ADVANCED CLEAN COAL TECHNOLOGY FOR POWER GENERATION-AN OPPORTUNITY FOR COAL REVITALIZATION

MIRO R. SUSTA
IMTE AG POWER CONSULTING ENGINEERS, SWITZERLAND
WWW.IMTEAG.COM

INTRODUCTION

Most of the coal fuelled power plants which are currently in operation as well as majority of US plants which are in planning, design or construction stage employ traditional pulverized coal burning technology.

Besides relatively low-priced electric power generation, these plants produce tremendous amounts of health-threatening toxins and climate-changing carbon dioxide (CO_2).

Controls can be installed to reduce many of these pollutants. However, even the most modern pulverized coal plants still produce thousands of tons of CO, SO_2 and NOx each year.

Up to the date, billions of dollars in federal subsidies have been and continue to be sunk into developing "clean coal" alternatives to traditional pulverized coal-burning power plants.

Currently, among others, the two following clean-coal technologies, the Pressurized Fluidized Bed Combustion (PFBC) and the Integrated Gasification Combined Cycle (IGCC) are well considered for advanced utilization of coal for clean power generation. While the IGCC has great potential, it must still clear a number of technical and economic hurdles to become fully competitive to pulverized coal power generation technology.

On a worldwide basis, the prospect for Advanced Clean Coal Technology (ACCT) for power generation is extremely good, especially in rapidly developing Asian markets as well as in both Americas.

PFBC and IGCC will realize power generation with respectable thermal efficiencies and competitive prices within this decade. Both, PFBC and IGCC represent a unique partnership between coal gasification and the most efficient Combined Cycle Gas Turbine (CCGT) cycle.

The gasification, which utilizes coal, residual heavy oils and other low value feedstock's in the cleanest possible way, is not new.

Converting coal to combustible gas has been practiced commercially since early 19^{th} century. The first gas producing companies were chartered in England in 1812 and in USA in 1816 to produce gas mainly for domestic and streets lighting.

The gas was produced by the coal heating or pyrolysis, technology which is still in use as a by-product of the carbonization of coal to produce coke for metallurgical purposes.

Currently, coal is used to generate around 40% of the electricity worldwide and is projected to supply over 50% of power generation plants worldwide beyond 2015.

Wide application of gasification for power generation purposes was mainly delayed by its economics. Even today the installed IGCC kW-price is still around 20 - 30% higher comparing to conventional pulverized coal technology and more than 50-60% (up to 100%) in comparison with CCGT using natural gas (NG) fuel.

When linked with CCGT, IGCC is one of the few technologies which not only significantly increases efficiency of coal fired power plants but also has a beneficial environmental effect in reducing considerably CO_2 and other emissions.

Additionally, an IGCC power plant produces marketable by-products, rather than large volumes of solid wastes typical of scrubber-equipped or fluidized bed combustion power plants using coal or petroleum-based heavy fuels.

The present experience in USA and Europe shows that coal based IGCC power plant technology is ever closer approaching strong commercial status.

Preliminary data from all demonstration projects confirm IGCC proponents' expectations of drastically reduced emission levels of criteria pollutants - such as SO_2, NOx, particulates and CO_2 - compared to pulverized coal plants.

As worldwide air emissions standards become stricter, the superior environmental performance of IGCC will take on added economic benefits due to the technology capability achieving greater emissions reductions at lower cost than other less advanced technologies.

COAL CONVERSION TO LIQUID AND GASEOUS FUELS

A number of processes have been developed for coal conversion to liquid or gaseous fuel. This conversion has a number of advantages. In a liquid or gaseous form, the fuel may be easier to transport, and additionally the conversion process removes a number of impurities from the coal.

In the process of liquefaction, solid coal is converted to a petroleum-like liquid that may be used as a fuel for motor vehicles and other applications.

The other conversion method is the gasification. In gasification, crushed coal is reacted with steam and either air or pure oxygen.

Converting coal to environmentally acceptable synthetic gaseous and liquid hydrocarbons would supplement the dwindling reserves of crude oil (oil) and NG as well as reduce dependence on these fuels, especially in the countries which have to import oil and NG.

Coal gasification yields a wide variety of products for power generation and industrial markets. Gas produced by coal gasification (syngas) may be upgraded to replace NG.

Coal liquidation, effected by hydrogenating coal at high temperature and pressure, yields low-ash, low-sulphur fuels for power generation, process heating and making high-grade fuels like gasoline.

Coal pyrolysis or thermal decomposition and the catalytic hydrogenation of CO are also sources of liquid fuels and chemical feedstock’s.

Both liquefaction and gasification are attractive technologies in the United States because of country's very large coal resources.

The following chart (Figure 1) shows simplified routes from coal to clean syngases and liquids.

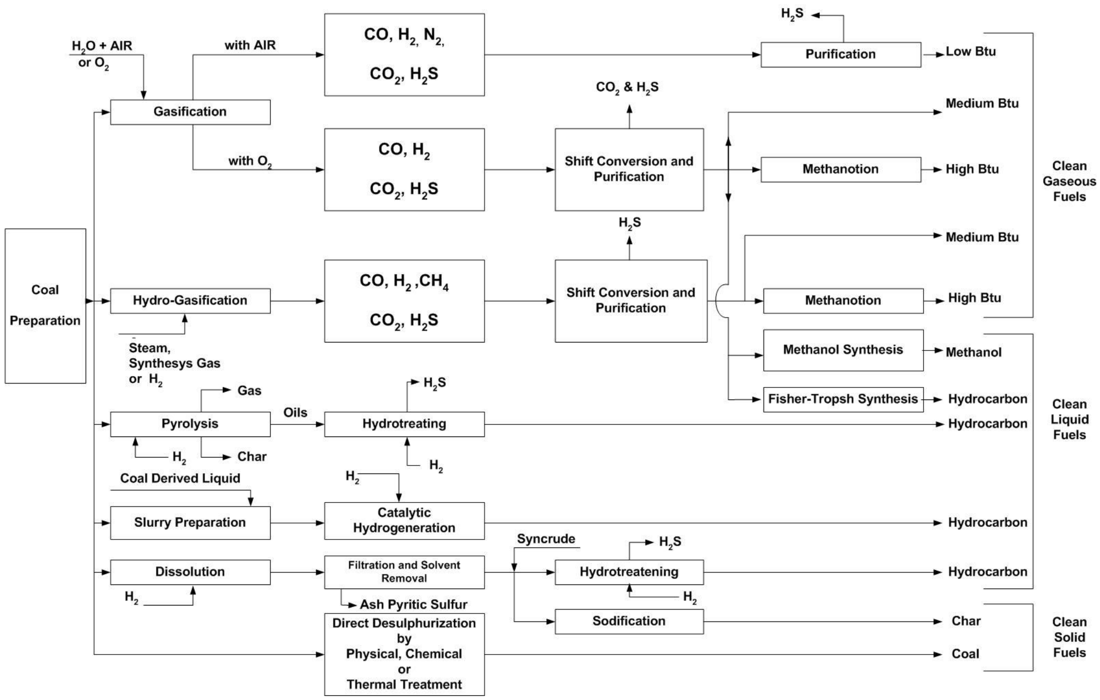


FIGURE 1 THE PRODUCTION OF CLEAN FUELS FROM COAL

Current development efforts are concentrating on technical and economical improvements in some of the coal conversion technologies toward seeking new ways to accomplish the most important result, the cheap and clean coal conversion processes.

