Available online at www.sciencedirect.com

SCIENCE DIRECT®

Energy Conversion and Management 46 (2005) 1767–1779

ENERGY CONVERSION & MANAGEMENT

www.elsevier.com/locate/enconman

Comparison of Shell, Texaco, BGL and KRW gasifiers as part of IGCC plant computer simulations

Ligang Zheng [a,*], Edward Furinsky [b]

[a] Natural Resources Canada, CANMET Energy Technology Centre, 1 Haanel Road Ottawa, Ont., Canada K1A 1M1
[b] IMAF Group, 184 Marlborough Avenue, Ottawa, Ont., Canada K1N 8G4

Received 30 April 2004; received in revised form 3 May 2004; accepted 19 September 2004
Available online 5 November 2004

Abstract

The performances of four IGCC plants employing Shell, Texaco, BGL and KRW gasifiers were simulated using ASPEN Plus software for three different feeds. Performance analyses and comparisons of all four IGCC plants were performed based on the established data bank from the simulation. Discussions were focused on gas compositions, gasifier selection and overall performance.

Keywords: IGCC; Coal gasification; Gasifiers

1. Introduction

The integrated gasification combined cycle (IGCC) is the most advanced technology for generating electricity from coal cleanly. The simplified flow sheet of an IGCC plant with Texaco gasifier is shown in Fig. 1. Most recently, petroleum refineries around the world have adapted this technology for conversion of petroleum coke, distillation residues and sludges to electricity, hydrogen and other products. The SO_x, NO_x and particulate emissions from an IGCC are in the range of

* Corresponding author. Tel.: +1 613 947 0288; fax: +1 613 992 9335.
E-mail address: lzheng@nrcan.gc.ca (L. Zheng).

0196-8904/$ - see front matter
doi:10.1016/j.enconman.2004.09.004

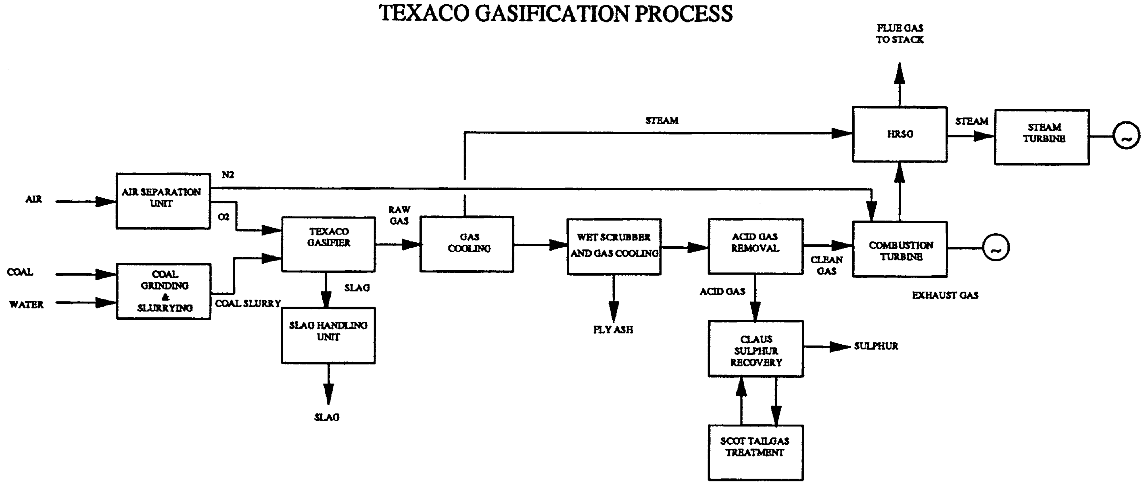

Fig. 1. IGCC plant with Texaco gasifier.

those from natural gas fueled combustion plants [1,2]. Because of the high temperature employed in the gasifier, the solid residues from an IGCC are environmentally benign.

Moreover, the overall thermal efficiency is higher than that of the conventional pulverized coal combustion plants. This translates into decreased emissions of CO_2 per unit of electricity generated by almost 20%. The IGCC technology can be modified to produce high concentration products such as H_2 and CO_2. This involves the water–gas shift of syngas, followed by the separation of CO_2 from H_2. The former can be either sequestrated or utilized industrially, whereas H_2 represents the prime, most clean available fuel.

