Impact of coal quality and gasifier technology on IGCC performance

Ola Maurstad[1]*, Howard Herzog**, Olav Bolland*, János Beér**

*The Norwegian University of Science and Technology (NTNU),
N-7491 Trondheim, Norway

**Massachusetts Institute of Technology (MIT),
77 Massachusetts Avenue, Cambridge, MA 02139, USA

Abstract
Integrated coal gasification combined cycle (IGCC) plants with pre-combustion capture of CO_2 represent one of the most promising options for power generation with carbon capture and storage. This work investigates to what extent IGCC performance (with and without CO_2 capture) is affected by coal quality for two different entrained flow slagging gasifiers. Based on an IGCC model developed in Aspen Plus and combined with GTPRO, mass and energy balances were computed. Two gasification technologies were considered: A dry feed gasifier with syngas heat recovery which represents the Shell technology, and a slurry feed gasifier with full water quench which represents the GE technology. For each gasifier, five different coals were used and alternatives with and without CO_2 capture calculated. It was found that the thermal efficiency, CO_2 emissions and net power output of the slurry feed IGCC was strongly dependent on coal type, and had lowest performance for low rank coals. On the other hand, the dry feed IGCC was little affected by coal type. The slurry feed IGCC performed closest to the dry feed IGCC when CO_2 was captured and the two highest rank bituminous coals were used.

Keywords: IGCC, pre-combustion, capture, coal quality, efficiency

Introduction

Integrated coal gasification combined cycle (IGCC) has emerged as an alternative to conventional pulverized coal (PC) plants for generating power from coal. If CO_2 capture and storage will be required, IGCC with pre-combustion capture is considered one of the most promising power generation technologies. Most studies have evaluated IGCC performance for bituminous coals [1], however it is estimated that 47 % of global coal reserves consist of lignite and sub-bituminous coals [2]. Several gasifier technologies have been developed to various extents, however only a few of these have reached the commercial stage [3]. The type of gasifiers most frequently considered for new gasification projects (i.e., entrained flow slagging gasifiers), are bounded operationally by the Shell dry feed gasifier and the GE (formerly Texaco) slurry feed gasifier. Therefore, this paper discusses the main effects of coal quality on gasifiers similar to the Shell and GE technologies and the performance of the corresponding IGCC plants with and without CO_2 capture.

Process description

The power block of an IGCC plant is similar to that of a natural gas fired combined cycle plant which includes a gas turbine and a steam cycle. An IGCC plant also includes the major functions necessary to produce a gaseous fuel: coal preparation, gasification, air separation and gas cleanup.

The Shell and GE gasifiers are both entrained flow slagging gasifiers which typically operate at around 40 bar and 1500 °C, well above the melting point of the ash to ensure that the molten ash (slag) has a

[1] Corresponding Author: ola.maurstad@ntnu.no, +47 73550843

low enough viscosity to flow easily out of the gasifier. Both gasifiers use pulverized coal with typical particle diameters of 100 µm. The Shell gasifier has a dry feed lock-hopper pressurization system, while the GE gasifier has a slurry feed system. Sufficient oxygen (95 mole % purity) from an air separation unit (ASU) is fed to the gasifier which through partial oxidization of the coal provides heat to achieve the desired operating temperature and converts the coal feed into a syngas mixture. When steam is required to ensure sufficient carbon conversion (avoid solid carbon product), this is bled from the power block's steam turbine.