COAL GASIFICATION

Coal-conversion technology dates back to 1670 when Reverend John Clayton of Yorkshire, England, reported generation of a luminous gas when coal was burned in a chemical retort. Converting coal to combustible gas has been practiced commercially since early 19th century. The first gas producing companies were chartered in England in 1812 and in USA in 1816.

In one of the first coal gasification process, the gas generator (producer) in which a downward-moving bed of coal is reacted with air and steam, was extensively used during early days of gas production, around 180 years ago.

This process delivered a syngas with relatively low energy content (calorific value) of around 3.0 – 6.0MJ/m^3 (80.5 – 161.0 btu/cuft).

The cyclic water-gas process which was developed around 1875 permitted the continuous, higher quality, gas production with calorific value in the range of 11.0 and 13.0 MJ/m^3 (295.0 – 345.0 btu/cuft).

By adding oil to the gas generator, the gas calorific value was increased to 18.0 – 21MJ/m^3 (383.0 – 564.0 btu/cuft).

This gas, called as "carburated water gas", was for example in commercial and residential use in USA until 1940, when it was replaced by cheaper high quality NG.

At the same time the development of oxygen-based coal gasification was initiated in USA and Europe. For example an early oxygen-based coal gasification process developed by Lurgi, Germany, which operated at elevated pressure is still in successful commercial use.

In general, coal can be considered a hydrogen-deficient hydrocarbon with a hydrogen-to-carbon ratio near 0.8, as compared with a liquid hydrocarbons ratio near 2 and a gaseous hydrocarbons ratio near 4. For this reason, any process used to convert coal to alternative fuels must add hydrogen (either directly or in the form of water or steam).

The chemistry of coal gasification is based on several well-known solid-gas and gas-phase reactions. First is the combustion of coal (carbon) and pure oxygen (or oxygen contained in the air), which is highly exothermic.

$$C + O_2 \rightarrow CO_2 \quad (1)$$

This reaction (solid-gas), the combustion, supplies most of the thermal energy necessary for gasification process (around 60%).

As hydrogen (H_2) and CO are produced by the solid-gas gasification reaction, these gases react with each other and with carbon.

$$C + 2H_2 \rightarrow CH_4 \quad (2)$$

This reaction is also exothermic and contributes heat energy for the gasification process (10-15%).

The conversion of carbon to combustible gases is pure endothermic reaction which is driven by heat from above listed exothermic reactions.

$$C + H_2O \rightarrow CO_2 + H_2 \quad (3)$$
$$C + CO_2 \rightarrow 2CO \quad (4)$$

As the H_2 and CO is produced by the gasification reaction, these gases react with each other and with carbon. The reaction of H_2 and carbon is shown in Formula (1). Both gas-phase reactions, the water-gas-shift:-

$$CO + H_2O \rightarrow H_2 + CO_2 \quad (5)$$

and the methanation

$$CO + 3H_2 \rightarrow CH_4 + H_2O \quad (6)$$

are also contributing heat energy to gasification process (water-gas-shift around 1% and methanation around 38-40%).

However, it is not possible to calculate the exact gas composition by using above listed reactions (1) – (6), but it is possible to utilize these reactions and their relationship with each other for predicting the effects of changes in the gasification operating parameters.

A great coal gasification deal depends on the gasifier system, coal reactivity and particle size as well as method of contacting coal with gaseous reactants (steam/air/oxygen). The coal properties required for successful gasification vary significantly from those required for conventional combustion. Accurate measurement of a coal's reactivity under gasification conditions plays a large role in both gasifier design and the assessment of coal for use in a particular gasifier.

The rate of reaction determines the time required for conversion of the coal and therefore gasifier volume, char recycle system capacity requirements, final syngas composition as well as oxygen and steam requirements.

Most important part of coal gasification process is the coal gasifier itself. The fundamental chemistry and physics of gasification motivate the design improvement of existing and advanced gasifiers.

Above listed reactions show that the contacting a solid particle (the coal) with gaseous reactant (steam/air/oxygen) is absolutely necessary for gasification process, and that the transfer of heat within the gasifier is one of most critical parameters.

Gasifier temperature and pressure together with the type of coal and coal composition have a strong influence on produced gas composition and applicability of various gasification systems. Three main types of coal gasifiers are shown in the following Figure 2, 3 and 4.

MOVING BED GASIFIER

This type of gasifier was one of the earliest used. It requires coal particle size between 2 and 50mm (0.08 – 2 in). The gaseous reactants are introduced at the bottom of the gasifiers (where also the ashes leave). The coal is fed and the produced gas is extracted at the top of the gasifier.

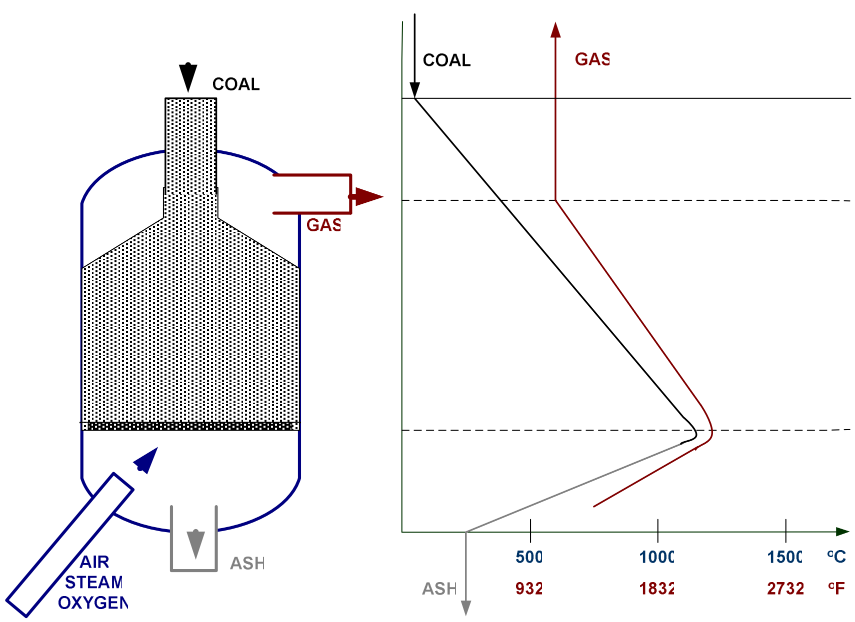


FIGURE 2 MOVING BED GASIFIER

The most advanced moving bed gasifier is the **Lurgi coal gasifier** in which the dry ash coal gasification takes place in a double shelled pressure gasifier (25 - 30 bar → 360 – 345 psi) with steam oxygen mixture.