In Canada, several feasibility studies to construct an IGCC plant were completed in the 80s and early 90s. One of them was a site specific study by Bechtel for a major Canadian utility [7]. In this case, coal was gasified to medium Btu gas in a state of the art gasification plant with maximum heat recovery. The plant incorporates one advanced GE 7F gas turbine generating 192 MW electricity and a reheat steam turbine. Based on this study, the flow sheets of four IGCC plants employing Shell, Texaco, British Gas Lurgi (BGL) and Kellogg–Rust–Westinghouse (KRW) gasifiers were developed. The performances of two coals and one lignite were simulated. The models were built by using the ASPEN steady state simulation software for the total of 12 cases. The models comprise several sections such as coal preparation, gasification, gas cooling, acid gas removing, sulfur recovery, heat recovery systems and gas turbine and steam cycles. Each section can be simulated independently.

Based on the results from the simulation, analyses and comparisons of the four IGCC power plants were performed.

2. Gasification processes

The features of the four gasifiers chosen for this study differ significantly. The typical ranges of the operating parameters of these gasifiers are given in Table 1. Texaco and Shell employ an en-

Table 1
Typical operating parameters of gasifiers

	Shell	Texaco	BGL	KRW
Bed	Entrained	Entrained	Moving	Fluidized
Feeding	Dry	Slurry	Wet	Wet
Temperature, °C	2000	1250–1550	2000	870–1040
Pressure, Mpa	3.0	4.1	2.5	2.1
Coal size, mm	<0.1	<0.1	4–5	<5

trained bed of the coal water slurry feeding system and a dry pulverized coal feeding system, respectively. The BGL gasifier consists of a down flow moving bed and is available either in the dry or slagging mode. The KRW gasifier employs a fluidized bed of coal either with or without injection of limestone for sulfur capture. The technical literature on the performance of these gasifiers is extensive [3–8]. Therefore, only a cursory account of the individual gasifiers will be given for the purposes of this article.

2.1. Shell gasifier

Pressurized coal, oxygen and, if necessary, steam enter the gasifier through pairs of opposed burners. The gasifier consists of an outer pressure vessel and an inner water cooled membrane wall. Gasification temperature is controlled by the cooling coils where saturated steam is generated. The raw gas (mainly H_2 and CO) leaves the reactor at near gasification temperature. It is subsequently quenched by a cool recycle gas before entering the convective cooler where superheated steam is generated. After leaving the syngas cooler, the cooled gas passes through the bag filter where about 98% of the fly slag is removed. Part of the cleaned gas is used as quench gas. The remainder of the gas enters the scrubber to remove particulates, ammonia and salts. The gas is then passed through a catalytic reactor to hydrolyze 95% of COS according to the following reaction:

$$COS + H_2O = H_2S + CO_2 \tag{1}$$

The hydrolysis unit is necessary if 99% + sulfur removal is desired in the downstream acid gas removal plant since up to 5% of sulfur in coal is released as COS. The gas is further cooled before entering the Selexol unit. The acid gas from the Selexol unit enters the Claus plant where about 95% of H_2S is converted to elemental sulfur according to the following reactions:

$$H_2S + 1.5O_2 = SO_2 + H_2O \tag{2}$$

$$2H_2S + SO_2 = 2H_2O + 3S \tag{3}$$

A SCOT tail gas treatment unit is used to treat the small amount of unconverted sulfur compounds in the gas exiting the Claus plant. The sulfur compounds are reduced to H_2S by reacting with a small amount of clean gas in a catalytic reactor according to the two reactions:

$$SO_2 + 3H_2 = H_2S + 2H_2O \tag{4}$$

$$COS + H_2 = H_2S + CO \tag{5}$$

The acid gas from the SCOT unit is then recycled to the Claus plant for sulfur recovery. The clean gas from the Selexol unit enters the fuel gas saturator where the cold fuel gas is contacted with hot water. The transfer of moisture and heat takes place from the liquid stream to the gas stream. The moisture in the gas inhibits NO_x formation and increases the mass flow through the turbine expander. The fuel gas from the saturator, air supplied by the compressor and nitrogen from the air separation unit are injected into the gas turbine combustion chamber. The gas turbine used for this study is GE's advanced gas turbine 7F, having the firing temperature of 1260 °C, 18 stages of compression and a nominal gross output of 192 MW at ISO conditions. The hot gas leaving the combustion chamber is directed to the gas turbine expander that drives the compressor and the generator. The gas turbine is coupled to the heat recovery steam generator (HRSG) that recovers heat from the turbine flue gas. The HRSG produces saturated steam and superheated steam. The latter drives the steam turbine, whereas the saturated steam supplies the plant's power requirements. The flue gas leaves the stack of the HRSG at about 90 °C. The steam turbine consists of high pressure, intermediate pressure and low pressure power turbines.

