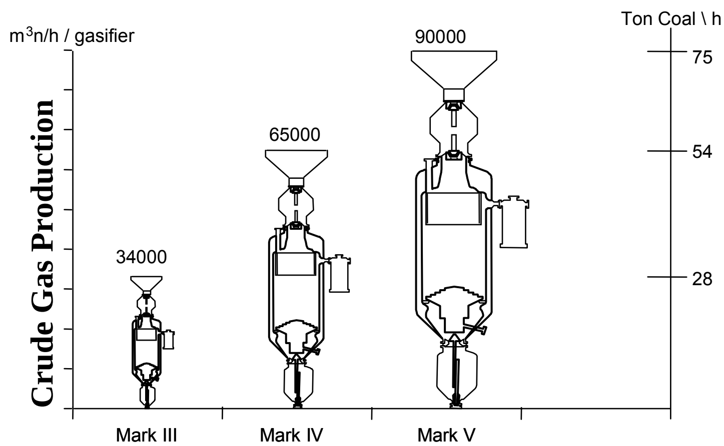
FIGURE 2
THE SASOL-LURGI GASIFICATION SYSTEM



At both Sasolburg and Secunda, all synthesis gas is currently produced from coal using the Sasol-Lurgi Fixed Bed Dry Bottom (FBDB) gasifiers. High ash content and high ash melting point coal is used to produce a high H_2/CO syngas to satisfy the high demand for hydrogen in Fischer-Tropsch synthesis.

Sasol One was originally equipped with ten Mark III gasifiers with an internal diameter of 3,66 m. Three gasifiers of similar design were added in 1966. In 1978 three Mark IV gasifiers, scaled up 55% above original design, were installed and a Mark V (114% scaled up above original) in 1980 (Figure 3) [3].

FIGURE 3
MAJOR DIMENSIONS OF GASIFIERS



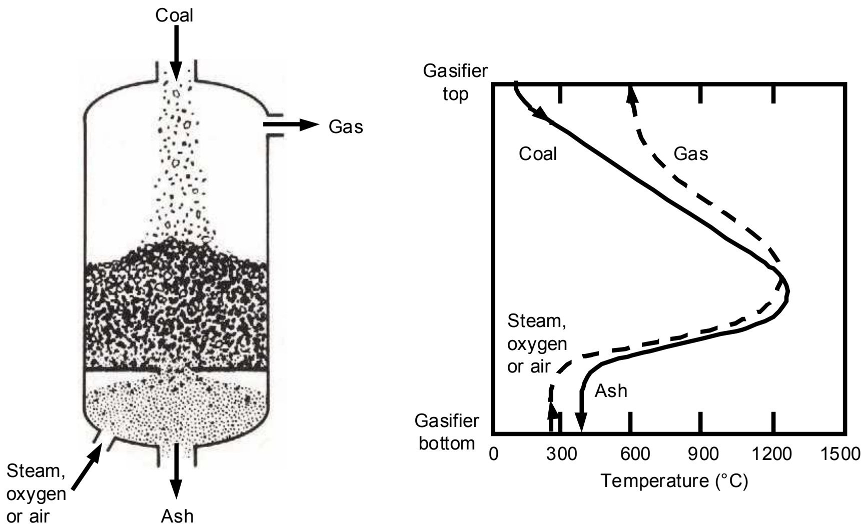
Sasol currently operates 83 Mark IV gasifiers of which Sasol Two and Three each have 40 units. These units can truly be seen as the “work horses” of syngas production from coal at Sasol. The demand for synthesis gas at Sasol increased steadily over the years, resulting in continuous pressure to increase production rates of individual units.

These processes are all linked together in an overall process scheme. The most important achievement of Sasol in this field is that gas from coal is produced on a mega scale, continuously improving on the output of the plants and achieving high mechanical availability of equipment. This could only be achieved through the technical break-throughs in each of the component plants in the overall flow scheme.