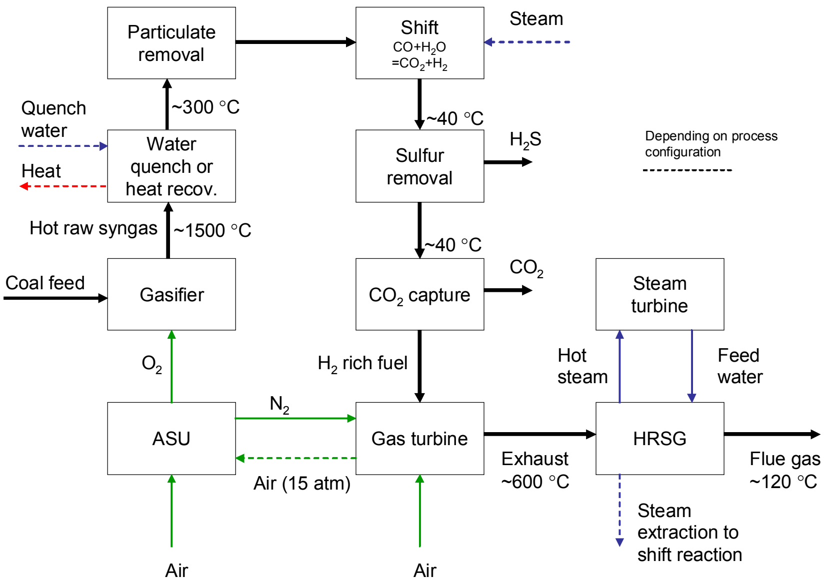

Figure 1 IGCC process description

The hot raw syngas exiting the gasifier needs to be cooled down for "cold" gas cleanup (including removal of slag particles and different trace elements, sulfur and if relevant CO_2 capture). A full water quench is one method of cooling the syngas, another method is to mix it with recycled syngas which has already been cooled. The latter method includes utilization of the sensible heat in the syngas by generating steam in syngas coolers which is sent to the steam cycle for increased power generation. In case of CO_2 capture, a shift reaction step (where CO and H_2O exothermically react to CO_2 and H_2) is necessary to achieve acceptable CO_2 capture ratios, and if the H_2O/CO mole ratio is less than 2, addition of steam generated in the shift and syngas coolers is required. Sulfur (as H_2S) and CO_2 is removed by the Selexol process (physical absorption).

The remaining gas mixture is the fuel for the gas turbine (GT). For standard IGCCs, this mixture consists of mainly CO and H_2. When CO_2 is captured, the fuel consists of mainly H_2. The fuel is moisturized, preheated and diluted with nitrogen from the ASU before combustion in the gas turbine's diffusion combustor. To achieve higher plant net power output, half of the ASU air is bled from the GT's compressor discharge (50 % air side integration between ASU and GT), therefore an ASU operated at elevated pressure (~15 bar) has been assumed. The heat recovery steam generator (HRSG) utilizes the GT exhaust heat to produce superheated steam at different pressure levels which is fed to a steam turbine.

Methodology and key assumptions

An IGCC model was developed by using the process simulator Aspen Plus in combination with the software GTPRO. The purpose of the model is to determine mass and energy balances for numerical evaluation of the thermal efficiency, CO_2 emissions (kg/kWh) and key process flow rates to get a qualitative understanding of process equipment size. Two gasification technologies were considered in the IGCC modeling:

- Case 1 (Dry feed IGCC)
  - Coal drying process similar to RWE's WTA[2] technology [4]
  - Dry feed gasifier similar to the Shell technology
  - Quench by gas recycle, and syngas cooler for heat recovery (steam generation)
- Case 2 (slurry feed IGCC)
  - Slurry feed gasifier similar to the GE technology (formerly Texaco)
  - Full water quench, no syngas heat recovery

In addition to the gasifiers, the other key components of an IGCC system were included in the Aspen Plus model. It was chosen to represent commercially available technology for the gas clean up (cold gas clean up with Selexol for sulfur removal and CO_2 capture), the gas turbine (F-class technology) and the steam cycle (three pressure levels, subcritical). To deal with the complexities of steam cycle heat integration, the software GTPRO was used in combination with the Aspen Plus model. The model was developed to consider plants with and without CO_2 capture. Five different coals as described in [5] were used in the calculations. These coals range in rank from lignite to low-volatile bituminous and differ significantly in moisture, ash content and heating value. Table 1 summarizes the key assumptions and input data used.