2.2. Texaco gasifier

The features of the entrained bed Texaco gasifier differ from those of the entrained bed Shell gasifier. In the former case, oxygen and the coal–water slurry are injected at the top of the reactor. The hot raw gases exiting the gasifier section are cooled in the radiant cooler before entering the convective cooler. This generates high pressure steam by heat exchange. The slag settles in the water quench at the bottom of the radiant cooler and is removed through the slag removal system. All particulates are then removed in the water scrubber. For the purpose of this study, the Texaco process uses the same method for treating the gas as the Shell process used. The system of gas and steam turbines coupled with the HRSG is also the same.

2.3. BGL gasifier

This is a moving bed gasifier where coal is fed into the top of the reactor via the lock hopper system, which is pressurized with nitrogen. If used as a flux, limestone is mixed with the coal on the conveyer belt before entering the coal feed lock hoppers. Steam and oxygen are injected through tuyere nozzles. Gasification and devolatilization occur in the main part of the coal bed. The product gas leaves the reactor via an off-take above the bed after heat exchange between the down flowing coal and the ascending hot gas. The hot gas leaving the gasifier is quenched with excess recycle water down to about 160 °C. Simultaneously, entrained dust and volatile coal products (hydrocarbons, ammonia and chlorides) are transferred into the liquid stream, which is discharged from the sump of the downstream heat exchanger to the gas liquor separation area. The raw gas is further cooled to about 30 °C before entering the gas cleaning system. The Purisol gas cleaning process was chosen instead of the Selexol used for the Shell and Texaco gasifiers. The other gas treating steps, as well as the system of gas and steam turbines, are similar to those used for the entrained bed gasifiers.

2.4. KRW gasifier

The pressurized fluidized bed gasifier operates either with or without limestone injection for sulfur capture. The latter mode was chosen for the present study. In this gasifier, coal is conveyed pneumatically to its base along with the recycle gas and recycle fines. As a result of the temperature employed, the ash particles agglomerate, becoming dense enough to travel to the base of the gasifier where the ash is removed. The hot gas exiting the top of the reactor carries with it the unconverted carbon in the form of char, which is removed by cyclones and returned to the gasifier bottom. The raw gas is cooled and then scrubbed to remove the remaining particulates before passing to the gas cleaning system. The gas cleaning steps used for this study are identical to those used for the Shell gasifier.

3. Methodology

Most of the information used to set up models for the present study was based on the study conducted by Bechtel [7]. However, whenever the required data were not available, either suppliers were contacted or the data base in the technical literature was used [8–10]. The flow sheet of such model was composed of several naturally grouped sections such as coal preparation, gasification, gas cooling and cleaning, acid gas removal, gas turbine, HRSG, steam cycle etc. Once the initial conditions were given, each section can be simulated and studied independently. Most of the sections were composed from the ASPEN standard unit operation blocks such as compressors, separator, mixer, reactor etc. However, because of the complexities of the process, several routines developed with in-house expertise were used, especially in the gasification section. The flow sheets used for simulation are very complex and extensive. Each contains hundreds of unit operations and simulation controllers. Those flow sheets are available on request from the authors.

Simulation was controlled by several FORTRAN routines and design specifications. Any functional relationship was put into those FORTRAN routines to reduce the number of initial conditions and to adjust automatically those associated variables. Design specifications will change one or several settings of the variables until a specified objective is achieved.

Since this is a large and complicated simulation with many nested loops, it has been recognized that the simulation is very sensitive towards the loop's break points and their initial conditions. After detailed mathematical analysis, a specific computational sequence was set up for each model, and the ranges of initial conditions were established.

