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This document appeared in

Detlef Stolten, Thomas Grube (Eds.):
18th World Hydrogen Energy Conference 2010 - WHEC 2010
Parallel Sessions Book 3: Hydrogen Production Technologies - Part 2
Proceedings of the WHEC, May 16.-21. 2010, Essen
Schriften des Forschungszentrums Jülich / Energy & Environment, Vol. 78-3
Institute of Energy Research - Fuel Cells (IEF-3)
Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, 2010
ISBN: 978-3-89336-653-8

Hydrogen Production from Coal and Biomass Co-gasification Process with Carbon Capture and Storage

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1 Introduction

Introduction of hydrogen in energy system as a new energy carrier complementary to electricity and conventional fuels (e.g. natural gas, oil derived products, coal etc.) is raising much interest, as this offers significant advantages including reduction of greenhouse gas emissions at the point of end use, enhancement of the security of energy supply and improvement of economic competitiveness. Hydrogen is used in chemical industry for various processes, e.g. ammonia and methanol synthesis, hydrogenation, hydro-cracking and hydro-desulphurization processes and it is currently produced from natural gas, oil derived products and coal. Among these feedstock types, solid fuels (fossil sources like coal and lignite but also renewable energy sources like biomass) are likely to play a key role using gasification-based processes for large-scale hydrogen production, as required for the development of the hydrogen economy.

By gasification process, a solid feedstock is partially oxidized with oxygen and steam to produce syngas which can be used for conversion into different valuable compounds (e.g. hydrogen, ammonia, synthetic fuels) or to generate power in a combined cycle gas turbine. Integrated Gasification Combined Cycle (IGCC) is one of energy conversion processes having the highest potential for carbon capture with low penalties in term of efficiency and cost. In a modified IGCC scheme designed for carbon capture and storage, the syngas is catalytically shifted to maximize hydrogen level and to concentrate carbon species in form of carbon dioxide that can be later capture in a pre-combustion arrangement. After CO_2 and H_2S capture in a double stage Acid Gas Removal (AGR) system, hydrogen-rich gas is used in a combined cycle gas turbine (CCGT) for power generation and/or for production of purified hydrogen stream which can be used in (petro)chemical industry or for transport sector in hydrogen-fuelled fuel cells (PEM).

The paper assesses from technical point of view the hydrogen production through co-gasification process of coal and biomass (e.g. sawdust, agricultural wastes, meat and bone meal) simultaneous with carbon capture and storage (more than 90 % feedstock carbon capture rate). The main aim of the paper is to describe the methodology to design and evaluate the plant performances using critical factors like: fuel selection criteria, choice of gasification reactor, heat and power integration, carbon capture and storage (CCS) technologies, ancillary power generation, plant flexibility, methods to increase the plant energy efficiency, hydrogen and carbon dioxide quality specifications considering the use of hydrogen in transport sector (PEM fuel cells) and carbon dioxide storage in geological formation or using for Enhanced Oil Recovery (EOR). The case studies were investigated in detail by process flow modelling (using ChemCAD software package) and the most promising plant concepts identified.

2 Plant Configuration of Hydrogen Production Based on Coal and Biomass Co-gasification with CCS

A conventional Integrated Gasification Combined Cycle (IGCC) without carbon capture uses syngas resulted from gasification (after removing ash and hydrogen sulphide) for power production by burning in a gas turbine. The hot flue gases coming from gas turbine are used to raise steam in Heat Recovery Steam Generator (HRSG), which by expansion in a steam turbine generates extra electricity in addition to the one generates by the gas turbine. The case studies investigated in this paper are producing only hydrogen, the electricity generated by the gas and the steam turbines are used only to cover the plant ancillary demand.

Compared with conventional IGCC concept which is designed for power production only, design modifications for hydrogen generation as well as introduction of carbon capture stage using pre-combustion method like gas – liquid absorption (e.g. chemical or physical solvents) involve some critical changes in the plant configuration. The conceptual layout of a modified IGCC scheme for hydrogen production with simultaneous carbon capture is presented in Figure 1 (as exemplification, a dry-feed gasifier with water quench was used e.g. Siemens gasifier) [1].

