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Hydrogen from coal: Production and utilisation technologies

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Abstract

Although coal may be viewed as a dirty fuel due to its high greenhouse emissions when combusted, a strong case can be made for coal to be a major world source of clean H_2 energy. Apart from the fact that resources of coal will outlast oil and natural gas by centuries, there is a shift towards developing environmentally benign coal technologies, which can lead to high energy conversion efficiencies and low air pollution emissions as compared to conventional coal fired power generation plant. There are currently several world research and industrial development projects in the areas of Integrated Gasification Combined Cycles (IGCC) and Integrated Gasification Fuel Cell (IGFC) systems. In such systems, there is a need to integrate complex unit operations including gasifiers, gas separation and cleaning units, water gas shift reactors, turbines, heat exchangers, steam generators and fuel cells. IGFC systems tested in the USA, Europe and Japan employing gasifiers (Texaco, Lurgi and Eagle) and fuel cells have resulted in energy conversions at efficiency of 47.5% (HHV) which is much higher than the 30–35% efficiency of conventional coal fired power generation. Solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC) are the front runners in energy production from coal gases. These fuel cells can operate at high temperatures and are robust to gas poisoning impurities. IGCC and IGFC technologies are expensive and currently economically uncompetitive as compared to established and mature power generation technology. However, further efficiency and technology improvements coupled with world pressures on limitation of greenhouse gases and other gaseous pollutants could make IGCC/IGFC technically and economically viable for hydrogen production and utilisation in clean and environmentally benign energy systems.

Keywords: Energy; Hydrogen; Gasifiers; Water gas shift; Fuel cells and coal

1. Introduction

Hydrogen is currently being widely examined as a possible energy carrier to reduce carbon emissions from electricity production and transportation. It can be produced from any hydrocarbon, water and some industrial by-products. The choice of production method is likely to vary depending on local source availability and cost. Coal is the most abundant fossil fuel on the planet, with current estimates from 216 years global recoverable reserves (British Petroleum,

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2002) to over 500 years (Williams, 2001) at current usage rates. But because of the high rate of greenhouse gas emissions associated with current stationary electricity production, alternative technologies are being sought to reduce the environmental impact associated with coal utilisation. One technology that has increasingly attracted attention in recent years is gasification to produce hydrogen. Gasification may offer greater potential than other hydrogen production methods for CO_2 sequestration, as well as the reduction of other pollutants such as NO_x and SO_x as compared with conventional electricity production. Gasification is a well-established commercial technology, although it is little used, except where oil and/or NG is expensive (e.g. South Africa and China) (Padro and Putsche, 1999). Coal and petroleum products are currently the predominant fuels for gasification, although other fuels, including biomass, may also be used.

Of all fossil fuels, coal has the lowest hydrogen to carbon ratio, so more CO_2 is produced per mole of H_2. With gasification, however, there is the possibility of achieving very high purity hydrogen or highly efficient electricity production and low emissions with separation and capture of CO_2, which is found in high concentrations in the product stream. Much research has been done on Integrated Gasification Combined Cycle (IGCC) processes, with 5 prototype plants in operation worldwide–3 in the USA and 2 in Europe–with efficiencies close to 50% (Haupt et al., 2001)). With sequestration, coal gasification-produced hydrogen has the potential to be a very low emissions fuel on a life cycle basis. More research into sequestration and gasification is necessary before widespread implementation can occur.

2. Gasification technology

Worldwide, there are around 417 active or planned gasification projects, with a total production capacity of 428,866,510 N m^3/day (International Gasification Organisation [IGO], 2003). Of these, more than 300 producing syngas rather than electricity. The highest concentration of units is at SASOL in South Africa, with around 100 fixed-bed gasifiers, whilst China and USA also have close to 20 gasifiers licensed. The overall energy production is equivalent to about 20,000 MW. Approximately 42% of these gasifiers are coal-fed (Stiegel and Maxwell, 1999).