In gas purification process ammonia and phenol are removed. Coal (lignite) graded 10 - 30mm (0.4 – 1.2 in) enters the top of the gasifier through a lock hopper and moves down through the bed.

Steam and oxygen enter at the bottom and react with the coal as the gases move up the bed.

Ash is removed at the bottom of the gasifier by a rotating grate and lock hopper. The countercurrent operation results in a temperature drop in the reactor.

Temperatures in the combustion zone, near the bottom of the gasifier, are in the range of 1,100℃ (2,000℉), whereas gas temperatures in the drying and depolarization zone, near the top, are approximately 260 - 540℃ (500 – 1,000℉).

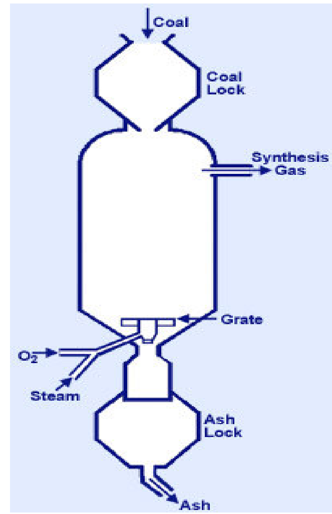


FIGURE 2
MOVING BED GASIFIER

The raw gas is quenched with recycle water to condense tar. A water jacket cools the gasifier vessel and generates part of the steam to the gasifier.

The thermal efficiency of the gasifier is high but since it produces the tars and oils, the gas clean up is more complex, and the gasifier cannot handle fines in the feed.

The British Gas Lurgi gasifier which is similar to the original Lurgi in many respects, however, recycles the tars and oils separated from the gas to the gasifier by introducing these components in to the bottom section of the gasifier along with fines.

FLUIDIZED BED GASIFIER

Fluidized bed gasifiers convert coal into a combustible gas that can be fired in a boiler, gas turbine or other energy load. In a fluidized bed gasifier, the bed material can either be sand or char, or combination of both. The fluidizing medium is usually air; however, oxygen and/or steam are also used.

The large thermal capacity of inert bed material plus the intense mixing associated with the fluid-bed enable this system to handle a much greater quantity and, normally, a much lower quality of coal. Worldwide experience with fluidized bed gasifiers has indicated the ability to utilize coals with up to 55% moisture and ash contents in excess of 25%.

Because the operating temperatures are lower in a fluid-bed than in other gasifiers the potential for slagging and ash fusion at high temperatures is reduced, thereby increasing the ability to utilize high slagging fuels.

The commercial coal gasification with oxygen and steam began with the use of fluidized bed gasifier developed by Winkler in 1922.

The coal for use in fluid-bed gasifier shall be ground to size around 8mm (0.3 in). In contrast to moving bed reactor, the coal is essentially a completely mixed with oxidants in fluid-bed gasifier. The gaseous reactants are injected at two levels of the gasifiers, the ash ashes leave at the bottom, the coal is fed from the lower side and the produced gas is extracted at the top of the gasifier.

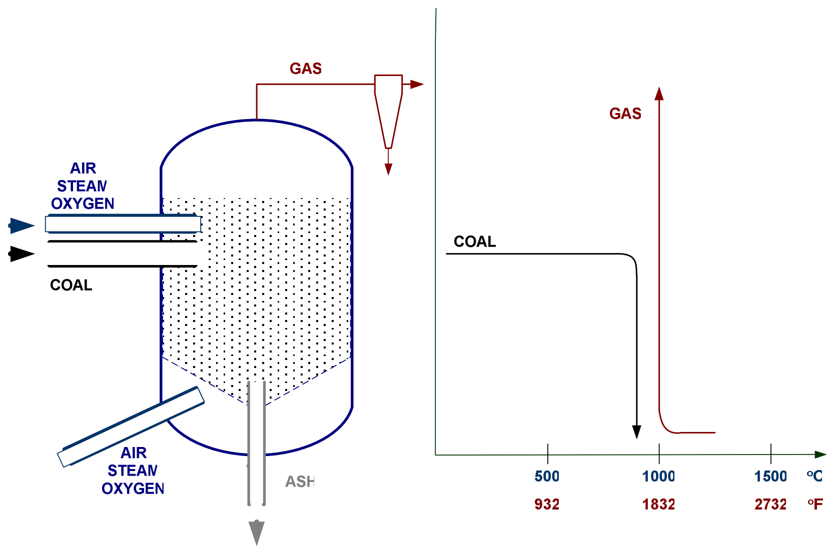


FIGURE 3 FLUIDIZED BED GASIFIER

Kellog-Rust-Westinghouse is using an air-blown fluidized-bed gasification technology. Gasification takes place by mixing steam and air (or O_2) with the coal at a high temperature.

The coal crushed to below 7mm (0.27 in) and the oxydants enter the bottom of the gasifier through concentric high velocity jets, which assure thorough mixing of the fuel with oxidant and the bed of char and limestone that collects in the gasifier.

Upon entering the gasifier, the coal immediately releases its volatile matter, which burns rapidly, supplying the endothermic heat of reaction for gasification.

The combusted volatiles form a series of large bubbles that rise up the center of the gasifier, causing the char and sorbent in the bed to move down the sides of the reactor and back into the central jet.

The recycling of solids cools the jet and efficiently transfers heat to the bed material. Steam, which enters with the oxidant and through a multiplicity of jets in the conical section of the reactor, reacts with the char in the bed, converting it to fuel gas.

At the same time, the limestone sorbent, which has been calcined to CaO, reacts with H_2S released from the coal during gasification, forming CaS.

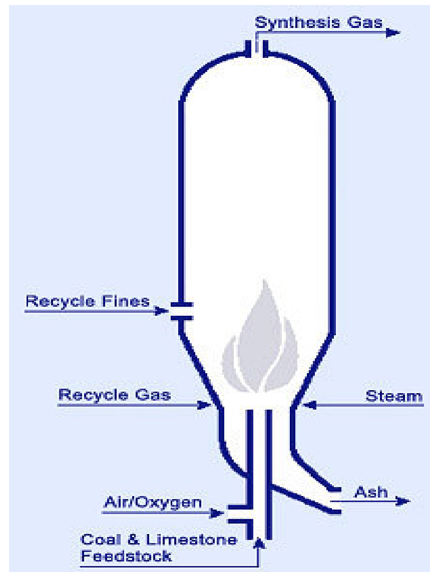
As the char reacts, the particles become enriched in ash. Repeated recycling of the ash-rich particles through the hot flame of the jet melts the low-melting components of the ash causing the ash particles to stick together.

These particles cool when they return to the bed, and this agglomeration permits the efficient conversion of even small particles of coal in the feed. The velocity of gases in the reactor is selected to maintain most of the particles in the bed.

The smaller particles that are carried out of the gasifier are recaptured in a high efficiency cyclone and returned to the conical section of the gasifier, where they again pass again through the jet flame.

Eventually, most of the smaller particles agglomerate as they become richer in ash and gravitate to the bottom of the gasifier.