4. Input data

The properties of the three coals used for the study are shown in Table 2. Coal A is the Prince coal from Eastern Canada, coal B is the sub-bituminous Genessee coal from Alberta and coal C is the lignite from Saskatchewan. Extensive evaluation of these coals was undertaken elsewhere [11]. The feeding rates of these coals are given in Table 3. For the Shell and Texaco gasifiers, the coals were dried to enable pulverization to attain an average particle diameter of about 40 μm. For the

Table 2
Properties of coals (wt.%)

Coal	A	B	C
Proximate			
Moisture	8.9	19	18.6
Ash	10.7	17	13.3
Volatiles	32.5	24.4	30.8
Fixed carbon	47.9	39.6	37.3
Ultimate, DB			
Carbon	69.71	48.9	61.2
Hydrogen	4.8	5.2	3.9
H/C	0.82	1.28	0.77
Nitrogen	1.4	0.6	0.8
Sulphur	3.64	0.22	0.92
Oxygen	7.83	24.9	16.8
Ash	11.8	21	16.4
HHV*, MJ/kg	29.4	24.19	23.41

* Higher heating value.

Table 3
Gasifier input data

Gasifier	Coal	Moisture, %	Coal flow, 10^3 kg/h	Oxygen/coal	Steam/coal
Shell	A	1	180.8	0.9	0.09
	B	0	227.5	0.4	0.01
	C	0	219.6	0.73	0.02
Texaco	A	0	191.9	0.97	*
	B	0	267.3	0.64	*
	C	0	238.2	0.84	*
Lurgi	A	8.9	167.6	0.56	0.372
	B	19	271	0.2	0.001
	C	18.6	240.7	0.45	0.002
KRW	A	8.9	451.3	0.79	0.34
	B	19	645.3	0.28	0.008
	C	18.6	592.9	0.53	0.165

* Slurry concentration 65%.

BGL and KRW gasifiers, the coals were used without drying. In the case of the Shell, Texaco and BGL gasifiers, the relative feeding rates were chosen so as to give a similar heat rate determined from the HHV of the coals. The parameters such as oxygen/coal and steam/coal ratio reflect differences in the gasifier features and coal composition. For example, the higher oxygen/coal ratio for the Texaco gasifier compared with the Shell gasifier indicates the need to carry out the partial oxidation of coal to a higher stage to generate extra heat for evaporation of the water in the coal slurry. The oxygen/coal ratio increases with decreasing oxygen content of coal, and it is the lowest for coal B. This suggests that most of the oxygen in coal will be released as CO and CO_2. This is

particularly true for the entrained bed gasifiers because of the high temperatures employed (Table 1). In the case of the BGL gasifier, pyrolysis is an important contributor to the overall conversion of coal, and therefore, the oxygen requirement is lower.

5. Discussion

The model can generate all the important data of an IGCC plant. This includes the detailed composition of the gaseous streams with all the contaminants and the heating value of the clean gas as well as the mass and volume of clean gas. The set of performance parameters obtained by simulation consists of the total power generated (gas turbine and steam turbine), power consumed in the plant and the overall thermal efficiency. The effect of various parameters on the performance of the IGCC plant can be studied by changing the input file, e.g. coal feeding rate, type of coal, oxygen/coal ratio, steam/coal ratio etc.

5.1. Composition of gaseous streams

The results in Tables 4 and 5 illustrate the effect of the different gasifiers on the compositions of the four gaseous streams obtained from coal A. As expected, the fuel gas from the slurry fed gasifier contains more CO_2 and H_2 and less CO than that from the dry fed gasifier because the excess of steam is consumed in the following reaction:

$$CO + H_2O = CO_2 + H_2$$

Table 4
Conditions of various gases of Shell and Texaco processes

Component (mol%)	Shell				Texaco			
	Raw	Clean	Acid	Stack	Raw	Clean	Acid	Stack
O_2	0	0	0	12.5	0	0	0	11.5
N_2	4.1	4.2	0	75	1	1.3	0	75.5
H_2	27.6	28.8	0.2	0	28.6	36.1	0.1	0
CO	61.3	63.8	2.3	0	38.4	48.3	0.7	0
CO_2	2.2	2	21.5	6.9	12.6	12.9	69.4	7.1
H_2O	2.5	2	0	4.7	17.4	0.2	0	5.1
CH_4	0.1	tr	0	0	0.15	tr	0	0
Ar	0.8	0.9	0	1	0.7	0.9	0	1
H_2S	1.15	6*	75.9	0	0.96	4*	29.8	0
SO_2	0	0	0	<1*	0	0	0	<1*
COS (ppm)	848	44	0	0	412	25	278	0
Average molecular weight	21.1	20.9	36	29.3	30	20.8	40.9	29.2
Total volume, $10^3 m^3/h$	31.3	6.9	2.1	2093	30.4	7.4	5.8	1989
Temperature, K	1811	311	322	378	1644	311	322	380
Pressure, bar	36	27	1.5	1	44	27	1.5	1

* Values in ppm.