In general, the gasification process takes crushed/pulverised coal feed (either dry or as a slurry), which is then mixed with the oxidant (typically air or oxygen and steam). The feed enters the gasifier, where it is devolatilised at 1000–1500 °C and the resulting hydrocarbons react to give carbon monoxide and hydrogen (syngas) via Eq. (1).

$$CH_xO_y + (1-y)H_2O \rightarrow \left(\frac{x}{2} + 1 - y\right)H_2 + CO \quad (1)$$

There are currently a variety of different gasification technologies in existence. These technologies differ in the feed preparation and state on delivery, ash removal method and configuration. Different systems are appropriate for different coal types. The most widely studied commercial gasifiers are summarised below in Table 1.

Other gasification technologies have been developed in the past, for example fluid bed systems and the high temperature Winkler process, but these seem out of favour with the major companies at the present. Technologies, such as using concentrated solar thermal energy to provide the necessary heat for gasification, and underground coal gasification (UCG) (where the coal is not removed from the ground but gasified in situ) are however also being developed (Blinderman and Jones, 2002; Zedtwitz and Steinfeld, 2003).

3. IGCC/IGFC

The gasification of coal produces syngas consisting of predominately carbon monoxide and hydrogen, with some remaining hydrocarbons, carbon dioxide and water. This syngas can then be used directly to produce electricity, or further processed and purified to give pure hydrogen product for such end uses as ammonia production or hydrocracking of petroleum. In the future, it may also be used as fuel for fuel cells to power vehicles and for stationary electricity production. The energy in the syngas can be recovered by integrating the gasifier with a combined cycle gas and steam turbine (IGCC) or a fuel cell (IGFC) to produce electricity. Typically the raw gasifier syngas undergoes preliminary purification and is either utilised directly in a fuel cell or gas turbine or put through a

Table 1
Characteristics of gasification technologies (National Energy Technology Laboratories/US Department Of Energy [NETL/DOE], 2003; Schellberg, 1997)

Gasifier	Type	Feed	Oxidant	Temperature
Texaco	Entrained flow	60–70% coal/water slurry	95% pure oxygen	1450–1500 °C
E-GAS	Entrained flow (two-stage)	50–70% coal/water slurry (75–80% fed to first stage)	Oxygen	Stage 1: 1315–1425 °C Stage 2: 1040 °C
Shell	Entrained flow	Dry pulverised coal (nitrogen or product gas transported)	Air or oxygen and steam	>1370 °C
PRENFLO (MHI, ABB-CE, VEW/Steinmuller, Hitachi, GSP)	Entrained flow	Dry pulverised coal	85% pure oxygen	–
KRW	Fluidised bed	Crushed coal (mixed with limestone sorbent for sulphur removal)	Air or oxygen	–
Kellogg	Transport reactor	Crushed coal (mixed with limestone sorbent for sulphur removal)	Air or oxygen and steam	~1040 °C
Lurgi dry ash	Moving bed	Crushed coal	Air or oxygen and steam	260–540 °C (top) 1100 °C (bottom)
British Gas/Lurgi	Fixed bed	Coal/briquette/fines/flux mixture	Air or oxygen and steam	~570 °C (exit)

water gas shift (WGS) reactor to increase the hydrogen content (International Energy Agency [IEA], 2003). Following the WGS, H_2 can be purified and acid gases disposed of (possibly by sequestration).

The integration of a gasifier with a combined cycle gas and steam turbine (ICCC) depicted in Fig. 1 allows the overall efficiency of the plant to be increased. Both electricity and hydrogen can be pro-