Since the ash and spent sorbent particles are substantially denser than the coal feed, they settle to the bottom of the gasifier, where they are cooled by a counter-flowing stream of recycled gas.



This both cools and classifies the material; sending lighter particles containing char back up into the gasifier jet.

The char, ash, and spent sorbent from the bottom of the gasifier flow to the fluid-bed sulphator, where both char and calcium sulphide are oxidized.

The CaS forms $CaSO_4$, which is chemically inert and can be disposed of in a landfill. Most of the spent sorbent from the gasifier contains unreacted CaO. Sulphur released from burning residual char in the sulphator is also converted to $CaSO_4$

ENTRAINED FLOW GASIFIER

Entrained flow is the most aggressive form of gasification, with the pulverised coal (<0.1mm → < 0.004 in) at short residence times. The process is co-current with coal particles entrained in turbulent reactant gases.

High reaction intensity is provided by a high pressure (20-30 bar → 290-435 psi), high temperature (up to 1,500℃ → 2,730℉) environment. Extremely turbulent flow sees the coal particles experience significant back-mixing, and residence times are measured in seconds.

Entrained flow gasification is specifically designed for low reactivity coals and high coal throughput. Single pass carbon conversions are in the range of 95-99%.

To experience smooth operation, the gasifier temperature must lie above the coal AFT Ash Fusion Temperature), which lower the melting temperature of the coal mineral matter, must be used. A number of system constraints impose an economic limit on gasification temperature at 1,400–1,500℃ (2,552-2,730℉).

Because of the short reaction time, coal particles are very rapidly de-volatilized and lose any inherent char particles of the fed coal.

All types of coal can be handled in entrained bed gasifiers. The high operating temperature effectively gasifies all hydrocarbons and tars which may be formed during gasification process. This reduces gas purification and water-condensate handling problems.

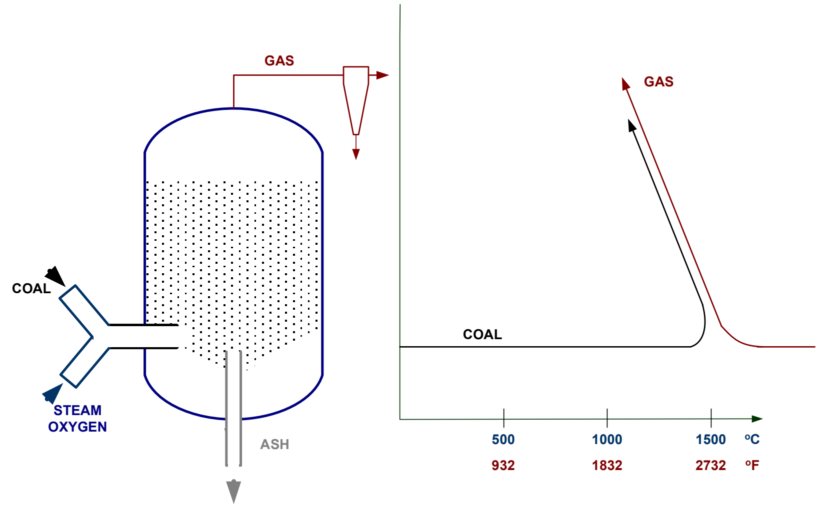
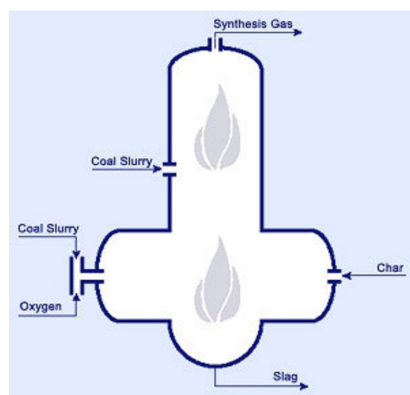


FIGURE 4 ENTRAINED FLOW GASIFIER

The entrained flow gasifier offers many advantages including the ability to handle wide variety of coals.

The E-GAS (Conoco Phillips) coal gasifier is a typical slurry-feed pressurized up flow entrained slogging gasifier whose two-stage operation makes it unique.



Wet crushers produce coal slurries. About 80% of the total slurry feed, combined with 95% pure O_2, is injected into the first (bottom) stage of the gasifier.

The highly exothermic gasification/ oxidation reactions take place rapidly at temperatures of 1,300 – 1,430ºC (2,370 – 2,550ºF) and 28 bar (406 psi).

The coal ash is converted to molten slag which flows down through a tap hole. The hot raw gas from the first stage enters the second (top) stage which is a vertical cylinder perpendicular to the first stage.

In the second stage, the examining 25% coal slurry is injected in to the hot raw gas.

The endothermic gasification/devolatilization reactions in this stage reduce the gas temperature to about 1,040℃ (1,904ºF) and add some hydrocarbons to the product gas. Particulates are removed in a hot/dry filter and recycled to the gasifier.

The gas is water scrubbed to remove chlorides and passed through a catalyst that hydrolyzes COS into H_2S. H_2S is removed in the acid gas columns.

The 1,040°C (1,904ºF) hot gas leaving the gasifier is cooled in a fire-tube product gas cooler to 600°C (1,112ºF) generating saturated steam which is sent to the steam consumers and the "sweet" gas is then moisturized, preheated, and piped to the gas consumers or storage.

Other significant coal gasification technologies include TEXACO and SHELL Entrained Flow Gasifier, PRENFLO Entrained O_2 Blown Gasifier and KELLOG Transport Gasifier.

IGCC TECHNOLOGY

IGCC is an advanced technology that represents the cleanest of currently available coal technologies. It is increasingly important in the world energy market, where low-cost opportunity feedstocks such as low-quality coal and heavy residual oils are the fuels of choice. IGCC technology produces electricity while meeting strict environmental regulations.

IGCC, like PFBC technology, combines both gas turbines (GT) and steam turbines (ST) in combined cycle operation. Depending on the level of integration of the various processes, IGCC may in short term achieve 40 to 42% (8,530-8,125 Btu/kWh) and in long term up to 50% (6,825 Btu/kWh) efficiency. Using IGCC, approximately 60-70% of the power comes from the GT, compared with about 20% using PFBC.

The emission limits in an IGCC power plant versus a pulverized coal fueled facility are significantly lower than any other technology. Sulfur scrubbing is in excess of 98%, with 99.9% scrubbing levels already achieved. Particulates from the combustion of gas are almost non-existent. Virtually no metals or hazardous air products are emitted and instead are captured as inert slag or as small amounts of inert fly ash.

New technologies are offering 90% mercury (Hg) scrubbing efficiency and in practice virtually 100% Hg is actually recovered.

NOx emissions are also dramatically lower than those produced from a pulverized coal fired power plants. In a standard coal plant, limits of 25 ppm are common whereas a gasification power plant can meet limits of 15 ppm without scrubbing and can be reduced to below 5 ppm.

Since the syngas leaving the gasifier must be properly cleaned as per specific utilization requirements, the gas cleanup system (GCS) represents an important attribute of each gasification technology.