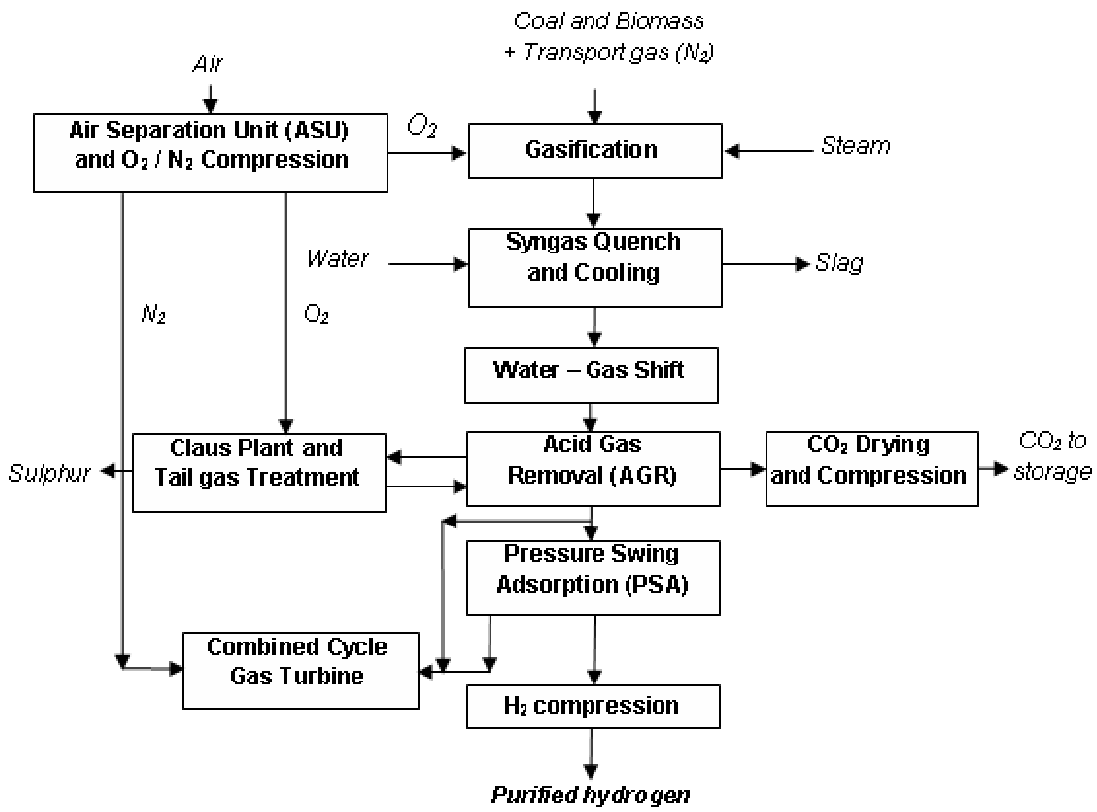

Figure: Layout of IGCC scheme for hydrogen production with carbon capture and storage (CCS).

Main differences of this scheme compared with conventional IGCC scheme without carbon capture are the following: introduction of catalytically conversion stage of CO (also called water gas shift – WGS); a modified Acid Gas Removal (AGR) system which captures, in addition of H_2S as in the conventional technology, also CO_2; the hydrogen purification stage by Pressure Swing Absorption (PSA) for the stream to be delivered to external customers (H_2 purity for export was set at 99.95 % vol. to be compatible with PEM fuel cells) and a combined cycle gas turbine (CCGT) running on hydrogen-rich gas.