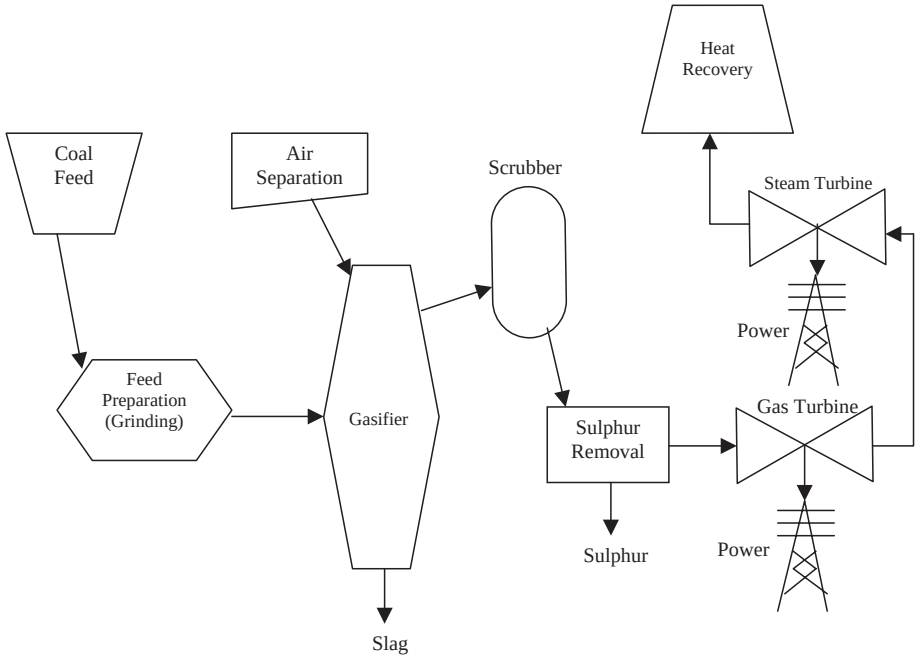

Fig. 1. Integrated gasification combined cycle flow diagram.

duced simultaneously, according to market factors. This flexibility of production is the aim of the US Vision 21 project, which also envisions further options of additional chemical production. The integration of an IGCC with a fuel cell stack (IGFC) is a future option for electricity generation. Apart from cost, the main disadvantage of utilising fuel cells would be the stricter requirements on certain gaseous contaminants that could poison fuel cell electrodes. There are many different types of fuel cells, all of which could be integrated with a coal gasifier. However, the most likely candidates would be the high temperature molten carbonate (MCFC) and solid oxide (SOFC) fuel cells due to their high operating temperatures and lower fuel purification requirements.

IGCC is a highly complex technology which requires a high level of integration of the unit operations shown in Fig. 1. In turn, there are major considerations related to shut downs, start up and process control. Large-scale IGCC shutdowns may lead to higher maintenance costs. Research towards reducing the level of complexity without sacrificing the effectiveness of the plant is being undertaken (Forrest, 2003).

4. Water gas shift reactors

The water gas shift reaction (WGSR) is an important reaction in extra H_2 production from syngas from coal gasifiers. In this catalysed reaction, steam and CO react to produce H_2 and CO_2 (Armor, 1998; Lyngfelt and Leckner, 1999) and the reaction is represented as:

$$CO + H_2O \rightarrow H_2 + CO_2 \quad \Delta H^0_{298} = -41.1 \text{ kJ/mol.} \tag{2}$$

The main traditional applications for the WGSR since the 1960s include the production of H_2 for ammonia synthesis, hydrotreating of petroleum stocks and coal processing. Recent applications relate to the incorporation in fuel processors for fuel cell applications (Choi and Stenger, 2003), the second-stage reactor in the partial oxidation of CH_4 to produce H_2 (Maiya et al., 2000), and tritium recovery from tritiated water in fusion reactor systems (Basile et al., 2001).

In coal processing, the WGSR is carried out in two reactors in series, high-temperature (HT) and the low-temperature (LT) shift reactors, respectively. $Cu/ZnO/Al_2O_3$ is the catalyst for the LT reaction (200–250 °C) whereas Fe_2O_3–Cr_2O_3 catalyst is used in the HT (320–450 °C) reaction. Although the $Cu/ZnO/Al_2O_3$ catalysts typically have relatively higher selectivities than Fe_2O_3–Cr_2O_3, their main disadvantage is lower resistance to S- and Cl-impurities (Amadeo and Laborde, 1995; Keiski et al., 1996). Apart from the LT/HT catalysts, some catalysts can also be used over wider ranges of temperatures, e.g. $Co–Mo/Al_2O_3$, which is also stable towards S-impurities. The WGSR may be carried out in conventional catalytic packed-bed reactors. An alternative approach where high purity hydrogen is required is to separate the hydrogen product via palladium diffusion membrane. Some researchers have carried out the WGSR inside a membrane tube over a suitable catalyst. Such membrane reactors have also been applied to other important industrial processes such as steam reforming. In addition to the use of palladium diffusion membranes which have a high selectivity for hydrogen separation, microporous ceramics have also been investigated. A measure of success has been achieved for example using microporous silica which has a much lower cost than Pd although a lower hydrogen selectivity.