The minimum requirements in terms of cleaning of the syngas are:-

- ✓ Solids such as ash must not pass through a GT because they lead to erosion, so must be removed.
- ✓ Alkali metals in combination with sulphur will lead to severe corrosion and therefore have to be removed.

In order to avoid condensation of volatile compounds in the GT, the temperatures at which the particulates and the alkali metals are removed from the GT shall preferably lay below the minimum GT temperatures.

In the following the typical steps for GCS aim at particulates, sulphur (SOx) and NOx removal are listed.

- Particulate Removal → Combination of Cyclone Filters & Ceramic Candle Filters.
- SOx & NOx removal → Combination of steam/water washing and removing the sulphur compounds for recovery of sulphur as a saleable product.

The syngas is normally cooled to around 50-100℃ (122-212℉), so that it can be cleaned before being burned and fed to the gas turbine. This, so called cold gas cleanup system (CGCS), decreases overall plant efficiency and indirectly increases power plant specific thus operational costs.

The better alternative, the highly efficient hot gas cleanup system (HGCS) technology, which operates under high pressure and temperatures of 500 - 600℃ (930 – 1,100℃), is currently under advanced demonstration phase.

Typical IGCC plant using CGCS is shown in the following picture, Figure 5.

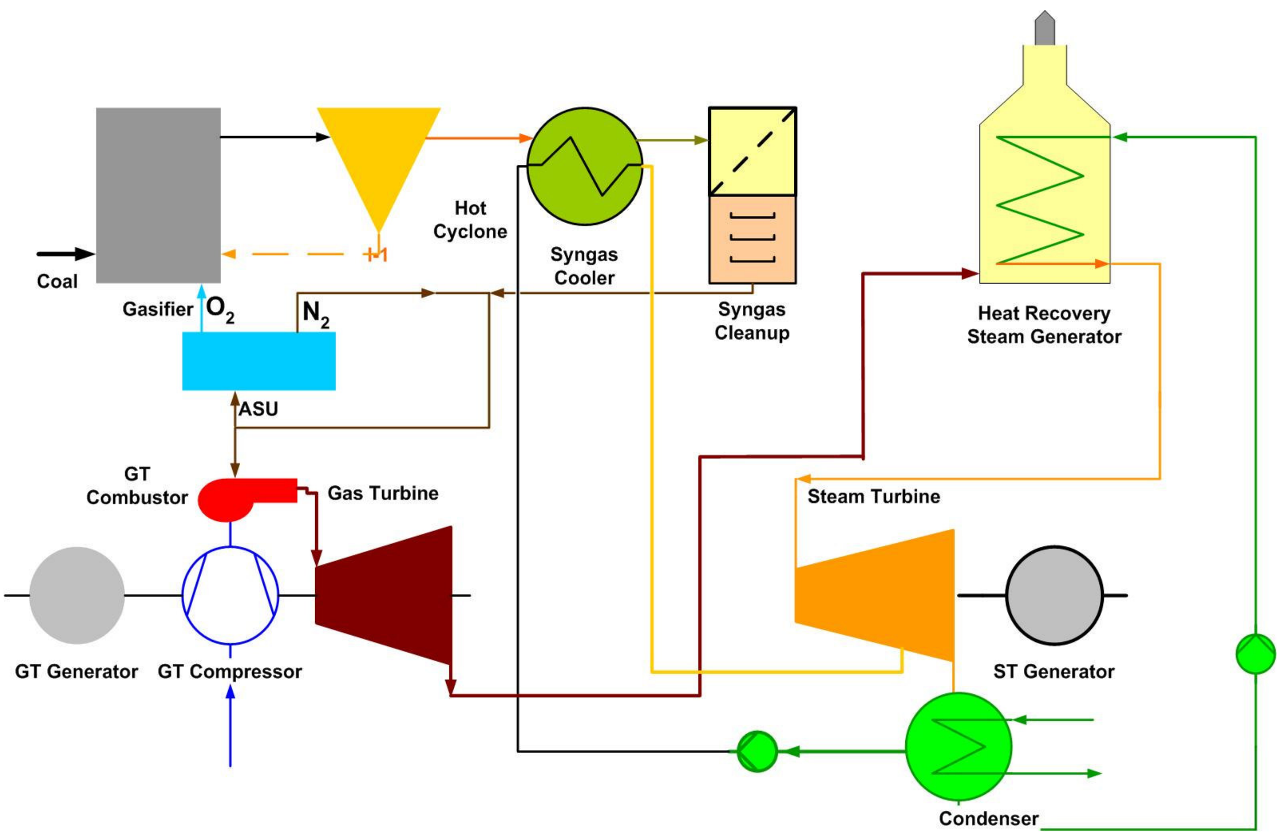


FIGURE 5 IGCC CYCLE

Each IGCC plant consists of three parts, the gasification, GT-gas burning & utilizing cycle and water-steam cycle.

Two of them, namely GT-gas burning & utilizing and water-steam cycle are analogical to the standard CCGT system working with NG.

Estimated costs of major IGCC components:

Coal Preparation (Coal Handling Equipment):	10%
Gasifier including Gas Treatment Equipment (cooling & cleaning):	40%
Power Generation (GT, ST & HRSG):	35%
Balance of Plant Equipment (Cooling, Ash Handling, Electrical):	15%

Specific Capital / Fuel Costs and NOx production comparison between miscellaneous power generation technologies is shown in the following Table 1.

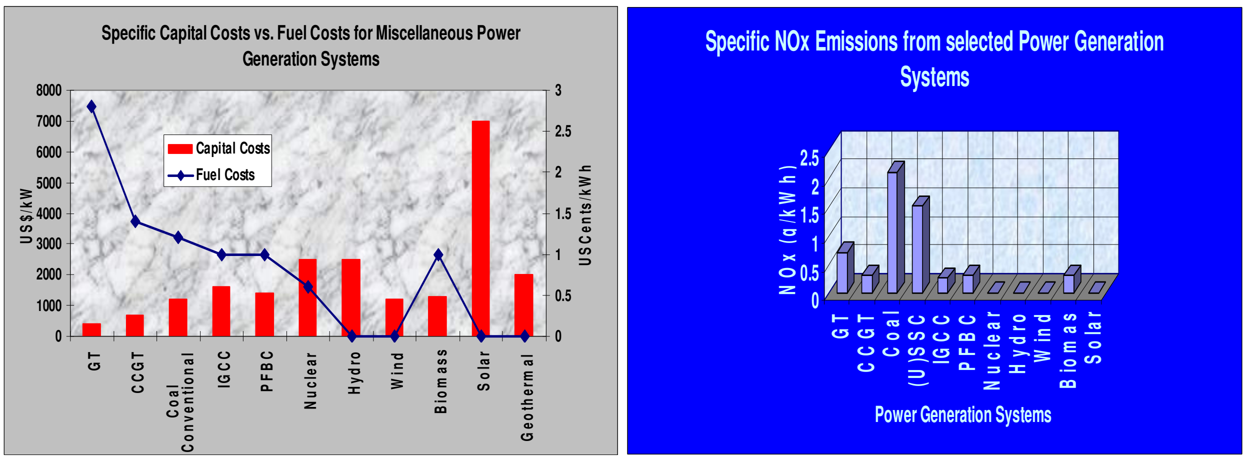


TABLE 1 IGCC POWER PLANTS VS. OTHER POWER GENERATION TECHNOLOGY

It is obvious that the IGCC technology is still more expensive, comparing with “classic” solid & gaseous fuels fired power plants (around 20-30% higher as pulverized coal fired power plants and up to 100% more expensive than NG CCGT power plants).

