Syngas Production from Coal

HIGHLIGHTS

- **PROCESS AND TECHNOLOGY STATUS -** Coal gasification – and virtually gasification of other carbon-based resources such as biomass or refinery residues - is a versatile conversion technology adding flexibility to the energy systems. In the gasification reactors, the feedstock is converted into a synthesis gas (syngas), a mixture of H_2, CO and CO_2, which enables the production a variety of downstream energy carriers. A large experience exists on coal gasification worldwide as the so-called town-gas was produced from coal as early as 1792, a high-temperature fluidized-bed gasifier was patented in 1921 by Winkler, and synfuels production from coal was common practice in Germany during world war II. According to the Gasification Technologies Council, in 2007, some 144 gasification plants and 427 gasifiers were in operation worldwide, adding up to an equivalent thermal capacity of 56 GW_{th}, of which coal gasification accounted for approximately 31 GW_{th}.
- **PERFORMANCE & COSTS -** Performance and costs of coal gasification plants depend largely on the plant design and on the final production objectives. A gasification system that is part of an integrated chemical plant producing methanol, ammonia and electricity differs substantially from a system whose only purpose is feeding an IGCC plant with carbon capture and storage (CCS). Coal quality is also very important for coal gasification output. The overnight capital cost of coal gasification plants is given per GJ of syngas output and ranges from $13/GJ for bituminous coal to $17.2/GJ for sub-bituminous coal (US$ 2005). Similarly, the syngas production cost decreases with increasing coal quality and ranges from $15.6/GJ to $19.3/GJ. The production cost is dominated by the investment cost. However, costs may significantly depend on location. Chinese plants may cost 60%-65% of the US and European installations. Syngas may be further upgraded to meet specific demands. Co-production of a 20% of H_2 using a H_2 separation unit is only slightly more costly than the basic process, resulting in 5% higher capital and 4% higher product costs. The conversion into synthetic natural gas (SNG), i.e. pipeline quality gas, requires additional processes and costs. If the syngas is converted into SNG, the capital cost increases by approximately 25% and the cost of the final product increases by 40%, while the conversion efficiency of the process decreases by some 14 percentage points, reaching about 60%.
- **POTENTIAL & BARRIERS –** There is a huge potential for coal gasification worldwide, as the technology allows fuels production for many applications such as transport, chemicals, heat and power production. High natural gas prices and limited availability at regional level are driving factors for investments in coal gasification. Based upon planned projects, the Gasification Technologies Council, a non-profit organization promoting technological advances and surveying the market, does expect further market growth to reach a global equivalent thermal capacity of 73 GW_{th} by 2010. Other projections indicate up to 155 GW_{th} by 2014. Most of the growth will materialize in Africa and Middle East (64%), Asia and Australia (27%), compared with only 9% in Europe and almost no investment in America. Marketable products from new gasification plants include Fischer-Tropsch (F-T) liquids (69%), chemicals (22%) and power (9%). However, because of the need to mitigate GHG emissions and climate change, these market projections appear realistic only if CCS technology will be made available.

PROCESS AND TECHNOLOGY STATUS – Gasification of coal - as well as gasification of other carbon-based resources such as biomass or oil residues - is a versatile conversion technology that adds flexibility to the energy systems. In a gasification reactor the feedstock is transformed into a synthesis gas (syngas), basically a mixture of H_2, CO and CO_2, which opens up to making a variety of downstream energy carriers. The syngas may be used as a fuel in integrated gasification combined cycles (IGCC, see ETSAP TB E01) or as a feedstock for producing H_2 or a synthetic natural gas (SNG). Depending on the CO to H_2 ratio, which can be adjusted using catalysts, the gas can also be used as a feedstock for a number of chemical processes, including Fischer-Tropsch synthesis (see ETSAP TB S02), conversion into CH_4 (methanation), methanol and ammonia production. The multiple production of fuels, chemicals and electricity from coal gasification is defined as poly-generation. Coal gasification in IGCC plants holds the potential for easy capture of CO_2 from the syngas and for CO_2 storage in geological formations (CCS).