Table 1 Key assumptions and input for the computations (mf = moisture free, ar = as-received)

Coal ID	Coal 1	Coal 2	Coal 3	Coal 4	Coal 5
Name	North Dakota lignite	Wyoming PRB	Illinois #6	Upper Freeport, PA	Pocahontas #3, VA
HHV [MJ/kg mf coal]	25.59	27.25	27.80	31.32	34.95
HHV [MJ/kg ar coal]	17.34	19.60	25.58	30.97	34.72
Moisture [kg/kg ar coal]	32.24 %	28.09 %	7.97 %	1.13 %	0.65 %
Moisture [g /MJ (HHV)]	18.6	14.3	3.1	0.4	0.2
Ash [kg/kg ar coal]	6.59 %	6.31 %	14.25 %	13.03 %	4.74 %
Ash [g/MJ (HHV)]	3.8	3.2	5.6	4.2	1.4
Case 1 (Dry feed with heat recovery)	p = 40 bar, 99 % carbon conversion, pre-drying to 5 % moisture				
Operating temperature [°C]	1400	1400	1450	1500	1550
Oxygen [kg/(kg mf coal)]	0.768	0.818	0.744	0.807	1.023
Steam [kg/(kg mf coal)]	0.000	0.000	0.044	0.186	0.178
Nitrogen [kg/(kg mf coal)]	0.070	0.070	0.070	0.070	0.070
Case 2 (Slurry feed with water quench)	p = 40 bar, 95 % carbon conversion				
Operating temperature [°C]	1400	1400	1450	1500	1550
Slurry solids concentration [%]	40.90	48.00	61.10	70.70	75.70
Oxygen [kg/(kg mf coal)]	1.193	1.106	0.844	0.818	1.006

The developed model is somewhat less detailed (e.g. fewer number of components in the flowsheet) than a corresponding model from an engineering study and the gasifier model has been based on the assumption of uniform operating temperature and chemical equilibrium; these simplifications, however, will probably not significantly change the results focused on in this work.

Results and discussion

The key computational results are summarized in Table 2 and include thermal efficiencies[3] (both LHV and HHV), CO_2 emissions and net power output. As shown in Figure 2, the efficiency of Case 2 is much more sensitive to coal type than Case 1. The observed drop in efficiency for lower rank coals is explained by the reduced energy density of the slurry, due to a combination of lower heating value coals (see HHV mf coal in Table 1) and reduced achievable solids slurry concentrations. The lower the energy density of

[2] The WTA (German acronym for "Fluidized bed dryer with integrated waste heat recovery") technology is being developed by RWE who has operated two demonstration plants at Frechen, Germany (1993-2004). RWE plans to start construction of a commercial scale demonstration plant (110 t/h dry lignite) in 2006 as a final step to demonstrate commercial viability. This information was provided by RWE (Schwendig F. Braunkohlentrocknung – ein Grundbaustein für CO_2-arme Kraftwerkstechnik. Konventionelle Kraftwerke – Techniktrends und zukünftige Entwicklungen, Nürnberg, 27 Oktober, 2005)

[3] The thermal efficiency is defined as the ratio between the net electricity delivered to the grid and the chemical energy in the coal feed. The chemical energy is based on either the lower heating value (LHV) or on the higher heating value (HHV).

the slurry feed, the higher is the need for energy to heat up the feed and vaporize water. The computations showed that 1) the cold gas efficiencies of gasification[4] were reduced from 79.3 % for Coal 5 to 49.1 % for Coal 1, and that 2) the auxiliary power consumption was more than doubled for Coal 1 compared to Coal 5, primarily because of higher oxygen demand, but also because of higher flow rates of CO_2 in the absorber and the compressor in the capture cases.