On the other side, IGCC can be considered much “cleaner than standard pulverized coal fired power plant. However, the expected larger difference between NG and coal price, which will follow the present NG price development, will make IGCC much more competitive.

REVIEW OF IGCC PROJECTS PROCESSING COAL AS THE MAIN FEEDSTOCK

The coal processing category of IGCC projects has just definitely overcome the demonstration stage of development and there are already many IGCC power plants either in operation or under construction.

The process of transferring the theory into practical commercial applications has proved to be difficult and still proves to be the main stumbling block behind their lack of widespread implementation. Globally, more than 110 sites with more than 380 gasifier units use coal based syngas to operate a variety of chemical manufacturing and refining processes. Around 15 worldwide locations produce power.

A brief technical and economical review of 12 selected IGCC power plants fueled with syngas from coal gasification process is given in Table 2 following by short plant description.

ID. No.	Project	Location	Gasification Technology	Fuel	Net Efficiency % (Btu/kWh)	Total Net Power Output MWe	Start of Commercial Operation	Capital Costs US$/kW
P1	SUV / EGT	Litvinov, Czech Republic	Lurgi	Lignite		350	1997	
P2	Elcogas SA	Puertollano Spain	Prenflo-O_2	High Ash Coal & Petcoke	42.7 (7,990)	288	1997	2,300
P3	Tampa Electric	Polk City USA	Chevron Texaco	Coal	33.0 (10,340)	250	1996	1,431
P4	PSI/ Destec	Wabash River USA*)	Conoco Phillip's E-GAS	Coal & Petcoke	39.7 (8,817)	260	1995	1,480
P5	Willem Alexander	Buggenum Netherlands	Shell	Coal	41.3 (8,262)	253	1994	1,890
P6	Lakeland Water/DOE	Lakeland USA	ACFBCC	Coal	45.0 (7,583)	260	2007	
P7	Steag Kellerman	Lunen	BGL	Coal	31.7 (10,764)	170	1969	
P8	LGTI	Plaquemine	E-GAS	Western Coal	36.0 (9,478)	160	1987	3,500
P9	SCE Cool Water	Cool Water USA	Texaco- O_2	Coal	31.2 (10,936)	100	1984	4,890
P10	Sierra Pacific	Pinon Pine USA	KRW-air	Lignite	39.0 (8,750)	99	1996	2,336
P11	Schwarze Pumpe	Cottbus Germany	Lurgi-O_2/BGL	Coal / Wastes		75	1995	
P12	Vresova	Vresova Czech Republic	HTW	Lignite		376	1996	

*) Wabash River is a repowering IGCC

TABLE 2 SELECTED IGCC POWER PLANTS

P1-SUV / EGT Power Plant

Owner SUV/EGT

Location Town of Litvinov, Czech Republic.

Gasification Technology Lurgi pressurized coal gasification.

Fuel Lignite

SUV/EGT, had been producing town gas (CO_2-25%, CO-15%, H_2-48%, CH_4-12% with LHV 14.5 kJ/kg) from lignite using 26 pressure gasification Lurgi reactors before this IGCC was commissioned.

P2-Puertollano Power Plant

Owner	Elcogas S.A, Spain, started commercial operation on syngas by the end of 1997.
Location	Pueratollano, Spain
Gasification Technology	Puertollano is the first project to use the PRENFLO gasification process, developed by Krupp-Koppers and Siemens/KWU.

Process parameters	Total Gross Power Output	317.7 MWe
	GT Power Output	182.3 MWe
	ST Power Output	135.4 MWe
	Auxiliary Consumption	39.0 MWe (12.3%)
	Total Net Power Output	287.7 MWe
	Gross Efficiency (LHV)	47.1% (7,244 Btu/kWh)
	Net Efficiency (LHV)	42.7% (7,991 Btu/kWh)

Design Emissions (6% O)	SO_2 → 138 t/year → 0.08 g/kW → 25 mg/Nm^3 NOx → 826 t/year → 0.40 g/kW → 150 mg/Nm^3 Particles → 41 t/year → 0.02 g/kW → 7.5 mg/Nm^3
Fuel	A mixture of ash-rich coal with petroleum coke from nearby refinery is used (50%/50%).
Gas Turbine	Siemens V94.3
Financing	Project was funded by CEC and by German Ministry of Research & Development. Investment cost was about 2,300 US$/kWe (IPP project without PPA).

Owing to the fact that Puertollano station is a single-train plant it can be considered as IGCC with the biggest output per train among all currently operating plants in the world.

At the same time it has the highest design efficiency among all IGCC plants in operation or under construction.

P3-Tampa Electric Power Plant

Owner	Tampa Electric Company, started commercial operation of this IGCC in locality of Polk Power Station in June 1996.
Location	Mulbery, Polk County, Florida, USA.
Gasification Technology	Texaco, Entrained Flow Gasifier.

Process Parameters	Total Gross Power Output	313.0 MWe
	GT Power Output	192.0 $MWe_{(GROSS)}$
	ST Power Output	121.0 $MWe_{(GROSS)}$
	Steam Pressure	165.0 bar (2320psi)
	Steam Temperature	540°C (1004 °F)
	Auxiliary Consumption	63.0 MWe (20%)
	Total Net Power Output	250.0 MWe

	Gross Efficiency	39.7% (8,600Btu/kWh)
Fuel	Coal→Illinois #6, Pittsburgh #8, Kentucky #11, and Kentucky #9; 2.5%-3.5% S	
GT	GE MS 7001F(A)	
Power Production	12.5 Mio MWh (Status July 2006)	
Investment cost	448 Millions US$ (50% of this cost was subsidized by the US Department of Energy-DOE).	
Financing	DOE	

The Tampa Electric IGCC project conducted at Polk Power Station in Florida, USA, has successfully demonstrated the commercial application of Texaco coal gasification in conjunction with electric power generation.

The gasifier operated more than 29,000 hours and processed coal at a rate of 2,300 tons/day, while the combustion turbine operated over 28,000 hours to produce over 8.6 million MWh of electricity on syngas.

Carbon burnout exceeds 95%, and emissions of SO_2, NO_x, and particulates are well below the regulatory limits set for the Polk plant site.

Along with other IGCC demonstrations in the CCT Program, the Polk Plant is one of the cleanest coal-based power generation facilities in the world.