Hydrogen is an essential element required for the production of fuels, chemicals and ammonium based fertilizers from coal. For example: hydrogen plays a key role in the mechanism of converting syngas to hydrocarbon products via FT synthesis. The specifications for a typical FT syngas require a hydrogen to carbon monoxide ratio 1.8-2 to 1. Ammonia synthesis feedgas requires a hydrogen to nitrogen ratio of 3.0 to 1. Hydrogen is also a key component of Sasol’s hydrogen rich pipeline gas (48% by volume) [3]. The dry raw gas composition is an important factor to consider when selecting a particular technology, especially with regards to downstream process requirements.

Within the gasifier bed, different reaction zones (Figure 4) are distinguishable from top to bottom, namely the drying zone where moisture is released, the devolatilization zone where pyrolysis takes place, the reduction zone where mainly the endothermic reactions occur, the exothermic oxidation or combustion zone, and the ash bed at the bottom. Due to the counter-current mode of operation, hot ash exchanges heat with cold incoming agent (steam and oxygen or air), while at the same time hot raw gas exchanges heat with cold incoming coal. This results in the ash and raw gas leaving the gasifier at relatively low temperatures compared to other types of gasifiers, which improves the thermal efficiency and lowers the steam consumption.

FIGURE 4
MOVING OR FIXED BED GASIFIER [9]



The chemistry of gasification is extremely complex. The topic is widely covered in the open literature, and a complete review will not be attempted here. The most important reactions relevant to the gasification process are similar to those of gas reforming, and the processes of gasification and reforming therefore have a lot in common. Both take place at relatively high temperatures (approximately 1000°C or more), which is a result of the exothermic combustion (oxidation) reactions which are required to drive the endothermic reduction reactions. The basic gasification reactions are the following:

Oxidation:

$C + ½ O_2$	→	CO	ΔH = -123 kJ/mol
$C + O_2$	→	CO_2	ΔH = -406 kJ/mol
$H_2 + O_2$	→	H_2O	ΔH = -248 kJ/mol

Reduction:

$C + CO_2$	→	$2 CO$	ΔH = 160 kJ/mol
$C + H_2O$	→	$CO + H_2$	ΔH = 119 kJ/mol

Water-gas shift:

$CO + H_2O$	→	$CO_2 + H_2$	ΔH = -40 kJ/mol

Methane formation:

$C + 2 H_2$	→	CH_4	ΔH = -87 kJ/mol
$CO + 3H_2$	→	$CH_4 + H_2O$	ΔH = -206 kJ/mol
$3C + 2H_2O$	→	$CH_4 + 2 CO$	ΔH = 182 kJ/mol

Cracking:

$C_nH_m \rightarrow (m/4)\, CH_4 + (n\text{-}m/4)\, C$

Hydrogenation:

$C_nH_m + (2n – m/2)\, H_2 \rightarrow n\, CH_4$

In addition to the reactions above, the coal goes through the stages of drying and pyrolysis as soon as it is exposed to heat. Pyrolysis reaction chemistry is complex, and involves free radical reaction mechanisms in addition to the cracking and hydrogenation reactions. In most gasification processes the pyrolysis reactions are not of much importance since the pyrolysis products are an any event destroyed, but in the Lurgi fixed bed gasification processes, which is the technology of choice for the Sasol process, pyrolysis products like tars, pitches, phenols, etc. are valuable byproducts from the gasification process. The important process parameters affecting pyrolysis product yields are coal petrographic composition, particle size, heating rate, final temperature, pressure, and the composition of the gaseous atmosphere within which pyrolysis occurs. The nett heat of reaction of pyrolysis can be positive, negative, or thermally neutral, depending on the maceral and mineral composition.

In almost all gasifiers the water-gas shift reaction proceeds fast to very near chemical equilibrium conditions. It is thus fairly easy to calculate approximate raw gas compositions for most gasifiers from general thermodynamic principles. Most importantly is the effect of gasifier choice and operating conditions on the H_2/CO ratio of the synthesis gas, and this issue will be discussed further in the next section. The water-gas shift reaction is however only mildly exothermic, and therefore the H_2/CO ratio has a very small effect on the heating value of the synthesis gas.