Application of membrane reactor (MR) technology brings to the WGSR the ability to operate at significantly lower H_2O/CO ratios (1–2 compared to 9.8), integrated gas separation, the generation of high purity H_2, and conversions above the equilibrium limit. The ability of the WGS-MR concept to effect integrated gas separation with an increased net electric efficiency (Bracht et al., 1997) in IGCC systems is a significant outcome since the overall economics of the IGCC process is very sensitive to the efficiency, e.g. a 10% decrease in efficiency typically results in about 50% increase in costs (Lyngfelt and Leckner, 1999). In a recent review of the published data on natural gas- and coal-based power systems, Lyngfelt and Leckner (1999) demonstrated that the WGSR offered the least efficiency penalty for coal-based systems among the CO_2 capture technologies; it is therefore to be expected that the WGS-MR concept is to be targeted on coal-based power systems first rather than natural gas systems.

5. Fuel cells

The use of coal gas in fuel cells has been investigated by several organisations since the 1960s. Of the major fuel cell types the SOFC and MCFC are particularly attractive because they can directly utilise both hydrogen and carbon monoxide. In other words they will run directly on the syngas generated by a coal gasifier. Work was funded by the US Department of Energy in the 1980s on the effects of fuel gas contaminants on the performance of both the MCFC and SOFC. This showed that both technologies are also fairly forgiving in terms of coal gas contaminants. The most troublesome are sulphur, halides, nitrogen compounds and solid particulates (National Energy Technology Laboratories/US Department Of Energy [NETL/DOE], 2003). This early work on bench-scale fuel cells was followed up with tests of kW-scale stacks running on gasifier product gas obtained from an oxygen-blown gasifier side-stream. More recently a report has been completed for the US Department of Energy reviewing the effects of contaminants and impurities on the integration of fuel cells in power plants (Schellberg, 1997).

In the 1980s work was also carried out in the US and Europe to devise ways of integrating fuel cells and coal gasifiers. Several schemes were devised and mass balances and other analyses carried out. For example at a 200 MW scale, studies indicated that using conventional gasification and cleanup technologies, an efficiency of 47.5% (HHV) could be achieved with Integrated Gasification Fuel Cell (IGFC) plants utilising Texaco oxygen-blown gasification and low temperature cleanup. A comparison of gasifiers showed that the British Gas/Lurgi gasifier has a particular advantage over other oxygen-blown gasifiers in that the product is relatively rich in methane (Brown et al., 1996). This can be steam reformed internally within the MCFC and SOFC and this offers a means of cooling the stacks. The internal reforming of methane has been demonstrated widely and one advantage is the increased energy conversion efficiency that arises because need for stack cooling is reduced. Later studies have indicated that higher efficiencies, 51.7–53.5%, could be achieved with higher methane producing gasifiers and by using hot gas cleanup.

As a result of such studies, a proposal was made in 1993 by the US DOE and Kentucky Pioneer Energy to integrate a BG/Lurgi gasifier and MCFC system built by Fuel Cell Energy in the US. This major project (over US$400 M) is now in the construction phase and as part of that, in August 2003 a 2 MW MCFC stack was moved to the Wabash River IGCC power plant for testing. The Wabash facility actually uses a Destec oxygen-blown two-stage gasifier and cleanup and a GE gas turbine. Calculations project that the combination of four BG/Lurgi gasifiers and MCFC will have a 40% LHV efficiency and when commercial this could rise to 42.5%. These efficiencies represent greater than 20% reduction in emissions of CO_2 when compared to a conventional pulverised coal plant equipped with a flue-gas scrubber. The SO_2 emissions from the IGCC system are expected to show a 99% reduction, and NO_x emissions a 90% reduction.