Table 2 Key results for the computed IGCC cases. A single gas turbine was assumed and the plant gross power was in the 430-480 MW range. The complete power plant system was considered in the energy balance (e.g. the auxiliary power consumption for coal drying and CO_2 compression was accounted for)

Coal ID	Coal 1		Coal 2		Coal 3		Coal 4		Coal 5	
Name	North Dakota lignite		Wyoming Powder River Basin (PRB)		Illinois #6		Upper Freeport, PA		Pocahontas #3, VA	
Capture of CO_2	Without	With	Without	With	Without	With	Without	With	Without	With
Case 1 (Dry feed with syngas heat recovery)										
Coal as-received [kg/s/MW]	0.131	0.171	0.115	0.149	0.089	0.115	0.071	0.091	0.063	0.082
Water removed [kg/s/MW]	0.038	0.049	0.028	0.036	0.003	0.004	0.000	0.000	0.000	0.000
CO_2 captured [kg/kWh]	0.000	0.848	0.000	0.815	0.000	0.767	0.000	0.735	0.000	0.780
Net power [MW]	410	343	412	346	420	353	421	358	419	353
Thermal efficiency (ar, HHV)	44.1 %	33.7 %	44.3 %	34.3 %	44.2 %	34.1 %	45.6 %	35.7 %	45.7 %	35.3 %
Thermal efficiency (ar, LHV)	48.1 %	36.8 %	47.9 %	37.0 %	46.1 %	35.6 %	47.0 %	36.8 %	47.0 %	36.3 %
CO_2 emitted [kg CO_2/ kWh el]	0.762	0.147	0.740	0.143	0.698	0.137	0.679	0.132	0.709	0.138
Case 2 (Slurry feed with full water quench)										
Coal as-received [kg/s/MW]	0.305	0.432	0.199	0.251	0.120	0.140	0.086	0.098	0.076	0.089
CO_2 captured [kg/kWh]	0.000	2.163	0.000	1.377	0.000	0.929	0.000	0.765	0.000	0.815
Net power [MW]	300	220	328	282	357	331	370	351	366	339
Thermal efficiency (ar, HHV)	18.9 %	13.4 %	25.7 %	20.4 %	32.6 %	27.9 %	37.6 %	33.0 %	38.1 %	32.4 %
Thermal efficiency (ar, LHV)	20.6 %	14.6 %	27.7 %	22.0 %	34.0 %	29.1 %	38.7 %	34.0 %	39.1 %	33.3 %
CO_2 emitted [kg CO_2/ kWh el]	1.704	0.253	1.227	0.168	0.907	0.131	0.790	0.136	0.817	0.143

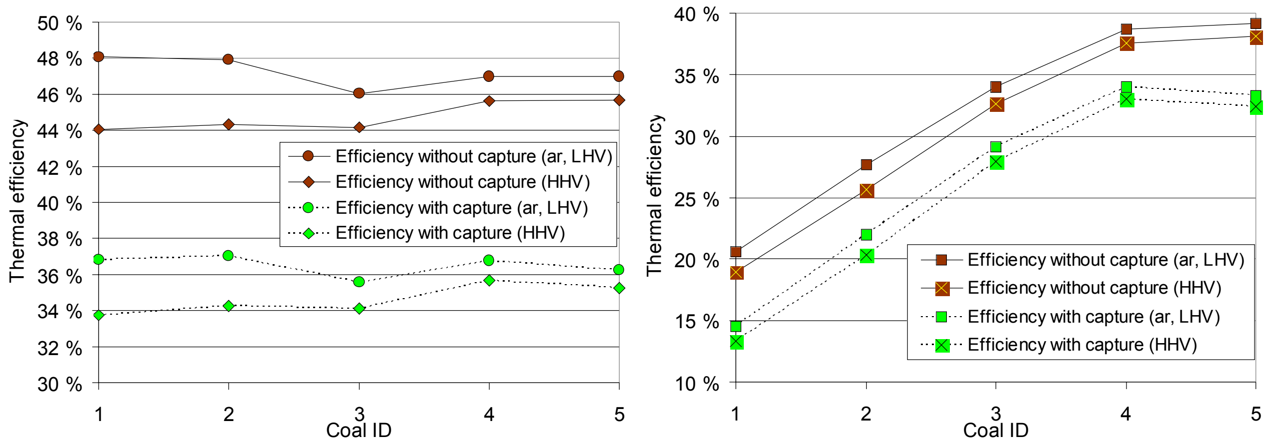

Figure 2 a) Efficiencies for Case 1 (IGCC with dry feed gasifier and heat recovery), b) Efficiencies for Case 2 (IGCC with slurry feed gasifier and water quench)