The Sasol-Lurgi FBDB gasification process is a viable process for the conversion of low-grade high ash content, high ash melting point coals to high value products. Such coals are abundant in many countries, including China and India. As these countries develop, energy demand growth will require that the low-grade coal resources be exploited. The coal from the sources used by Sasol varies in terms of chemical and physical properties and this directly relates to gasifier behaviour. The ability of fixed bed gasifiers to handle a variety of different feedstocks is seen as a significant advantage. At the Schwarze Pumpe site in the former East Germany, 7 fixed bed dry bottom Lurgi gasifiers are utilized for treatment of solid wastes, such as plastics, sewage sludge, rubber, contaminated wood, paint residues and household wastes [2]. Other distinct characteristics of fixed bed gasifiers are the following:

- It uses lump coal and limited grinding is required. Coal used for fixed bed gasification is mined, crushed down to <100mm and screened at a bottom size of 5-8mm.
- Coal with a high ash content can be gasified without severe losses in thermal efficiency, since the ash is not extracted in the molten state.
- High “cold gas” thermal efficiency is achieved through counter-current operation, which allows the gas and solid product streams to exit at relatively low temperatures.
- Low oxidant requirements due to the high thermal efficiency.
- Valuable co-products like tars, pitches, oils and chemicals are produced.
- A H_2/CO ratio of 1.7 to 2.0 is produced directly which is suitable for Fischer-Tropsch synthesis without the need for additional water-gas shift conversion to adjust the H_2/CO ratio, and this holds a cost advantage.

5. COAL MINING AT SASOL

The coal used by Sasol for Sasol-Lurgi Fixed Bed Dry Bottom gasification in South Africa has a low rank, is inertinite rich, and has properties which may vary significantly from one mine to the next.

Sasol Mining (Pty) Ltd. is responsible for coal mining in the Sasolburg and Secunda regions and supplies coal to Sasol’s synthetic fuels and chemical plants. The division operates regional operations comprising the Sigma Colliery and Wonderwater strip mining operations at Sasolburg and the Secunda Collieries, which consist of six underground operations.

The combined run-of-mine output from the Sasolburg and Secunda operations increased from a total production of ±20 million tons in the ten year period 1954 – 1964, to almost 51.6 million tons per annum in 2002.

During the 2002 financial year, the company supplied 45.7 million tons of saleable coal from the 51.6 million tons of coal extracted to the operations of Sasol Synfuels (SSF) at Secunda and Sasol Infrachem (SCI) at Sasolburg. The company commenced its coal export operations at Secunda during the 1997 financial year and produced 3.5 million tons of export quality coal, which was exported mainly to Europe, during the 2002 financial year (Tabel 1) [8].

TABLE 1
SASOL MINING (Pty) Ltd. PRODUCTION HIGHLIGHTS [4]

Production (millions of tons)	2001	2002
Total production	51.3	51.6
Sigma Colliery including Wonderwater	5.4	5.9
Secunda Collieries:		
Bosjesspruit Colliery	7.3	7.3
Brandspruit Colliery	8.5	8.3
Middelbult Colliery	8.2	8.1
Twistdraai Colliery	5.5	5.2
Twistdraai Export Colliery	7.4	8.1
Syferfontein (underground and strip) Colliery	9.0	8.7
Saleable production from all mines	49.5	49.5
International sales	3.6	3.5

6. COAL CHARACTERISTICS AND THE EFFECT ON SASOL-LURGI FIXED BED GASIFICATION PERFORMANCE

Coal is generally accepted to be the most heterogeneous natural resource and coal properties can vary extensively between geographical sites and even within the same regional location. Accordingly, coal properties will to a large extent determine the configuration of the gasification flow scheme, equipment and requirements for auxiliary process units i.e. oxygen and steam supply. It is therefore critically important to gain an accurate and fundamental understanding of the properties and expected behavior of the targeted coal feedstock in order to (1) prepare a suitable conceptual flow scheme and (2) to maximize the eventual probability of success in any proposed gasification venture and (3) to optimize the operation and profitability of existing plants and (4) effectively address the environmental aspects.