In the US IGFC plant, syngas from the gasification plant cleanup system is cleaned up further and moisturised. The moisturised syngas is fed to the anode side of the fuel cell where methane is internally reformed and CO is shifted to CO_2 and hydrogen. Spent fuel exits the anode and is consumed in the anode exhaust oxidizer to supply oxygen and CO_2 to the cathode. The resulting electrochemical reactions in the fuel cell anode and cathode produce DC output, which is inverted to AC. The cathode exhaust supplies heat to the fuel cleanup, steam boiler and cogeneration systems as it is vented from the plant.

Two fuel cell modules, each housing four fuel cell stacks, produce the DC power, and an inverter, including switchgear converts the DC power to AC. The balance of plant equipment includes fuel processing, thermal management, water treatment, instrument air system and controls.

The objective of this test is to demonstrate fuel cell operation on coal-derived gas at a commercial scale and to verify the efficiency and environmental benefits. Successful demonstration of this technology on coal could lead to future coal based applications at a larger scale with significant improvements in efficiency and emissions compared to existing technologies.

Another major coal gasification/fuel cell development is taking place in Japan. The Electric Power Development Company (EPDC) and NEDO are

undertaking research at the pilot plant testing facility of the EAGLE (coal Energy Applications for Gas, Liquid and Electricity) project (Sotooka, 2003). This differs from the US project in that the aim is to integrate pressurised molten carbonate fuel cells with the coal gasifier. Up to mid-2003 the gasifier had been constructed, commissioned and run through 15 operating cycles. The fuel cell system has been designed and provision made for integration in the pilot plant but it has yet to be built and incorporated in the scheme. The plant is shown schematically in Fig. 2.

The EAGLE coal gasifier is an oxygen-blown dry-feed entrained flow reactor running at 26.5 bar, and capable of gasifying up to 150 tons per day. Cold gas cleanup is used to provide a clean fuel for the MCFC stacks. Syngas from the gasifier is filtered and is cooled from 400 °C before entering a water scrubber to remove halogens and ammonia. The gas is then desulphurised using methyldiethanolamine (MDEA) and acid gas removed by this absorber is burnt in air and the sulphur oxide recovered in a limestone absorber. Because the fuel cells are designed to run at 15 bar, to match that the pressure of the gas turbine, the pressure energy of the syngas is recovered as power through an expansion turbine.

Because the syngas from the EAGLE gasifier has a high CO/H_2 ratio, the risk of carbon formation in the fuel cell is minimised by adding steam to the fuel cell inlet gas and employing anode gas recycle. The anode exhaust gas is combusted in a catalytic burner and the resultant gas fed to the cathode to provide the CO_2 necessary for operation of the MCFC. Further details of MCFC operation are given elsewhere (Larminie and Dicks, 2003). The aim is to provide cooling for the MCFC stack by recycling some of the cathode gas and cooling it in a heat recovery boiler. Complete integration of the fuel cell and IGCC is provided by sending cathode exhaust gas at ca. 700 °C to the inlet of the gas turbine. When the syngas is combusted in the turbine the temperature is increased to 1300 °C. Exhaust from the turbine is cooled in a Heat Recovery Steam Generator (HRSG) and the generated steam is sent to a steam turbine (150 bar and 538 °C).

The Integrated Gasifier-MCFC is expected to have a gross efficiency of almost 60% and a net efficiency of 53.4%. The gross power output of the plant is calculated to be 616.6 MW, of which the MCFC stacks are expected to generate 262 MW, the remainder being provided by the gas and steam turbines.