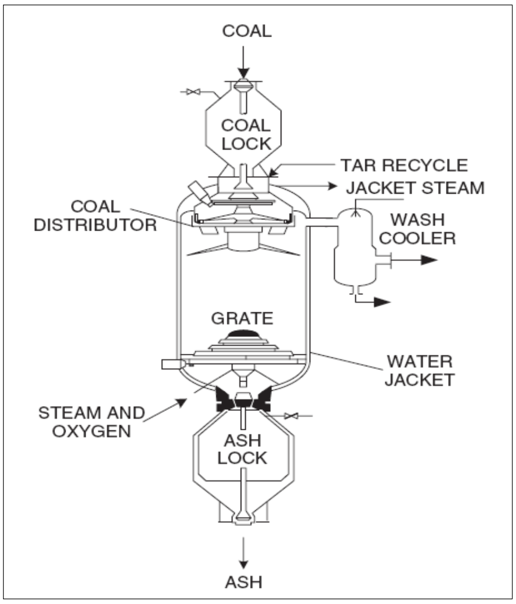

Fig. 1 - Moving Bed Gasifier concept

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Gasification takes place under oxygen shortage. Coal is first heated in a closed reaction chamber where it undergoes a pyrolysis process at temperatures above 400°C. During pyrolysis, hydrogen-rich volatile matter is released, along with tar, phenols, and gaseous hydrocarbons. Then, char is gasified, with the release of gases, tar vapours and solid residues. The dominant reactions consist of partial oxidation of char, which produces a syngas with high fractions of H_2 and CO. The process takes place at temperatures between 800°C and 1800°C. Specific operating conditions depend on coal type, on properties of the resulting ash, and on the gasification technology.

The most important variable in a gasification process is the oxidant. It can be either air (with its nitrogen component) or pure oxygen if the process includes an air separation unit (ASU) for oxygen production. The use of oxygen instead of air facilitates the partial combustion of coal, but involves higher investment costs due to costly additional equipment. As gasification takes place under stoichiometric shortage of oxygen, the reaction mechanism in the gasification chamber has to be adjusted with appropriate energy balance. The direct partial oxidation of carbon to CO, for instance, is strongly exothermic, leading to high release of energy in form of sensible heat. However, steam gasification of coal, (forming both CO and H_2) is strongly endothermic. As a consequence, a steam/oxygen mixture is commonly used. In the gasification practice, the basic equipment can be grouped in three main categories: moving-bed gasifiers, fluidized-bed gasifiers, and entrained-flow gasifiers. [1]

■ **Moving-Bed Gasifier** (Figure 1) - Sometimes called fixed-bed gasifier, this is the oldest gasification device in use. Lurgi developed an atmospheric reactor in 1927 and a pressurized version in 1931. It is characterized by a reaction bed where coal moves slowly downward under gravity and it is gasified by a blast (in general) in counter-flow to coal. An important feature of the Lurgi dry bottom gasifier is the low consumption of oxygen and the high steam demand. Moving-bed gasifiers need graded coal in the range 6–50 mm. Highly caking coals cannot be processed in moving-bed gasifiers. Mildly caking coals require the assistance of a stirrer in order to avoid pasting-up of the bed. Tars and other oxygenated compounds are produced as by-products. An advanced variant of the original Lurgi pressure gasifier has been developed jointly by British Gas and Lurgi during the 1950s and 1960s. The British Gas/Lurgi (BGL) **slagging gasifier** incorporates a molten slag bath. The much lower steam and somewhat lower oxygen consumption of the slagging gasifier results in much higher syngas production per unit of coal intake and much lower yield of pyrolysis products compared with the dry bottom unit. Further, the CO_2 content of the gas is lower and the methane content is halved.

■ **Fluidized Bed Gasifier** (Fig. 2) – This device offers the advantage of promoting excellent mass and heat transfer due to the intensive mixing. On the other hand, individual particles have widely varying residence time in the bed volume. Therefore, unreacted carbon particles are inevitably removed from the bed along with fully reacted particles (ash). The best existing fluidized bed devices offer a carbon conversion of 97%. In comparison, both moving-beds and entrained-flow processes offer carbon conversions of 99%.