New coal sources and areas under exploration for utilization in Sasol-Lurgi Fixed Bed Dry Bottom gasification are characterized in detail and the results compared with historical data in order to determine the suitability of a coal source for gasification purposes. Benchmark data, obtained when it was possible to operate the gasifier without problems and with relatively high stability, is used as a reference. Sasol has an extensive data base for the coal and gasification characteristics of a large number of coal sources, both local and foreign.

The coal characteristics that will be discussed below are not the only properties affecting gasifier performance and stability, but are those properties that are measurable on laboratory scale and are easily related to gasifier performance. Interpretation of these results gives an indication of expected gasifier performance, and also the suitability of a specific coal source for Sasol-Lurgi fixed bed gasification. Interpretation of standard coal analyses and uniquely developed laboratory tests, together with previous experience gained by Sasol over the past 50 years, have put Sasol in a position to identify suitable coal sources for a Sasol-Lurgi fixed bed dry bottom gasification process.

6.1 Proximate analysis

Ash content gives an indication of the amount of inorganic material in the coal from a source and includes mineral matter *in-situ* in the coal structure, as well as out-of-seam inorganic contamination. The measurement of ash content is used by Sasol Mining as blending parameter. Other properties of coal given by a proximate analysis are volatile matter, moisture content and fixed carbon content. The amount of fixed carbon in coal is directly related to the amount of syngas produced. Volatile matter gives an indication of the amount of liquid hydrocarbons that can be produced during gasification.

6.2 CO_2 reactivity

CO_2 reactivity is determined in order to get an indication of the expected rate of the gasification reactions. Reactivity is expressed as a mass loss per time at 50% burn-off under a CO_2 atmosphere.

The reactivity of coal from the various sources used by Sasol varies between 2-5 hr^{-1}, although coal sources with lower and higher reactivities have been gasified successfully in the past. Some of the non South-African coal sources tested for gasification purposes have showed reactivities of as low as 0.5 hr^{-1} and also as high as 9 hr^{-1}. However, it is uncertain what the lower limit for reactivity is below which the gasification reactions will become too slow for complete conversion.

6.3 Particle size distribution

Particle size distributions of coal blends are determined in order to estimate or predict which size distributions are more likely to cause unstable operation due to pressure drop effects. Pressure drop problems manifest themselves in a variety of ways, and include grate traction loss (due to bed fluidization), channel burning (leading to unacceptable gas outlet temperatures) and solids elutriation (carry-over). Probably the best known estimation method for pressure drop is the Ergun equation, which gives pressure drop as a function of bed voidage ε, viscosity μ, fluid density ρ, superficial velocity U_s and particle diameter d_p [5]:

$$\frac{\Delta P}{L} = 150\ \frac{(1-\varepsilon)^2 \mu U_s}{\varepsilon^3 d_p^2} + 1.75\ \frac{(1-\varepsilon) p U_s^2}{\varepsilon^3 d_p} \qquad \ldots(1)$$

When dealing with particle size distributions instead of uniformly sized particles, the particle size d_p has to be replaced by $\phi \overline{d_p}$, where ϕ is the particle sphericity and $\overline{d_p}$ the average particle size reflecting the mean surface area (also referred to as the Sauter mean diameter). The Sauter diameter of a coal sample with a specific particle size distribution is calculated as follows:

$$\overline{d}_p = \frac{1}{\sum_i \left(\frac{x_i}{d_{p,i}} \right)} \qquad \ldots(2)$$

where i = screen number
x_i = fraction (mass %) on screen i
$d_{p,i}$ = diameter (mm) of screen i

Experience has shown that $\overline{d_p}$ is a useful parameter for predicting which PSD's are more likely to result in gasifier instability. Extensive research on the effect of coal types and PSD on pressure drop and how the data fit the Ergun equation have been conducted, but will not be reported here. The value of $\overline{d_p}$ is extremely sensitive to the smaller particle sizes, or the so-called "tail" of the PSD.