Table 5
Conditions of various gases of BGL and KRW processes

Component (mol%)	BGL				KRW	
	Raw	Clean	Acid	Stack	Clean	Stack
O_2	0	0	0	13.4	0	14
N_2	2.5	2.8	0.1	73.5	0.9	71.2
H_2	26.1	29	0.2	0	29.1	0
CO	49.1	54.6	0.1	0	51.1	0
CO_2	3.5	2.4	52.3	6	12.3	6
H_2O	9.6	3.2	0	6.2	0.1	7.6
CH_4	6.5	7.1	0.3	0	5.1	0
Ar	0.5	0.5	1	1	1.3	1
H_2S	1.08	14*	44.4	0	65*	0
SO_2	0	0	0	2*	0	6*
COS (ppm)	638	0	2.6	0	0	0
Average molecular weight	20.8	19.8	39.9	29	22	29
Total volume, $10^3 m^3$ /h	16.7	5.6	0.13	2072	18.4	4965
Temperature, K	935	303	303	378	310	400
Pressure, bar	32	27	24	1	21	1

* Values in ppm.

Also, the higher oxygen/coal ratio used for the Texaco gasifier (Table 3) suggests that a larger part of the carbon in the coal was converted to CO_2 than that in the Shell gasifier, as it is shown in Table 4. In addition, the higher temperature employed in the latter gasifier slows the oxidation of CO to CO_2. The difference in CO_2 content is responsible for the significant difference between the composition of the acid gas from the Shell and Texaco gasifiers, i.e. CO_2 content of 21.5 and 69.4, respectively, and H_2S content of 75.9 and 29.8, respectively, whereas the concentration of CO_2 and H_2S in the clean gas from BCL gasifier (Table 5) is between these two extremes. This is significant for the scale up of the Claus and SCOT plants. The total volume of the raw gas from the Texaco gasifier is greater than that exiting the Shell gasifier. This results from the presence of unconsumed steam in the former. It will be shown later that this will translate into a greater amount of heat recovered in the syngas cooler in the Texaco gasifier.

The presence of methane in the clean gases from the BGL and KRW gasifiers (Table 5) represents the main difference compared with the clean gases from the entrained bed gasifiers (Table 4). It is noted that small amounts of C_{4-} hydrocarbons can also be present in the gas. This results from the significantly lower temperatures employed in these gasifiers compared with that used in the entrained bed gasifiers (Table 1). This suggests that a nearly complete incineration of organic matter cannot be achieved in both the BGL and KRW gasifiers because of the relatively low temperatures employed.

Although not shown, the composition of the gaseous streams for coals B and C reflect their analyses in Table 2. First of all, their content of H_2S was significantly lower than that for the same streams obtained from coal A. Moreover, the content of alkali species in the mineral matter of coals B and C is much higher than that in coal A [11]. Then, part of the sulfur will be captured

by the mineral matter during cooling of the gas. This suggests that the content of H_2S in the raw gas from coals B and C determined by the model represents an overestimate of the actual values. Another important difference that can be related to the coal analysis in Table 2 is the relatively high content of hydrogen in coal B. As a result of this, the H_2/CO ratio of the fuel gas is higher than that obtained from coals A and C.

Extensive information in the scientific literature confirms that the compositions of the gases from the Shell and Texaco gasifiers shown in Table 4 are similar to those obtained from commercial gasifiers [4–9]. Then, the calculations based on minimizing the total Gibbs free energy are suitable means for predicting the composition of gasifier products [12]. This is not surprising considering the high temperatures and small particle size of the coal employed in these gasifiers. This ensures that gasification conditions approach thermodynamic equilibrium. As it was indicated above, the situation in the BGL gasifier is much more complex. Thus, the model has to consider three different stages, i.e. drying, pyrolysis, gasification and, in the case of the slagging version of the gasifier, also combustion at the bottom part of the gasifier.