Improvements in gas turbine technology and cycle design have already resulted in relatively high efficiencies for IGCCs. So although the above figures demonstrate that an IGFC system may potentially also exhibit high efficiencies, that may not be enough,

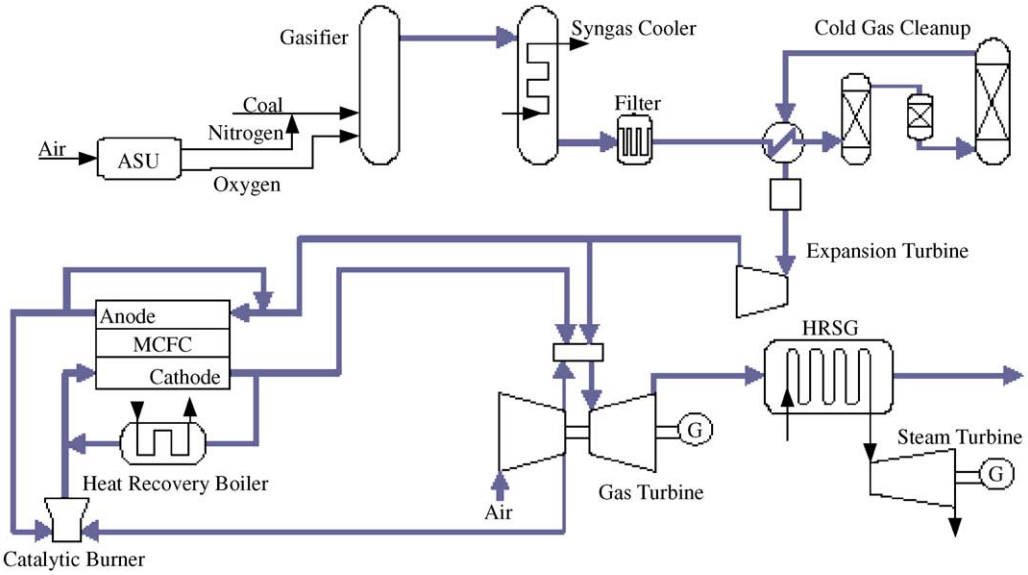

Fig. 2. Integrated pressurised MCFC and EAGLE coal gasifier.

certainly in the short term, to establish their commercial viability. However, another advantage that fuel cells possess is that they offer a direct means of separating and capturing CO_2 from combusted fuel gas. The anode exhaust of an MCFC and SOFC contains CO_2 but not depleted air, which appears on the cathode side. As explained elsewhere (Larminie and Dicks, 2003) this does not happen with low temperature proton exchange membrane (PEM) or phosphoric acid fuel cells. The stacks of the SOFC or MCFC themselves therefore act as gas separation membranes. This feature is already being demonstrated by Shell and Siemens Westinghouse in a joint project with Norsk Hydro in which the anode exhaust gas from a natural gas fuelled SOFC is recycled back into Norwegian natural gas fields.

In addition to their use for stationary power applications, fuel cells are being developed for use as power sources in vehicles and this is generating considerable interest in terms of a future hydrogen economy. Ultimately it is argued that hydrogen-fuelled vehicles will only emit water vapour from the tailpipe. Already BMW are working on hydrogen-fuelled internal combustion engines, and most of the other major automobile manufacturers are developing PEM fuel cell power trains. Over the next few years we are likely to see the emergence of more hybrid electric vehicles and these may well pave the way for fuel cell vehicles (FCVs) at some future point. However, there is a consensus amongst manufacturers that FCVs are unlikely to appear in significant numbers until at least 2010. The question immediately arises, even ignoring for the moment the issue of hydrogen storage onboard vehicles (a major problem in its own right), as to how hydrogen can best be produced and transported. Whilst there are many methods of generating hydrogen for transportation applications, we have to consider the whole energy supply chain from "well-to-wheels" to determine the most efficient means of supplying energy to vehicles in the most environmentally acceptable manner.