6.4 Thermal fragmentation

It is known that when lump coal from certain origins (e.g. South-African low rank inertinite rich coals) is exposed to high temperatures (above 600°C), it will tend to undergo fragmentation (primary and secondary fragmentation)[6]. Primary fragmentation occurs during devolatilization, while secondary fragmentation occurs during combustion of the char by burnout of carbon bridges connecting parts of the particle. In the case of fixed bed gasification, fine material formed in the gasifier may lead to the same kind of hydrodynamic problems as was described previously.

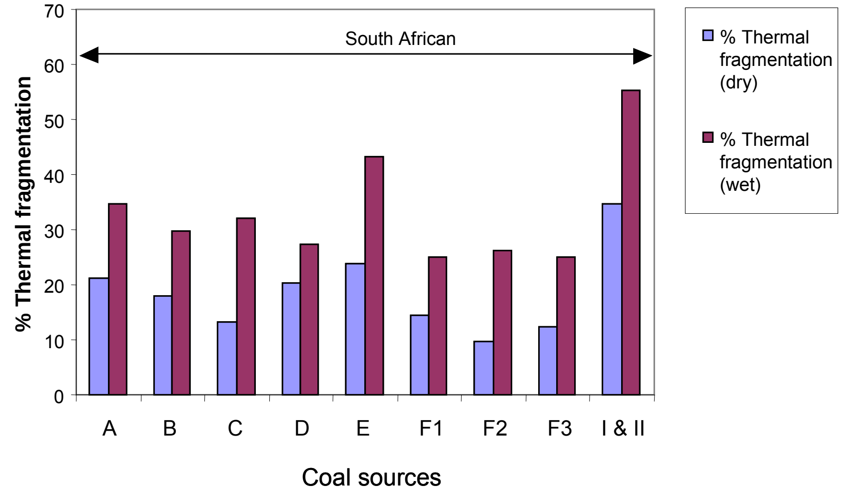
Thermal fragmentation of coal is measured by placing a sample with a specific predetermined size distribution into a pre-heated muffle oven at 100°C under atmospheric pressure [8]. The coal is then heated to 700°C. After the sample is cooled under nitrogen and screened again, the change in size distribution is calculated. The percentage thermal fragmentation of coal is given as a percentage decrease in Sauter diameter. The smaller the percentage decrease, the better the thermal stability.

Thermal fragmentation is defined as:

$$\%\, Thermal\ \ fragmentation = \frac{\overline{d}_p\, before\, test - \overline{d}_p\, after\ test}{\overline{d}_p\, before\, test} x100 \qquad \ldots(3)$$

As illustrated in Figure 4, weathering / oxidation and moisture content affect the thermal fragmentation of coal sources. An extensive study revealed that the effect of moisture contributes to ±75% of the thermal fragmentation of coal [6]. This is not only surface moisture, but a combination of surface moisture and inherent moisture captured within the pores and the coal structure. Although moisture contributes significantly towards fragmentation, it is also affected by a complex interaction with other factors.

FIGURE 4
THERMAL FRAGMENTATION OF COAL SOURCES (effect of moisture and weathering)



6.5 Caking

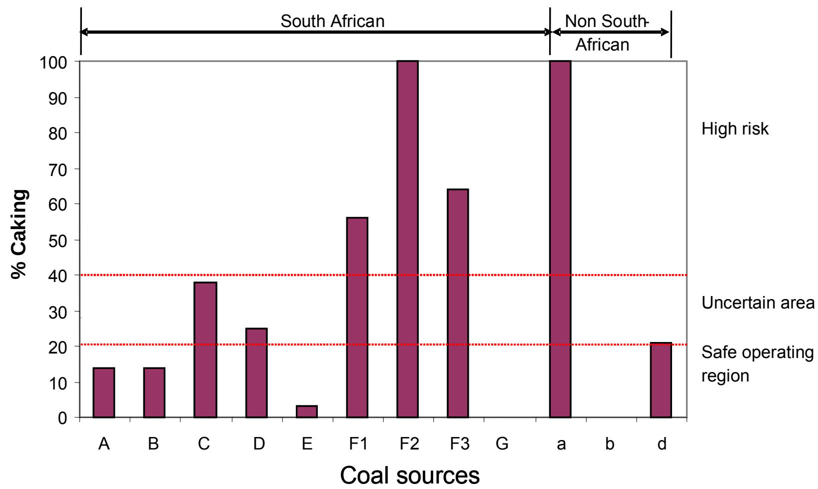
Caking of coal particles can be described as the softening or plasticity property of coal, which causes particles to melt or sinter together to form larger particles when heated. Caking of coal within the gasifier can cause pressure drop fluctuations and channel burning, resulting in unstable gasifier operation.