5.2. Heating values of clean gases

The chemical compositions of the clean fuel gases in Tables 4 and 5 were used to obtain the HHV and LHV shown in Table 6. The total volumes of gas in Table 6 represent the same volume of clean gas in Tables 4 and 5 recalculated to 288 K and one bar pressure. It is evident that the differences in the operating conditions of the gasifiers are reflected by the different HHV and LHV of the gas. The lower HHV and LHV of the gas from the Texaco gasifier result from the relatively high content of CO_2. It was indicated above that the amount of CO_2 from the Texaco gasifier in excess of that from the Shell gasifier results from the different conditions employed in the former. The higher HHV and LHV of the clean gas from the BGL gasifier compared with the other gasifiers are attributed to the presence of CH_4, which has about three times higher heating

Table 6
Heating values (MJ/m^3), yield (m^3/h) and heat rate (MJ/h) of clean gas

	Coal	HHV	LHV	Yield*	Heat rate*
Shell	A	11.12	10.58	172.5	1918
	B	11.76	11.03	161.7	1902
	C	11.53	11.03	176.1	2030
Texaco	A	10.15	9.47	185.6	1884
	B	9.58	8.81	186	1782
	C	9.65	8.96	190.8	1841
BGL	A	12.77	11.94	143.7	1835
	B	13.27	12.35	150.3	1994
	C	12.29	11.61	151.9	1867
KRW	A	11.56	10.86	356.6	4122
	B	12.66	11.7	331.4	4196
	C	12.16	11.28	365.4	4443

* At 288 K and 1 bar.

value than CO and H_2. The heating value would be even higher if the C_{4-} hydrocarbons were considered. Such hydrocarbons are almost certainly present in the gas from the Lurgi gasifier. It is shown that for the entrained bed gasifiers and BGL gasifier, the overall heat rates obtained from the HHV of the gases and the total gas volume differ by less than five percent. This follows from the coal flows in Table 3, which were chosen so as to obtain similar heat rates from each gasifier. For the KRW gasifier, the high yields of clean gas in Table 6 correspond with the higher coal feeding rates in Table 3. On the dry coal basis, the ratio of the feeding rate of coal A into the KRW gasifier to that into the BGL gasifier is about 2.7, whereas the ratio of the corresponding heat outputs in Table 6 is about 2.1.

5.3. Performance parameters

The performance parameters of the IGCC plants with the Shell and Texaco gasifiers are summarized in Table 7, whereas those with the BGL and KRW gasifiers are shown in Table 8. The similar gas turbine outputs for the IGCC plants with the Shell, Texaco and BGL gasifiers are in line with the similar input heat rates (Tables 2 and 3) used in the study involving these three gasifiers. It is noted that the study did not consider the fines agglomeration, which might be required for the BGL gasifier. The independent study was also conducted on the performance of an IGCC plant employing the KRW gasifier. The results from this study are included for comparison in spite of the different heat rates (Tables 3 and 6).

The high steam turbine outputs for both the Shell and Texaco gasifiers shown in Table 7 indicate the full heat recovery mode of the operation. For every coal, the steam turbine output for the Texaco gasifier was greater than that for the Shell gasifier. Definitely, this results from the greater volume of raw gas (including unconsumed steam) from the former. Thus, the total volume of the raw gas from the Shell gasifier, calculated for the same conditions as that for the Texaco gasifier, is $23.4 \times 10^3\,m^3/h$ compared with $30.4 \times 10^3\,m^3/h$ for the latter. Apparently, among the three coals, coal B is the most suitable for entrained bed gasification mainly because of the lower oxygen

Table 7
Overall performance of Shell and Texaco process

	Shell			Texaco		
	Coal A	Coal B	Coal C	Coal A	Coal B	Coal C
Power generated, MW						
Gas turbine	191.5	192.1	192	191.7	191.5	192
Steam turbine	133.6	136.2	129.3	145.1	193.1	141.3
Total (gross)	325.1	328.2	321.3	336.8	384.6	333.3
Power consumed, MW						
Air separation	40.4	25.5	39.7	34.8	32	37.2
Pumps and compressors	2.6	3.1	2.5	2.5	3.1	2.6
Miscellaneous	5.7	5.7	5.6	6.6	7.6	6.6
Total (consumed)	48.6	34.4	47.9	43.9	42.6	46.3
Total power (net), MW	276.5	293.9	273.4	292.9	342	287
Thermal efficiency, %	41.7	42.37	42.22	41.2	41.97	40.83