Case 1 is less sensitive to coal type because of less variation in the energy density of the coal feed to the gasifier. An efficient coal drying process recovers the heat of evaporation by compressing the dried off steam and condensing it in a heat exchanger (heat pump principle). Figure 2 a) needs to be commented on. When comparing the efficiency for Coal 1 and Coal 5, the LHV efficiency for the lowest rank coal is actually higher than for the highest rank coal. This may seem like a strange result. First, note that the HHV efficiency gives the expected result that the efficiency is higher for Coal 5 than for Coal 1. The explanation of the opposite results lies in the definition of LHV. Coal 1 is a lignite with high moisture

[4]Cold gas efficiency is the chemical energy (HHV basis chosen here) of the product syngas divided by the chemical energy of the coal feed

content and by definition LHV excludes the energy required to vaporize the water (normally cannot be recovered) from the coal heating value, even though in Case 1 this energy is actually recovered in the drying process. Therefore, the LHV definition in this specific case understates the chemical coal energy which actually goes into the process. Compared to the efficiencies (LHV) calculated in [6] (used bituminous coal similar to Coal 3), the current efficiencies are somewhat higher[5] for Case 1 and somewhat lower[6] for Case 2. These differences may be attributed to several factors (e.g. drying process configuration, slurry concentration, ASU/GT integration) but this was not investigated in detail.

The emissions of CO_2 per unit electricity are shown in Figure 3a. In the model, 90 % capture of the CO_2 in the syngas after a two-stage shift reaction was assumed in the capture cases. The unconverted carbon in the gasifier ends up as slag or flyslag and binds some of the carbon in the coal. The emissions of CO_2 depend strongly on efficiency (because it gives the amount of coal and thus carbon per unit electricity), but is also affected by the carbon content of the coal. Due to the very poor Case 2 efficiencies for low rank coals, the corresponding CO_2 emissions are very high.

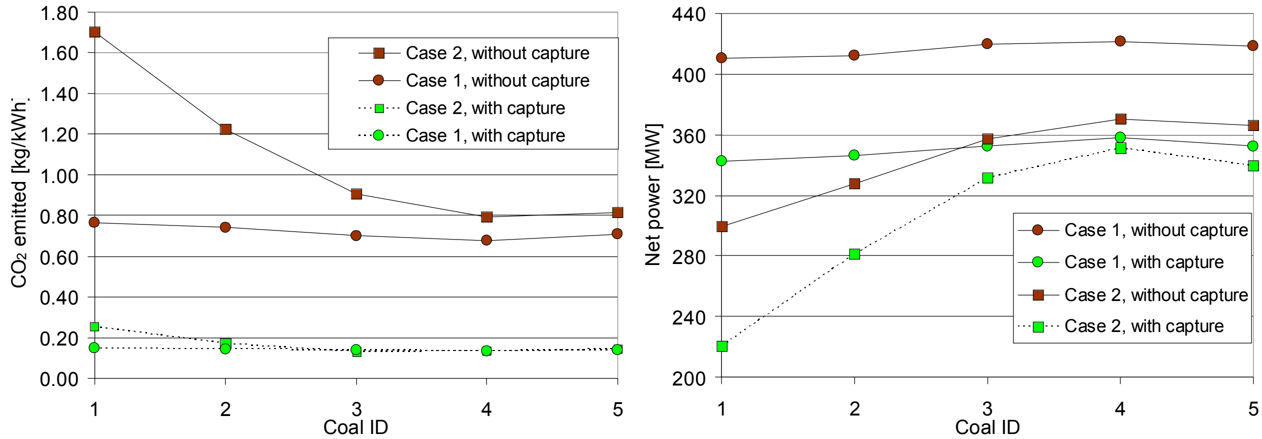

Figure 3 a) Emissions of CO_2 per unit electricity, b) Net power produced by the IGCC plant