The caking propensity of coal is determined by pyrolizing a coal sample with a specific predetermined size distribution in an inert atmosphere at the typical gasifier pressure. The sample is screened afterwards and the increase (if any) in particle size determined. This test is unique and was developed in-house by Sasol for characterizing coal under pressure and temperature conditions similar to those prevail within the gasifier.

Pressure significantly influences the caking propensity of coal. Coal with a medium to low caking propensity under pressure shows no caking at atmospheric conditions, and a highly caking coal will have a much lower caking propensity at atmospheric conditions than at 26 bar.

According to previous experience, coal from sources with a relatively high caking propensity resulted in unstable gasifier operation and are therefore mixed with other coal sources having a low caking propensity to obtain an acceptable blend. Normal blends used for gasification at Secunda have a caking propensity of ±20 % and coal blends used in the Sasolburg plant have no or a very little caking. The variation in caking properties between the different coal sources used for gasification in Secunda and Sasolburg, as well as non-South African coal sources tested, are given in Figure 5. It should be noted that coal sources with caking propensities as high as 100% can be gasified successfully with a suitable blending strategy.

FIGURE 5
CAKING PROPERTIES OF SASOL'S COAL SOURCES



6.6 Ash fusion temperatures and ash composition

The ash fusion temperature (AFT) of a coal source gives an indication to what extent ash agglomeration and ash clinkering is likely to occur within the gasifier. Ash clinkering inside the gasifier can cause channel burning, pressure drop problems and unstable gasifier operation.

The results of an AFT analysis consist of four temperatures, namely the initial deformation temperature, softening temperature, hemispherical temperature and flow temperature. Ideal gasifier operation is to operate at a temperature above the initial deformation temperature in order to obtain enough agglomeration to improve bed permeability, but to operate below the ash <u>melting</u> temperature to prevent excessive clinkering. Secunda and Sasolburg coal sources currently used for gasification have an ash melting temperature > 1350^{o}C and an initial deformation temperature of >1300^{o}C, but successful gasification in Sasol-Lurgi gasifiers is not limited to these temperatures.

6.7 Maximum theoretical pure gas yield

In order to calculate and to compare the maximum theoretical pure gas yield of different coal sources, a detailed experimental evaluation, together with thermodynamic modeling, is conducted on the coal to simulate the gasification process.

7. CONCLUSIONS

It is the view of the authors that fixed bed gasification technology has a bright future in the areas mentioned above and that the role of Sasol in the future application and commercialization of gasification technology globally, is unique. Not only does the company have valuable and unique operating experience gained over 50 years of successful operations, but has also been at the forefront of technological breakthroughs in optimizing and streamlining the technology. The unique skills of Sasol could however be complementary to those of other parties who share our view on the future of gasification and related technologies.

Preliminary studies have indicated that there are selected geographical regions in the world and also specifically in South Africa where the economic conversion of coal to liquid fuel and chemicals may be feasible. In such cases coal should be relatively inexpensive, and markets for the total spectrum of products should be available. Sasol, with its experience in gasification technology combined with GTL and other technologies, can play a leading role in such projects. The coal characteristics discussed in this paper are not the only properties affecting gasifier performance and stability, but are those properties that are measurable on laboratory scale and are easily related to gasifier performance. Interpretation of these results gives an indication of expected gasifier performance, and also the suitability of a specific coal source for Sasol-Lurgi fixed bed gasification. Interpretation of standard coal analyses and uniquely developed laboratory tests, together with previous experience gained by Sasol over the past 50 years, have put Sasol in a position to identify suitable coal sources for a Sasol-Lurgi fixed bed dry bottom gasification process.

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