6. Economics

The economics of hydrogen and electricity production depend on a variety of internal and external factors. External factors can rarely be controlled by the project team, whereas internal factors can usually be adjusted to some extent. External factors include feed cost, legislation and variation in the market, whereas internal factors could be the plant design and operating conditions. Table 2 summarises the current best estimates of hydrogen production costs using a variety of different processes, and gives some indication of the current achievable efficiencies. It can be observed that the current predominate method of hydrogen production, steam reforming, is signifi-

Table 2
Summary of hydrogen production methods

Method	Fuels	Overall efficiency (%)	H_2 cost (US$/GJ)	TCI (US$/GJ H_2 capacity)	Notes
Steam reforming	NG, oil	65–75 (LHV)	5–8	9–15	Well-established, extensive infrastructure
Partial oxidation	NG, oil	50 (LHV)	7–10	9–22	No infrastructure, well-established, variety of fuels
Gasification	Biomass, oil, coal	42.5–46.5 (LHV)	10–12, 9–13	33–34, 20–42	Minimal infrastructure, concentrated CO_2 stream ideal for sequestration, uses cheap fuels, potential for use with solar energy
Pyrolysis	Biomass, coal	47.9 (HHV)	9–13	15–19	No infrastructure, uses cheap fuels, concentrated CO_2 stream ideal for sequestration
Electrolysis	Water, H_2S	35–42 (HHV) (electricity source included) 70 (NG assisted)	20–25 (large), 11–42 (small)	3–30 (large), 32–486, (small)	Potential zero emissions with renewable electricity, environmental/economic benefits depend on electricity supply, water supply possibly unreliable

(a) TCI=specific total capital investment (Padro and Putsche, 1999).

cantly less expensive in terms of both capital and operating cost per gigajoule of hydrogen produced. One of the reasons for this is that coal has a much lower H:C ratio (external factor). IGCC plants also tend to have higher maintenance costs deriving from the high level of complexity and low reliability of current plants (Forrest, 2003) (internal factor).

Current predictions based on the relative abundance of coal as compared to other fossil fuels and the increase in demand for petroleum and natural gas indicate that both oil and gas are likely to increase significantly in price, whilst coal should remain relatively inexpensive (Ogden et al., 2001). If this trend is realised, then hydrogen production from coal may eventually become competitive, or even surpass steam reforming of natural gas in terms of cost. The flexibility of integrated gasification systems allowing the production of the electricity and hydrogen could prove to be a great advantage, as it would permit the plant to adapt production according to market fluctuations. Increasingly strict environmental legislation could require industry to improve emissions of pollutants such as CO_2 or SO_x and NO_x. IGCC/IGFC plants have achieved higher efficiencies than subcritical coal power plants, thus producing less CO_2. They also have far lower SO_x and NO_x emissions. The ability to avoid penalties associated with new legislature could prove to be a very important economic benefit, as well as reducing environmental damage.

The configuration of a gasification system depends strongly on the properties of the coal being utilised, and this in turn affects the economics of the plant. Some properties of particular importance are sulphur content, caking properties, reactivity and ash content, composition, fusion temperature and distribution (Basu and Ramani, 1999). Coal mixing to change properties may only be feasible where transport costs from offsite are low enough. Alternatively, locating the plant nearer to low sulphur coal may be applicable if transport to end-use is less expensive.

Sulphur content affects the requirements for desulphurisation of syngas. Caking coals may require pretreatment to prevent blockages in the process. Both of these properties may require large physical changes to the plant, which can change capital and operating costs. Ash composition and properties determine the required minimum temperature for slag viscosity to remain reasonably low in the case of a slagging gasifier, and whether flux addition is required or not. The fusion temperature and slagging temperature depend on the composition of the ash—particularly the percentages of silica, alumina, Fe_2O_3, CaO, MgO and other oxides (Basu and Ramani, 1999). These properties could be taken into account in the selection of slagging or non-slagging gasifiers, flux ratios and operating temperatures, hence they have a direct affect on both capital and operating costs.