Tampa Electric Company is planning a future Polk Power Plant extension up to 1,150MWe

P4-Wabash River Power Plant

Owner	JV Destec Energy, Inc & PSI Energy, Inc., Indiana	
Location	West Terre Haute, Indiana, USA	
Gasification Technology	E-GAS entrained flow.	
Fuel	Illinois basin bituminous high-sulphur coal.	
Gas Turbine	GE MS 7F(A)	
Process Parameters	Syngas Capacity	495.0 MWt
	GT Power Output	192.0 MWe
	ST Power Output	104.0 MWe
	Total Gross Power Output	296.0 MWe
	Auxiliary Consumption	36.0 MWe (12.2%)
	Total Net Power Output	260.0 MWe
	CCGT Net Efficiency	52.8 %
	Gasification efficiency	75.2 %
	IGCC Net Efficiency	39.7 % (8,817 Btu/kWh)
	Sulphur Removal Efficiency	>99.0 %
Power Production	9.5 Mio MWh (Status July 2006)	

Investment cost	438 Millions US$ (50% of this cost was subsidized by the US DOE).
Financing	DOE

As one of 40 USA government/industry funded projects in the ACCT program, the Wabash River project repowered the oldest of six pulverized coal units using a "next-generation" coal gasifier, an advanced GT and a heat-recovery steam generator.

The demonstration unit is designed to use 2’550 tons/day of high-sulfur (2.3-5.9% S), Illinois Basin bituminous coal.

The design heat rate for the repowered unit is 9’530 kJ/kWh (approximately 37.7% efficiency).

P5-Willem Alexander Power Plant

Owner	NUON, Netherlands	
Location	Bruggenum, The Netherlands	
Gasification Technology	Shell Entrained Flow gasifier.	
Fuel	Internationally Traded Coal	
Gas Turbine	Siemens V 94.2	
Process Parameters	Total Net Power Output	253.0 MWe
	Net Efficiency	41.3 % (8,262 Btu/kWh)
Investment Costs	535 Millions US$	

The Willem Alexander plant was one of the first successful IGCC power plants in the world. The project was ordered in 1990.

Construction was completed at the end of 1993, and the plant was commissioned in 1994. It was a pioneering example of combined-cycle technology applied to coal-fired power generation.

The operator, Demkolec BV, currently faces the challenging prices of the French nuclear electricity power in the new deregulated market.

P6-Lakeland (Mc Intosh) ACFBCC Power Plant

Owner	Tampa Electric Company & City of Lakeland, DOE and Water Utilities, USA.	
Location	City of Lakeland, Florida, USA.	
Gasification Technology	Foster&Wheeler’s (F&W) advanced circulating fluidised bed combined cycle (ACFBCC) technology.	
Fuel	Coal	
Process Parameters	GT Power Output	60.0 MWe
	ST Power Output	200.0 MWe
	Steam Pressure	165.0 bar

Steam Temperature 538.0 °C

The power plant integrates two steps. First step is partial gasification of coal resulting in syngas production for GT fuel supply and the second is PCFB process for steam generation for ST drive.

Because this unit operates at temperatures much lower than gasifiers currently under development, it also produces a char residue.

Lime-based sorbents are injected into the carboniser, to catalytically enhance tar cracking and capture of sulphur as calcium sulphide.

Sulphur is captured in-situ, and the raw syngas is fired hot. Thus, expensive, complex, fuel gas heat exchangers and chemical or S-capturing bed cleanup systems otherwise typical for IGCC are eliminated.

Time schedule of this project is planned as follows:

- Demo operation initiated 07/2005
- Demo operation completed, final report issued 2007

P7-Lunnen Power Plant

Owner	Steag & Kellerman
Location	Lunen, Germany
Gasification Technology	BGL (British gas Lurgi)
Process Parameters	Net Power Output 170.0 MWe Net Efficiency 31.7 %
Fuel	Coal

This project is believed to be historically the first true IGCC plant. STEAG Kellermann, Lunnen, Germany, commissioned it in 1969.

After 10,000 hours of operation it was decommissioned in 1972. BGL (British Gas Lurgi) was the technology applied.

P8-Plaquemine Power Plant

Owner	Destec & Dow Chemical
Location	Plaquemine, Louisiana, USA
Gasification Technology	DOW 2-stage, entrained, coal-fired, oxygen-gasification, ash slagging, with CGCU
Process Parameters	Net Power Output 160.0 MWe Net Efficiency 36.0 %
Fuel	Western coal
Investment Costs	560 Millions US$

This IGCC was commissioned by LGTO in Plaquemine, Louisiana in 1987. Destec and Dow Chemical gasify the 2500 tons of western coal per day.

P9-Cool Water Power Plant

Owner	EPRI, USA	
Location	Barstow, Mojave Desert, California, USA.	
Gasification Technology	Texaco Entrained Flow, O_2 gasifier.	
Process Parameters	Total Net Power Output	100.0 MWe
	Net Efficiency	31.2 %
Fuel	Coal	
Investment Costs	489 millions US$	

The pioneering 100 MWe Cool Water demonstration in California commissioned in 1984, the first of its kind in the world, operated for 4 years. It was decommissioned in 1989.

P10-Pinon Pine Power Plant

Owner	Sierra Pacific Power Company	
Location	Reno, Nevada, USA	
Gasification Technology	KRW (Kellog-Rust-Westinghouse) air-blown fluidized-bed gasification with HGCS.	
Gas Turbine	GE MS 6F(A)	
Process Parameters	GT Power Output	61.0 MWe
	ST Power Output	46.0 MWe
	Gross Power Output	107.0 MWe
	Auxiliary Consumption	8.0 MWe (7.5%)
	Net Power Output	99.0 MWe
	Net Efficiency	39.0 %
Fuel	Coal Southern Utah bituminous, with 0.5%-0.9% sulphur.	
Investment Costs	250 Millions US$	
Financing	50% funded by US DOE	

P11-Schwarze Pumpe Power Plant

Owner	Sekundarrohstoff-Verwertungszentrum Schwarze Pumpe GmbH, Germany	
Location	Cottbus, Germany	
Gasification Technology	1st Phase: Lurgi dry ash fixed-bed, O_2-blown. 2nd Phase: BGL slagging fixed-bed.	
Process Parameters	Net Power Output	75 MWe
Fuel	Pelletised refuse & lignite (85 % town waste and 15 % lignite)	

After the German reunification, the "Schwarze Pumpe" town gas plant near Cottbus was converted within a short period of time from producing town gas from local lignite to making syngas for methanol and fuel gas for IGCC.

75 MWe power is produced from a mixture of lignite with wide variety of solid and liquid wastes, residues and contaminated materials.

P12-Vresova Power Plant

Owner	Sokolovska Uhelna (SU) is a joint-stock company at Sokolov, Czech Republic, around half publicly owned and another half privately owned.	
Location	Sokolov, Czech Republic	
Gasification Technology	KRW	
Process Parameters	Gross Power Output	376.0 MWe
	Auxiliary Consumption	18.0 MWe (5%)
	Net Power Output	358.0 MWe
Fuel	Lignite	

SU main activities are coal (lignite) mining, and electricity generation. SU built fixed bed pressurized lignite gasifier and gas purification plant in 1960's to convert lignite to gas and supply town gas.

It was one of the largest town gas generation plant in Central Europe until 1996. However, the town gas has been replaced by NG from Russia since 1996.