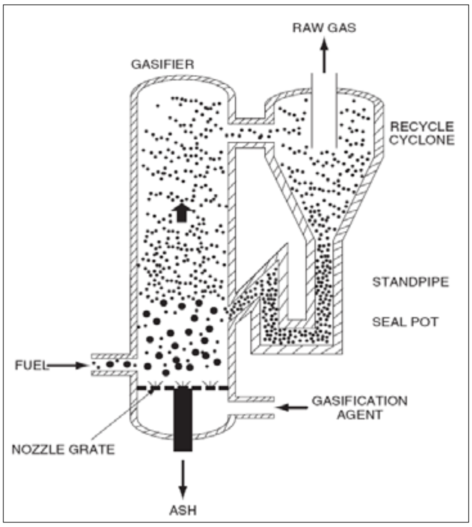

Fig. 2 – Fluidized Bed Gasifier concept

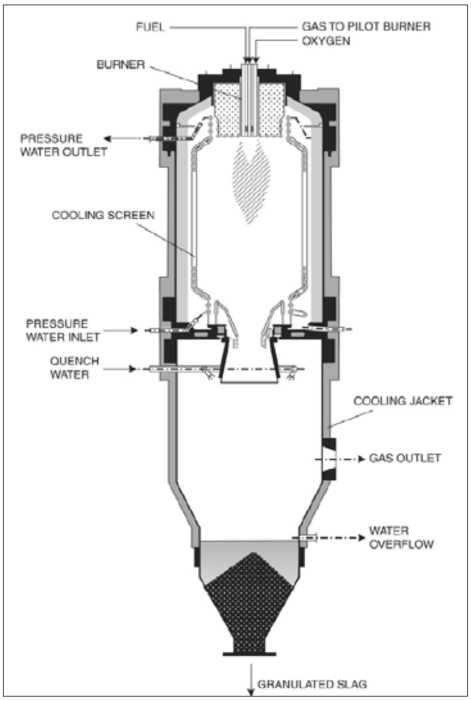

Fig. 3 – Entrained Flow Gasifier concept

[1] Manufacturers of gasification reactors:
a) Moving-bed reactor: Lurgi and Sasol-Lurgi (dry bottom), British Gas Lurgi (BGL) (slagging)
b) Fluidized-bed reactor: High Temperature Winkler (HTW) process (earlier Rheinbraun, now RWE), HRL Ltd. Australia, Bharat Heavy Electricals Limited (BHEL),
c) Entrained reactor: Koppers-Totzek, Shell Coal Gasification Process (SCGP), Prenflo, Siemens, GE Energy,E-Gas, Mitsubishi Heavy Industries (MHI), Eagle

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■ **Entrained Flow Gasifier** (Figure 3) - The advantage of the entrained flow gasifiers is the ability to handle any coal feedstock and produce a clean, tar-free gas. Additionally, the ash is produced in the form of inert slag or frit. This is achieved with the penalty of additional effort in coal preparation and high oxygen consumption, especially in the case of coal-water slurries or coals with a high moisture or ash content. The majority of the coal gasification processes that have been developed after 1950 are based on entrained-flow, slagging gasifiers operating at pressures of 20 to 70 bar and at high temperature (≥1400°C). Entrained-flow gasifiers have become the technology of choice for hard coals, and have been selected for the majority of commercial-sized IGCC plants.

There is a large experience with coal gasification covering several decades: town gas was manufactured from coal as early as 1792; the first process to produce methanol from syngas was installed in 1913 (BASF); an improved high temperature fluidised bed gasifier was patented 1921 by Winkler; during world war II, Germany produced large amounts of synthetic fuels from coal. According to the Gasification Technologies Council, in 2007 there were 144 gasification plants and 427 gasifiers in operation worldwide, adding up to an equivalent thermal capacity of some 56 GW_{th}. Coal gasification accounted for approximately 31 GW_{th}, with the remaining gasification plants running on petroleum, gas, petcoke, biomass and waste feedstock (NETL, 2007). A large part of the world's coal-based syngas is produced in 97 gasifiers of Sasol's plants in South Africa: in 2008, an estimated conversion capacity of 14 GW_{th} enabled the conversion of some 43 Mt/y of coal into 7,4 Mt/y of transport fuels and chemicals (Sasol, 2008). Most of the remaining coal-based syngas produced in other regions of the world is used for ammonia or methanol production, and, in China, for the production of town-gas. China has become the global test case for large-scale coal conversion activities. In 2008, China held licenses from Shell for the installation of 18 coal gasification plants; among these, 11 commercial size coal gasification plants were already in operation, most of them for the industrial production of methanol or ammonia. Plans for the installation of further large-scale coal conversion plants include one direct liquefaction and five Fischer-Tropsch (FT) plants for liquid fuel production. While syngas is the primary product of the gasification plants, marketable products obtained from syngas include chemicals (45%), FT liquid fuels (28%), gaseous fuels (8%), and electric power (19%). Among other products, gaseous fuels include synthetic natural gas (SNG). In the IGCC power plant of Great Plains in the US, the syngas is used to produce SNG (NETL, 2007]).