Hydrogen produced is intended to be used in PEM fuel cells for transport sector which imply very strict quality specification (>99.95 % H_2 and virtually no CO and H_2S due to the possibility of fuel cells poisoning) [2]. Also, a major factor which influences the ancillary power consumption of the plant is the compression of captured carbon dioxide stream to more than 100 bar before being sent to geological storage or utilized for Enhanced Oil Recovery (EOR). This additional step gives a significant difference compared with conventional IGCC scheme. The compression of carbon dioxide stream is requiring a significant amount of energy which in the end will imply an energy penalty of the carbon capture design. The captured CO_2 stream will have to have very low concentration of water (<500 ppm) and hydrogen sulphide (<100 ppm) as these components could give corrosion problems along the pipeline network [3].

3 Modeling and Simulation of Hydrogen Production Scheme

In conventional IGCC process, a wide range of gasification reactors were and continue to be used to convert coal or lignite into syngas with good energy efficiency. But for hydrogen production with carbon capture, gasifier options are much more restricted because of this design particularity. For instance, air-blown gasifiers are unsuitable, mainly because of the nitrogen dilution which negatively influences the overall thermal balance of the plant and hydrogen purification step. Considering all the criteria (described in literature [4]) to be taken into account when choosing a gasifier for hydrogen production with carbon capture, it appears that entrained-flow gasifiers are the most promising reactors for this plant concept. Having that in mind, in the following paragraphs, the evaluation is geared mainly towards this type of reactors. The commercial gasification reactors of this type include: Shell, Siemens, GE Texaco, E-Gas etc.

As gasification reactor considered in modelling, as mentioned before the option was in favor of entrained-flow type operating at high temperature (slagging conditions) which give a high fuel conversion (~99 %). From different commercial gasification technologies available on the market, Siemens gasifier (formerly known Future Energy) was chosen, the main factors for consideration being dry feed design (which increases the energy efficiency compared with slurry feed type) and water quench which ensures the optimal condition for shift conversion (pre-condition for CO_2 capture).

When discussing the fuel selection for IGCC plant, the approach used for conventional power plants (steam plants) has to be changed radically. The coal used in steam plants is advised to have low content of ash and sulphur (to reduce corrosion and SOx emissions), but most important is that the ash has to have a relatively high melting point to prevent ash build up on the boiler heat transfer area. When analyzing IGCC concept, one of the advantages of this technology over the conventional power plant is the ability to use lower grade coals or alternative fuels (e.g. biomass and solid wastes) most of them unable to be processes in a conventional power plant because of high ash, sulphur and chlorine content and low ash melting point. Processing lower grade coals or renewable energy sources has also an important economic benefit because these fuels are presumed to be cheaper. This paper investigates the possibility to blend the coal with various sources of biomass (e.g. sawdust, agricultural waste) for hydrogen production based on an IGCC scheme. Table 1 presents the composition and thermal characteristics of evaluated fuels.

Table 1: Feedstock composition and thermal properties.

Parameter	Coal	Sawdust	Wheat straw	Corn stalks	MBM
Proximate analysis (% wt.)					
Moisture (a.r.)	8.10	10.00	10.00	8.00	1.90
Volatile matter (dry)	28.51	80.05	69.94	73.40	73.40
Ultimate analysis (% wt. dry)					
Carbon	72.04	49.20	41.11	44.80	46.20
Hydrogen	4.08	5.99	5.20	5.39	6.70
Nitrogen	1.67	0.82	1.01	0.85	9.70
Oxygen	7.36	42.98	37.36	41.75	17.07
Sulphur	0.65	0.03	0.24	0.21	0.65
Chlorine	0.01	0.00	0.60	0.00	0.88
Ash	14.19	0.98	14.48	7.00	18.80
Calorific value (kJ/kg dry)					
Gross (HHV)	28 704.40	19 436.40	16 091.57	17 206.46	21 163.74
Net (LHV)	27 803.29	18 113.45	14 943.10	16 016.02	19 683.98
Ash composition (% wt.)					
SiO_2	52.20	9.44	54.64	63.30	0.00
Al_2O_3	27.30	1.56	5.73	0.00	0.00
Fe_2O_3	5.10	1.88	6.16	4.70	2.90
CaO	6.40	62.00	5.02	0.60	66.28
MgO	2.10	2.18	2.45	4.80	0.00
TiO_2	1.50	0.10	0.23	0.00	0.00
K_2O	1.00	15.00	14.09	8.40	13.00
Na_2O	0.30	0.61	2.16	0.50	17.82
SO_3	2.40	2.72	3.03	7.20	0.00
P_2O_5	1.30	1.23	2.43	2.10	0.00
SrO	0.00	0.15	0.00	0.00	0.00