Table 8
Overall performance of BGL and KRW process

	BGL			KRW		
	Coal A	Coal B	Coal C	Coal A	Coal B	Coal C
Power Generated, MW						
Gas turbine	186.9	191.9	192	389	389	389
Steam turbine	78.4	113.5	85.7	274.7	267.9	282.9
Total (gross)	265.3	305.4	277.9	663.7	656.9	671.9
Power consumed, MW						
Air separation	21.5	13.5	26.7	66.3	33.6	58.4
Pumps and compressors	1.4	1.7	1.2	5.2	4.8	5.2
Miscellaneous	5.2	6	5.5			
Total (consumed)	28.1	21.2	33.4	71.5	38.4	63.6
Total power (net), MW	237.2	284.2	244.4	592.1	618.4	608.3
Thermal efficiency, %	41.95	42.47	42.3	38.88	38.81	42.72

requirements. This results from the high oxygen content in coal B. As it was indicated above, this oxygen will be predominantly released as CO and CO_2. For every coal, the overall thermal efficiency of the Shell gasifier is greater than that of the Texaco gasifier. To a certain extent, this results from the incomplete recovery of the heat used to evaporate the water in the slurry.

For the BGL gasifier, the low steam turbine output (Table 8) reflects the much lower temperature of the raw gas than that from the Shell and Texaco gasifiers, i.e. less recoverable heat to generate steam is available. As expected, the total volume of the clean gas produced in the BGL gasifier is less than that in the entrained bed gasifiers. This results from the presence of methane and other hydrocarbons in the clean gas. Thus, if all methane is converted to CO and H_2 via steam reforming, the equivalent volume would increase by almost a factor of four. The lower volume of the clean gas from the BGL gasifier is compensated by its higher heating value, as it is shown in Table 6. Moreover, the low total power consumed in the BGL gasifier (Table 8) compared with that in the entrained bed gasifiers is another reason for the similar overall thermal efficiency of these gasifiers. For the BGL gasifier, the type of coal had a pronounced effect on the total power consumed, which was the lowest for coal B. This results mainly from the low oxygen/coal ratio due to the reasons mentioned earlier. Yet, the overall thermal efficiency for coals B and C is similar in spite of the significantly greater amount of power consumed for the latter. This is attributed to the total volume of the gas produced, which was about 15% greater for coal C than that for coal B in spite of the more than 10% higher feeding rate for the latter (Table 3).

It should be noted that the coal feeding rates for the KRW gasifier were more than two times greater than those for the other gasifiers. This is in line with the greater power outputs and consumption shown in Table 8. Both the steam turbine and combustion turbine outputs were similar for all three coals. To achieve this, the feeding rate of coal B had to be more than 30% and 10% higher than that of coals A and C, respectively. The lower power consumption for coal B could not offset its higher feeding rate. The significant difference between the overall thermal efficiency of coal C and those of coals A and B should be noted. In comparing coal B with coal C, the higher efficiency results from the greater volume of clean gas for the latter coal (by about 10%) in spite of

the greater feeding rate of coal C (by about 10%). Almost certainly, the high power consumption for coal A was the reason for its overall thermal efficiency not being better than that for coal B.

5.4. Selection of gasifiers for IGCC plant

With respect to IGCC technology, the experience around the world indicates a preference for entrained bed gasifiers over the BGL and KRW gasifiers, although the same is not clearly indicated by the performance parameters determined by this model. Definitely, the capital cost of the BGL and KRW gasifiers is lower than that of the entrained bed gasifiers. Thus, the selection of materials for entrained bed gasifiers requires special attention because of the high temperatures employed (Table 1). For example, a molten slag resistant refractory lining and a syngas cooler made of super alloys are necessary to ensure long life operation of a Texaco gasifier. Because of the much lower temperatures, the selection of materials for the BGL and KRW gasifiers is rather straightforward. However, if the slagging mode of the former gasifier is chosen, its bottom part requires materials that are resistant to molten slag.

The advantages of the entrained bed gasifiers includes feedstock flexibility. Essentially, any carbonaceous solid that can be pulverized can be successfully fed into the entrained bed gasifier. Moreover, the Texaco gasifier is suitable for gasification of molten feeds such as distillation residues. If a slurry mode is used, refinery sludges (K-sludges) can be readily gasified, suggesting that entrained bed gasifiers can function as incinerators of organic waste. The same cannot be achieved in the BGL and KRW gasifiers because of the lower temperatures employed. The BGL gasifier cannot handle fine particles. Therefore, fines agglomeration may be required to achieve complete utilization of coal feed. Moreover, some difficulties may be experienced with caking coals, although this problem can be minimized by a specially designed coal bed. In a slagging mode, the BGL gasifier can handle non-reactive coals, whereas an incomplete conversion of such coals is expected in the KRW gasifier. If limestone injection is employed in the latter, the ''aeration'' of the solid residue to convert CaS to $CaSO_4$ must be part of the operation. It should be noted that in the present study, neither fines agglomeration nor limestone injection were considered for simulation of the BGL and KRW gasifiers. For the former gasifier, the addition of the fines agglomeration process would affect the overall efficiency, whereas for the KRW gasifier, limestone injection would result in either downsizing or elimination of the acid gas treatment plant. Apparently, the gas cleaning system, as considered in the present study for the KRW gasifier, ensures the emissions level required by regulations.