While coal gasification is a commercial technology, research aims to further increase product yields, reduce consumption of catalysts and energy, and lower capital and operation costs. In IGCC plants with CCS, reducing the energy input to produce oxygen represents an essential research area.

PERFORMANCE & COSTS – Performance and costs of coal gasifiers depend largely on the plant design and on final production objectives. A gasifier that is part of an integrated chemical plant for methanol and ammonia production, with cogeneration of electricity, has completely different characteristics from a gasifier producing feedstock for an IGCC plant with CCS. Depending on the type of gasifier and on desired syngas composition, the energy conversion efficiency of the gasification process may range from 70% to 80%. As far as cost is concerned, overnight investment costs of the gasification plants depend on geographical location as a number of components can be manufactured locally. A study regarding IGCC costs indicates a 0.65 China ''location'' factor vs. the US overnight investment cost. Similarly, Shell China typically applies a location factor of 0.60 to the European costs of gasification projects, on the basis of its own detailed evaluations of local Chinese manufacturing and construction costs (Larson, 2003).

Coal gasification performance and costs have been explored in various studies. Table 1 draws on detailed engineering and cost studies of coal gasification plants for two locations in the US (NETL 401, 2007). These plants with oxygen blown BGL slagging moving-bed gasifiers have basically identical design, but use different coal qualities as feedstock: Illinois No.6 bituminous and Wyodak Powder River Basin sub-bituminous. Both plants are commercial-size installations that produce syngas from a feed of some 930-1.030 t/d cola (802-1180 GJ/h), with no CO_2 capture. The two examples demonstrate that the influence of coal quality on the output is very significant. The overnight capital cost is \$13.5/GJ for bituminous coal, compared to \$17.2/GJ for sub-bituminous coal. The syngas production cost is likewise lower for the higher quality coal, i.e., \$15.6/GJ vs. \$19.3/GJ.

Syngas may be further upgraded to meet specific demands. Co-production of a 20% H_2 using H_2 separation devices is only slightly more costly, resulting in 5% higher capital and 4% higher product costs. The conversion into SNG, i.e. pipeline quality gas, requires additional processes and considerable costs: the capital

Table 1 - Performance and Costs of Syngas Production from Different Coal Quality

Performance		Illinois #6bitum.	Wyodak sub-bitum.
Gasif. capacity, output	MWt_h	310	207
Syngas production (HHV)	GJ/h	1005	671
Coal feed	GJ/h	1180	802
Net efficiency	%	74.7	72.8
Costs (US $2005)			
Tot. plant cost		118.7	101.3
Specific capital cost	$/GJ	13.5	17.2
O&M cost			
Fixed O&M cost	Mill.$/y	6.0	5.8
Var. O&M cost, output	$/GJ	1.4	1.6
Coal cost, input	$/GJ	1.3	0.9
Production cost	$/GJ	15.6	19.3

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cost increases by approximately 25% and the production cost by 40%, while the conversion efficiency decreases by over 14% percentage points (NETL 401, 2007). The application of CCS technologies increases the capital cost. For example, in a coal gasification plant for H_2 production, the devices for CO_2 drying and compression account for 5% of total investment cost. At the same time, the overall efficiency decreases by around 3% points (IEA, 2005).