It can be noticed from Table 1 that all alternative fuels investigated in the present paper (sawdust, agricultural wastes and meat and bone meal - MBM) have significant increased content of modifier oxides (calcium, magnesium, sodium and potassium oxides) and lower silica and alumina content which means low slag viscosity temperatures [5]. These alternative fuels could be added to the coal to reduce the slag viscosity in a blending ratio (up to 20 – 30 % wt. alternative fuels) which does not change significantly reactor characteristics and performances compared with operating only on coal. At the same time, blending coal with these alternative fuels offers good option to find a useful way of recover the energy content of these materials in condition of reducing consumption of non-renewable energy sources (coal).

The plant concepts for hydrogen production with carbon capture and storage based on coal with or without addition of sawdust, wheat straw (WS), corn stalks (CS) and meat and bone meal (MBM) were modeled and simulated to quantify the overall plant performance indicators. Five case studies were investigated thoroughly in this paper (for all five cases, the feedstock thermal energy was 1000 MW):

- Case 1 – Coal only as feedstock;
- Case 2 – Coal with addition of sawdust (80 / 20 % wt. blending ratio);
- Case 3 – Coal with addition of wheat straw (80 / 20 % wt. blending ratio);
- Case 4 – Coal with addition of corn stalks (80 / 20 % wt. blending ratio);
- Case 5 – Coal with addition of meat and bone meal (80 / 20 % wt. blending ratio).

4 Results and Discussions

Hydrogen and electricity co-production schemes were modeled and simulated using process flow modelling software (ChemCAD). As thermodynamic package used in all simulations, Soave-Redlich-Kwong (SRK) model was chosen considering the chemical species present and process operating conditions (pressure, temperature etc.). Simulation of plant configurations yields all necessary process data (mass and molar flows, composition, temperatures, pressures, power generated and consumed) that are needed to assess the overall performance of the processes.

In all cases, the plant models were optimized by performing heat and power integration analysis (using pinch technique) of the combined cycle block (CCGT) for maximization of energy efficiency. Steam generated in gasification island (HP steam from gasifier cooling wall) and syngas conditioning line (HP and LP steam) was integrated in the steam cycle of the combined cycle gas turbine. After process optimization by heat and power integration studies, the overall plant performance indicators were calculated.

An overview of the main plant indicators for all four investigated case studies is presented in Table 2 (the electricity production was limited only to cover the plant ancillary demand).

Table 2: Overall plant performance indicators.