SU installed two units of 200 MWe CCGT cycle to generate electricity to be fed by the gas produced by the gasification plant.

After studying several alternatives, SU concluded that installing new units of fluidized bed gasifier with HTW gasification technology is most economical solution.

FUTURE IGCC PROJECTS PLANNED IN USA AND OTHER COUNTRIES

Around the world, over 50 IGCC projects have been announced or have entered planning in the past few years.

In this boom of project activity, the USA is clearly leading the way with 30 projects in 17 states at some stage of development with a combined capacity of more than 15,000MW.

Through 2015, the potential for refinery residue- or coal-based IGCC power plants is estimated to be 135 GW.

Currently over 6GW (unit size between 50 and 500MWe) of coal and refinery residue based IGCC projects are either, under construction or are planned, mainly in USA, Europe and Japan (World Bank 2007).

In the private sector the following plants, as shown in Table 3 are in various stages of development.

ID. No.	DEVELOPER	LOCATION	GASIFICATION TECHNOLOGY	NET POWER OUTPUT (MWE)	ESTIMATED COSTS (MIO USD)
A1	American Electric Power	West Virginia		600	1,000
A2	American Electric Power	Kentucky		600	1,000
A3	Duke Energy	Indiana		600	900
A4	Energy Northwest	Washington	E-Gas	2 x 300	900 - 950
A5	Tondu Corporation	Indiana	Shell	550	1,000
A6	Mitsubishi Heavy Industries	Nakoso-Japan	MHI-Air Blown	225-450	

The project called "FutureGen" is an initiative to build the world's first coal based integrated sequestration and hydrogen production research power plant.

The one billion USD project is intended to create the world's first zero-emissions fossil fuel plant. The 275 MWe (net equivalent output) will produces both electricity and hydrogen as output and sequesters one million metric tones of carbon dioxide per year. The project will take at least ten years to complete. To prove sequestration technology it must be tested and validated at a large scale and with real-world conditions.

Last year, the Institute of Clean Coal Technology, East China University of Science & Technology, announced that the startup of the very first IGCC power generation plant in China took place in March, 2006.

In addition to power generation using a modified GE Frame 6B (45 MW) gas turbine, it was stated that the plant has a capacity to co-produce annually 240,000 ton of methanol.

In Japan, Mitsubishi Heavy Industries (MHI) has started coal gasification test results with their air-blown gasification process. The conclusion was that their standard 500MWe commercial design would operate well, and produce 495MWe gross output with low quality coal.

SUMMARY & CONCLUSIONS

In this paper we have presented a factography review describing the most advanced coal gasification technologies and the present status of technological progress of IGCC applications.

We did so with the intention to support our firm belief that a smooth, yet visible declination trend from NG in favour of solid fuel power generation reliance will take place in the next decade. Reasons for such conclusions could be assorted in the following four statements.

- Global warming and the worldwide increasing public and governmental pressure not to build conventional pulverized coal fuelled power plants, huge low-quality, low-price coal reserves, uncertainty over NG prices, limited or not accessible hydro-power reserves, and various restrictions and limitations for construction of new nuclear power plants, the IGCC technology is poised to grow more than any other power generation technology option available.
- Many modern IPPs are also considering to invest in low-quality, low-cost coal based IGCC projects seeking a competitive advantage in this emerging power generation technology, and to hedge the risk to their coal-dominant business operations as carbon constraints appear inevitable in the next few years.
- In USA and some European countries the implementation of IGCC technology has been encouraged through the allocation of tax credits, loan guarantees, and other incentives helping to bridge the commercial gap between IGCC and conventional pulverized coal fuelled power plant projects.
- NG prices are anchored in a long-term relationship with crude oil prices. It is not to expect that the current high crude oil market price level will be considerably reduced in the short or long term future.
- Fuel option for gas turbines in favour of solid fuel reliance will be ever more abundant. IGCC technology is one of the technical tools which will make such shift viable somewhat earlier than 2015.
- Gasifiers may be able to use coals that would otherwise be difficult to use in pulverized coal fuelled power plants, such as those with a high sulphur content, or high ash content.
- Especially low-rank coals with higher sulphur & ash content which so far have hardly had any market chance vs. CCGT NG fired technology will acquire their competitive renaissance with wide implementation of IGCC power plants.
- Biggest power generation growth is expected in the countries whose power sector is tightly coal-dependent, e.g. the USA, China, India, Australia and South Africa.
- The main incentive for IGCC development has been that IGCC units may be able to achieve higher thermal efficiencies than pulverized coal fuelled power plants, and be able to match the environmental performance of NG-fired power plants.
- Using syngas in a gas turbine increases its output, especially when nitrogen from an oxygen blown unit is fed to the turbine. Thus a turbine rated at 240MW when fired on NG can yield 265MW or more on syngas. Furthermore, output is less dependent on ambient temperature than is the case with natural gas.
- The emissions of particulates, NOx and SO_2 from IGCC units is expected to meet, and possibly to better, all current standards.
- The gasification process in IGCC enables the production of not only electricity, but a range of chemicals, by-products for industrial use, and transport fuels.

There are significant technical challenges which have to be considered in further development of IGCC and PFBC technology, to make it technically and commercially fully acceptable and most competitive.

- In all IGCC plants, there is a requirement for a series of large heat exchangers, which become major components. In such exchangers, solids deposition, fouling and corrosion may take place.
- Currently, cooling the syngas to below 50 - 100℃ is required for conventional cleaning, and it is subsequently reheated before combustion, resulting in energy loss.
- Ash behavior in a gasifier is a critical parameter, both in terms of the satisfactory formation of a slag in entrained flow, and the possibility of solids deposition in the syngas cooler/heat exchanger.
- At lower temperatures, such as those in fluidized and fixed bed gasifiers, tar formation and deposition may prove to be a difficulty.
- IGCC power plants tend to have longer start-up times, comparing to pulverized coal fuelled power plants, and hence may only be suitable for base-load operation.
- The supply of coal into the PFBC system is considerably more complex in comparison with pulverized coal system.
- As gasifiers are pressure vessels, they cannot be fabricated on site in the same way that pulverized coal boilers can. Large gasifiers are difficult to transport, simply because of their weight and sheer size, and this may prove to restrict their eventual use for sizes above 300 MWe.

The driving force behind the development of IGCC technology is to achieve high thermal efficiencies together with low levels of emissions.

Net efficiencies of around 40% have been already achieved, and it is expected that net efficiencies as high as 45% may be achieved with current IGCC technology.

At the moment, the syngas cleaning stages for particulates and sulphur removal can only be carried out at relatively low temperatures, which restricts the overall efficiency obtainable; however, higher efficiencies are possible when further increase of gas turbine inlet temperatures can be achieved.

With coal being an abundant, readily available and low-cost resource in the USA States, it is prudent for utilities to encourage development of clean coal technologies such as IGCC.

Worldwide final goal of IGCC implementation is meeting urgent electricity needs in a highly competitive context while complying, to the largest possible extent, with environmental protection requirements and make use of local coals.