EPRI and Process Power Plants LLC have recently surveyed the main gasification technologies offered by ChevronTexaco, Shell and ConocoPhillips (EGas) (Dong, 1997). Capital costs vary between 1300 and 1450 US$/kW for E-Gas and Texaco based power plants respectively to 1470 US$/kW for comparative Shell based plants. Processing low rank coals such as lignite increases the capital cost by about 400 US$/kW, and including CO_2 capture increases the capital cost by US$350/kW. The study concluded that for CO_2 capture, there is a distinct advantage in gasification operation at high pressures (55–69 barg). However, the costs of CO_2 capture and sequestration from new IGCC plants adds 40–50% to the cost of electricity (COE) whereas for new pulverised coal plant the added COE costs can be 80–90%.

Compared with IGCC, IGFC would require higher levels of purity for the syngas entering the fuel cell. Removing contaminants to this level may increase the costs of the plant significantly, as additional units such as desulphurisation and additional water gas shift reactors may be required.

The employment of WGS-membrane reactor (WGS-MR) concept will depend on its techno-economic profile relative to the conventional technologies used for the WGSR. Bracht et al. (1997) in a techno-economic feasibility study investigated the concept of integrating the WGS-MR into the IGCC power generation system for CO_2 removal by using microporous silica membranes. Their evaluation showed that the net electric efficiency was 2.8% higher than IGCC with conventional CO_2 recovery but 8% lower in overall CO_2 recovery efficiency. With the overall economic appraisal in its favour, the authors concluded that the WGS-MR concept in IGCC systems is an attractive future option for CO_2 removal compared to conventional options. The study also noted that commercialization of high temperature gas cleaning and the development of membranes with

higher H_2 selectivities and permeances that are stable under the conditions of the reaction will make the case for WGS-MR concept even more viable. Advanced high temperature gas cleaning is under development and is an important step since a high inlet temperature is required for the integrated WGS-MR in IGCC systems.

Air separation units (ASUs) are another expensive section of an IGCC/IGFC, both in terms of capital and operation. ASUs are utilised to decrease gas flowrates across the plant by providing high purity oxygen instead of air as the feed. ASUs tend to use cryogenic separation, but current research is towards membrane separation units which have the potential to use less energy and be more compact. As with other aspects of process design, cost optimisation is a balance between costs implied by higher flowrates and those related to operating an ASU.

Predictions of long-term economics are always tentative at best, especially in areas of high technological development. Currently extensive research is being undertaken, especially into such processes as high temperature gas cleanup, membrane reactors and fuel cells. Potential advances in these areas could dramatically affect the efficiency of IGCC/IGFC, and hence the cost of hydrogen production.

7. Conclusions

Currently there is extensive research and development in the area of hydrogen production and utilisation. Coal gasification is one of the potential processes for producing hydrogen, and is being developed through the US Vision 21 and other projects. The potential for a new market for coal is a big driver behind this coupled with reducing gas emission pollution. At present hydrogen from coal would only be competitive under conditions of oil and natural gas scarcity and low environmental standards, but there are a number of developments that could advance its position.

IGCC technology can lead to high energy efficiencies but the integration is highly complex. There are several gasifier systems under development around the world whilst in situ underground coal gasification is also under consideration. The front runners in fuel cell technology for energy production are the SOFC and MCFC. These fuel cells can operate at high temperature and are more robust to cope with gas impurities that otherwise would poison catalysts at low temperatures. Several schemes in the USA, Europe and Japan are already integrating Texaco gasifiers (Texaco, Lurgi and Eable) with fuel cells resulting in energy conversions at an efficiency of 47.5% (HHV) for IGFC technologies. As the integration process and unit operation technologies are optmised, it is likely that overall efficiencies will be in excess of 50%.

The established nature of current coal fired power generation may limit the willingness to adopt a new approach to energy production, which could be disadvantageous. The low cost of coal as compared to other sources is an advantage to its use, and may improve as oil and gas become scarcer. The economics of different gasifier technologies vary widely depending on the properties of the specific coal feedstock to be used. Compared with current coal utilisation technologies, IGCC and IGFC are currently economically unviable. However, further efficiency improvements and pressures to reduce gaseous pollutants could make the technology more competitive. Membrane technology for air separation, hot gas cleanup and water gas shift reactors may hold the key to the required efficiency improvements that could make IGFC/IGCC technically and economically competitive.

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