The environmental performance of the gasifiers is another factor to be considered. It is evident that the content of SO_x, NO_x and particulates in the clean gas is determined by the cleaning system employed. Because of the similar systems, the clean gas from all four gasifiers will meet specifications. The entrained bed gasifiers do not produce any liquid effluents, although the scrubbing and quench water may require a treatment before being discarded and/or recycled. The properties of the solid residues such as slag, fly slag and ash, particularly their leachability, depend on the temperature employed in the gasifier. High temperatures, such as used in the entrained bed gasifiers, ensure slagging of the mineral matter. The glassy form of the slag is virtually non-leachable and can be either utilized industrially or safely discarded. The same applies for the slag from the BGL gasifier operating in a slagging mode. The slagging of mineral matter cannot be achieved at the temperatures used in the KRW gasifier, suggesting that the leachability of such ash deserves

attention. Among the four gasifiers compared in this study, the BGL gasifier is the only one generating a sizeable amount of oil and tar. Therefore, the liquid separation system has to be part of the operation. In the case of advanced BGL gasifiers, the liquids are recirculated and reinjected into the combustion zone of the coal bed for incineration. Overall, the environmental performance of the entrained bed gasifiers seems to be better than that of the BGL and KRW gasifiers.

6. Conclusions

The ASPEN software is a suitable tool for simulation of the performance of IGCC plants. The data base of technical parameters required for comparison of the different flow sheets of the plants can be generated in a relatively short time. This includes performance parameters such as the net power generated and power consumed in the plant as well as the overall thermal efficiency. The yield and composition of the gaseous streams can be estimated for the given input of coal feed. Such data base forms the basis for feasibility studies before making a major decision on the construction of commercial IGCC plants.

It is evident that the overall performance of IGCC plants depends on the type of gasifier as well as on the properties of the feedstock, particularly its heating value and the proximate and ultimate analyses. For eight cases involving Shell, Texaco and BGL gasifiers, the overall thermal efficiency varies within less than 0.5%. The greater difference is only observed for the Texaco case with coal C (lignite) because of the larger power consumption in the plant. Then, the selection of gasifier for a commercial IGCC plant has to take into consideration other factors, e.g. environmental performance, feedstock flexibility, capital, operational costs etc. The results suggest that the performance of the KRW gasifier is influenced by the feedstock properties to a greater extent than that of any of the other gasifiers. Apparently, lignite is a more suitable feed than the sub-bituminous and bituminous coals.

References

[1] Furimsky E. Fuel Proc Technol 1998;56:263.
[2] Geosits RF, Mohammad-Zadeh Y. Power-Gen. Americas 93, Dallas, TX, November 1993.
[3] Clarke LB. Management of by-products from IGCC power generation. IEA Coal Research. Report IEACR/38, London, UK, 1993.
[4] Kristiansen A. Understanding coal gasification. IEA Coal Research. Report IEACR/86, London, UK, 1996.
[5] Takematsu T, Maude C. IEA Coal Research. Report IEACR/37, London, UK, 1991.
[6] Furimsky E. Rev Inst Fr Petr 1999;5:597.
[7] Bechtel Canada Inc. Nova Scotia power coal gasification implementation development program: phase I vol. 1&2, December 1992.
[8] Fluor Engineers. Cost and performance for commercial applications of Texaco-based gasification-combined cycle plants, vol. 1&2, EPRI AP-3486, April 1984.
[9] Ralph M. Parson Co. Evaluation of British Gas Corporation/Lurgi slagging gasifier in gasification-combined cycle power generation. EPRI AP-3980, March 1985.
[10] Vlaswinkel EE. Fuel Proc Technol 1992;32:47.
[11] Furimsky E, Palmer A, Kalkreuth W, Cameron A, Kovacik G. Fuel Proc Technol 1990;25:135.
[12] Furimsky E, Zheng L, Baudreau F, Kovacik G. Erdol und Kohle 1993;10.