POTENTIAL & BARRIERS – There is a huge potential for coal gasification worldwide, as the technology enables production of fuels and feedstock for many applications such as transport, chemicals production, heat and power generation. As coal is the most abundant fossil resource available on earth and even low-grade coal can be used for gasification, the technology is of primary interest in many regions. Increasing gas prices and limited availability of natural gas in regional consumer markets are driving factors for investments in coal gasification technology. The Gasification Technologies Council, a non-profit organization promoting technological advances and surveying the market, expects a further growth in gasification to reach a global equivalent capacity of 73 GW_{th} by 2010 based upon planned projects. Experts forecast 155 GW_{th} by 2014 (Higman, 2008). Most of the growth will materialize in Africa and Middle East (64%), in Asia and Australia (27%), with 9% in Europe and no investments in America. Marketable products from new gasification plants include Fischer-Tropsch liquids (69%), chemicals (22%) and power (9%) (NETL, 2007). However, these market projections appear realistic only if the CCS technology is used in gasification plants to mitigate the CO_2 and other GHG emissions. As a matter of fact, coal gasification technology enables easy CO_2 capture and separation, with limited additional components and costs. Today's typical cost of CCS in power plants may range from $ 30 to 90/tCO_2. The cost includes capture $ 20-80/t; transport $ 1-10/t per 100 km; storage and monitoring $ 2-10/t. Coal gasification in IGCC plants enables significant reduction of the capture cost, the most important component of the CCS cost. (IEA, 2006)

Table 2 – Summary Table: Key Data and Figures for Coal Gasification Technology

Technical Performance	Typical current international values and ranges		
Ranges refer to different coal qualities: 20.700 - 27.300 kJ/kg HHV			
Coal Gasification System: ASU, oxygen blown fixed-bed BGL 1000 gasifier, acid gas removal (Rectisol), sulphuric acid plant			
System Output	Syngas	Syngas/H_2	SNG
H_2 production system		Pressure swing adsorption (Rectisol)	
SNG production system			Water gas shift reactor, methanation reactor
Gasification capacity, output, MWth	210 -310	210 - 310	170 - 260
Coal input, GJ/h	800 - 1.200	800 - 1.200	800 - 1.200
Output – main product, GJ/h HHV	Syngas: 670 – 1.000	Syngas: 560 - 810, H_2: 110 - 190	SNG:560 - 840
Output – By-product H_2SO_4, kg/h	120 - 1.350	120 - 1.350	120 - 1.350
Efficiency, thermal %	73 -75	73 -75	60
Construction time, yr	4	4	4
Technical lifetime, yr	20	20	20
Load factor and availability, %	90	90	90
Environmental data			
CO_2 emissions, kt/$PJ_{total\ output}$	55	55	78
CH_4 emissions, kt/$PJ_{total\ output}$	0.0061	0.0061	0.0061
N_2O emissions, kt/$PJ_{total\ output}$	0 (only marginal emissions depending on the nitrogen content of the coal)	0 (only marginal emissions depending on the nitrogen content of the coal)	0 (only marginal emissions depending on the nitrogen content of the coal)
Reduction of CO_2 emissions if CCS is applied, %	up to 99%	up to 99%	up to 99%
Costs (US $_{2005}$)			
Capital cost, $/GJ output	17,2 - 13,5	18,3 - 14,1	27,2 - 20,1
Fixed O&M, $/GJ output	1,0 - 0,7	0,7 - 1,0	1,6 - 0,8
Variable O&M cost, $/GJ output	1,6 -1,4	1,6 - 1,4	2,1 - 1,9
Coal cost, $/GJ input	1,3 - 0,9	1,3 - 0,9	1,3 - 0,9
CO_2 capture and compression, $/t CO_2	20 - 80	20 - 80	20 - 80
Transport and storage of captured CO_2, $/t CO_2	6 - 20	6 - 20	6 - 20

Data Projections	2020	2030	2050	2020	2030	2050	2020	2030	2050
Efficiency, thermal %	76 - 78	78 - 80	80 - 82	76 - 78	78 - 80	80 - 82	63 - 64	65 - 66	67 - 68
Capital cost, $/GJ output	16,2 - 12,5	15,7 - 12,0	15,2 - 11,5	17,3 - 13,1	16,8 - 12,6	16,3 - 12,1	25,2 - 18,1	24,2 - 17,1	23,7 - 16,6

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