The gross power varies little for the different coals. This is because the gas turbine has the same power output (286 MW) for all the cases, while the required amount of syngas feed is calculated by the gas turbine model[7] which represents the GE 9FA gas turbine which is rated as 286 MW. In spite of some variation in gas turbine exhaust mass flow, temperature and composition, the steam turbine power output does not vary very much (3-10 MW) as a function of coal type. Therefore, the decline in net power output for low rank coals observed in Figure 3b, is explained by increased auxiliary power consumption mainly in the ASU and CO_2 absorber and compressor.

Figure 4 has been added to illustrate how process flow rates differ between Case 1 and Case 2 as a function of coal type. For example, it is shown that the gasifier volume flow for a given power output is a factor (4-5 for Coal 1) higher for Case 2 than for Case 1. Assuming similar reactor residence times, this factor would also indicate the relative gasifier volumes between Case 2 and Case 1. This would naturally have implications for an economic analysis which, however, has been outside the scope of this work.

[5] 3.0 %-points higher without capture, 1.1 %-points higher with capture
[6] 4.0 %-points lower without capture, 2.4 %-points lower with capture
[7] This simplified model assumes fixed isentropic efficiencies independent of reduced flow rates

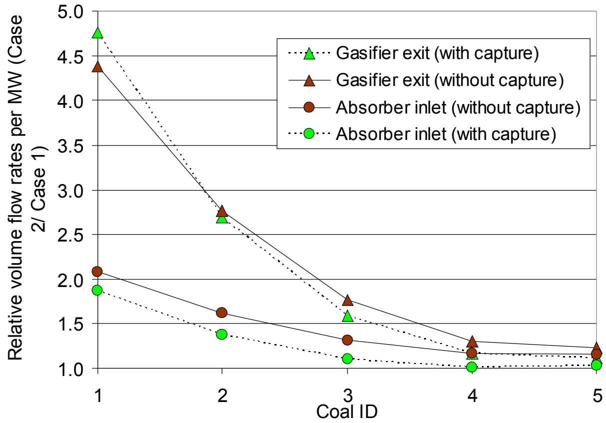

Figure 4 Comparison of the volume flow rates (for a given net power output) at the gasifier exit and at the absorber inlet for Case 1 and Case 2.

Conclusions

Slurry feed IGCCs are less efficient and have lower net power output for low rank coals because the less energy dense slurry fuel demands that more of the coal's energy is converted to heat instead of syngas and increases the auxiliary power consumption. In contrast, dry feed IGCCs are little affected by coal type in terms of thermal efficiency and power output. This explains why the Canadian Clean Power Coalition selected the Shell gasifier for lignite in their study [7]. Furthermore, the computations showed that for high moisture coals treated in efficient drying processes, the use of lower heating value in efficiency calculations overstates the efficiency.

The slurry feed IGCC performed closest to the dry feed IGCC when CO_2 was captured and the two highest rank bituminous coals were used (Coal 4 and Coal 5). This is explained by the high achievable slurry concentrations and the fact that slurry feed IGCCs are less penalized by CO_2 capture because sufficient water vapor is present in the water quenched syngas, and extra steam import for the shift reaction is eliminated.

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Professor John Dooher, Adelphi University provided the slurry solids concentrations using the Dooher Institute Coal Slurry Model. Christopher Higman has contributed with helpful discussions on drying technology and gasifiers. This work has been sponsored by the Norwegian Research Council in the KLIMATEK program.

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