Main Plant Data	Units	Case 1	Case 2	Case 3	Case 4	Case 5
Solid fuel flowrate (a.r.)	kg/h	141994	153230	157044	155235	149159
Coal / Sawdust / WS / CS / MBM LHV (a.r)	MJ/kg	25.353 / 16.057 / 13.204 / 14.539 / 19.263				
Feedstock thermal energy – LHV (A)	MW_{th}	1000.00	1000.00	1000.00	1000.00	1000.00
Thermal energy of the syngas (B)	MW_{th}	801.00	793.30	788.04	795.00	825.20
Cold gas efficiency (B/A * 100)	%	80.10	79.33	78.80	79.50	82.52
Thermal energy of syngas exit AGR (C)	MW_{th}	711.83	706.43	700.39	706.79	736.73
Syngas treatment efficiency (C/B *100)	%	88.86	89.05	88.87	88.91	89.28
Gas turbine output	MW_e	56.42	56.12	56.66	56.17	57.81
Steam turbine output	MW_e	33.28	33.62	34.43	34.12	33.91
Gross electric power output (D)	MW_e	86.70	89.74	91.09	90.29	91.72
Hydrogen output – LHV (E)	MW_{th}	571.24	566.83	559.84	567.00	592.97
ASU consumption + O_2 compression	MW_e	38.32	38.32	39.05	38.45	36.77
Gasification island power consumption	MW_e	6.92	7.02	7.02	6.97	7.18
AGR + CO_2 drying & compression	MW_e	34.35	34.42	35.05	34.94	37.27
H_2 compression	MW_e	7.69	7.60	7.56	7.57	7.97
Power island power consumption	MW_e	2.42	2.38	2.41	2.36	2.53
Total ancillary power consumption (F)	MW_e	89.70	89.74	91.09	90.29	91.72
Net electric power output (G = D - F)	MW_e	0.00	0.00	0.00	0.00	0.00
Hydrogen efficiency (E/A * 100)	%	57.12	56.68	55.98	56.70	59.29
Carbon capture rate	%	92.35	92.83	93.64	93.25	92.24
CO_2 specific emissions (fossil+renewable)	kg/MWh	45.63	44.99	42.19	43.99	45.34
CO_2 specific emissions (fossil)	kg/MWh	45.63	38.54	37.01	38.06	38.71

As can be noticed from Table 2, in term of hydrogen production all case studies produce about 560 - 590 MW_{th} (based on hydrogen LHV) with an efficiency in range of 56 – 59 %.

Regarding the plant overall hydrogen efficiency, for cases 2 to 4 there is little to be differentiated among them (less than 0.7 % in term of overall hydrogen efficiency of the plant) and they are comparable with case 1 (coal only). Case 5 (coal blended with MBM) is more efficient with about 2.15 – 3.3 % compared with rest of the cases. This increase of plant efficiency can be explained by the cumulative effect of optimizing gasifier performances (lowering slag viscosity comparing with case 1 – coal only) and improved calorific value of alternative fuel used to be blended with coal, in this case MBM (comparing with cases 2 to 4).

Also, it can be noticed the fact that coal to alternative fuels blending ratio does not influence significantly the plant performance (comparing case 1 vs. cases 2 to 5). Specific CO_2 emissions (fossil and renewable) are in the range of 42 – 45 kg/MWh with about 92 – 93 % carbon capture rate. When counting only the fossil specific CO_2 emissions, the cases 2 to 5 are performing better than case 1 (only fossil). IGCC technology has also other benefits from environmental point of view: very low SOx and NOx emissions, possibility to process lower grade coals or other types of solid fuels (as evaluated in this paper) which are difficult to handle by conventional energy conversion process (e.g. steam plant).

5 Conclusions

The paper assesses the technical aspects of hydrogen production scheme with carbon capture based on a modified IGCC plant design. The aim was to develop a set of criteria that can be used to select the most appropriate gasification concepts for hydrogen and electricity co-production plant with carbon capture and storage and then to quantify the overall energy efficiency of the plant. A particular attention was devoted to the fuel selection (e.g. fuel blending) for both optimization of the gasifier performance and promote the usage of non-fossil fuels (various biomass sorts).

The most promising plant concepts for hydrogen production with carbon capture are all based on entrained-flow gasifiers. For one case of entrained-flow gasifier reactor (Siemens) with various feedstock (coal only or coal blended with various biomass sorts) different case studies were presented in detail for assessing the main plant performance indicators (e.g. hydrogen output; plant ancillary demand; hydrogen efficiency, specific CO_2 emissions etc.).

Acknowledgements

This work was supported by Romanian National University Research Council (CNCSIS-UEFISCSU), project number PNII – IDEI code 2455: “Innovative systems for poly-generation of energy vectors with carbon dioxide capture and storage based on co-gasification processes of coal and renewable energy sources (biomass) or solid waste”.

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