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"CAESAR: SEWGS integration into an IGCC plant"

M.Gazzani, E. Macchi, G. Manzolini[1]

"Politecnico di Milano, Dipartimento di Energia"

Abstract

This paper investigates the performance of SEWGS (Sorption Enhanced Water Gas Shift), an innovative reactor for CO_2 capture, applied to Integrated Gasification Combined Cycle (IGCC). Firstly, two IGCC reference cases based on dry feed slagging Shell gasifier, with and without CO_2 capture, are defined. Then, two different integrations of SEWGS are investigated. The first assumes a conventional low-temperature acid gas removal process adopted upstream the SEWGS; this solution shows slight thermodynamic advantages towards the reference case with CO_2 capture (higher efficiency of 1% point), but not from lay-out simplification and equipment savings. The second solution assumes a simultaneous CO_2 and sulphur separation from the syngas; this results in a net electric efficiency gain over the reference case of about 2 percentage points. Moreover, this solution allows a significant plant simplification and equipment reduction with further advantages from economic point of view, which is not evaluated in this work. This activity is carried out under the FP7 project CAESAR financed by the EU community.

"Keywords: CO2 capture, SEWGS, IGCC, CO2 avoided"

Nomenclature and Acronyms:

AGR:	Acid Gas Removal
ASU:	Air Separation Unit
HTS:	High Temperature Shift
IGCC:	Integrated Gasification Combined Cycle
LTS:	Low Temperature Shift
HRSC:	Heat Recovery Steam Cycle
SEWGS:	Sorption Enhanced Water Gas Shift
SPECCA:	Specific Primary Energy Consumption for CO_2 Avoided [MJ_{LHV}/kg_{CO2}]
TIT:	Turbine Inlet Temperature
WGS:	Water Gas Shift

1 Corresponding author. Tel.: +39 02 2399 3810; fax: +39 02 2399 3913.
E-mail address: giampaolo.manzolini@polimi.it

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1. Introduction

Sorption-Enhanced Water Gas Shift (SEWGS) is a concept for pre-combustion CO_2 capture in which the water-gas-shift and the CO_2 separation steps are integrated. Removal of the CO_2 produced in the WGS reaction enhances CO conversion and enables a reduction in CO_2 emissions up to 98%. SEWGS comprises multiple fixed beds running in parallel that adsorb CO_2 at high temperature and pressure, and releases it at low pressure. Several studies investigated SEWGS integration in Natural Gas Combined Cycle showing good performances [1]. This paper addresses the application of SEWGS into a coal fuelled Integrated Gasification Combined Cycle (IGCC).

2. Reference cases

In order to investigate potential advantages of SEWGS integration in IGCC, two reference IGCC power plants are first defined, one without and one with CO_2 capture. These reference cases were developed together with other FP7 European project on Carbon Capture, CESAR and DECARBit, within the European Benchmark Task Force (EBTF). Gasification plants are built around an entrained flow, oxygen blown, dry feed slagging Shell gasifier. The gasification pressure is 44 bar, high enough to feed the gas turbine without syngas compression. The choice of a dry feed gasifier with high carbon conversion (99%), as allowed by the Shell gasifier, gives a higher cold gas efficiency, and consequently higher plant efficiency, compared to a slurry fed gasifier. The oxygen is supplied by an Air Separation Unit (ASU); present experience of reliability and availability of coal gasification power plants suggests the adoption of 50% integration between gas turbine compressor and ASU. Before feeding, coal is pulverised and dried with an auxiliary fuel. Gasifier mass and energy balances are calibrated towards Shell data [2]. Acid gas removal (AGR) section is based on conventional single stage Selexol™ process; the H_2S is sent to the Claus plant where the flue gas is recycled. The solvent is regenerated at the reboiler with saturated steam available at 150°C; the heat requirement for the reboiler is 5.82 kWh/kg H_2S and the electric consumption in the AGR is 0.5382 kWh/kg_{H2S}. The combined cycle is based on an average F-Class Gas Turbine with a net electric efficiency of 38.5%, a net power output of 275 MW and a TIT of 1360°C [3]. Syngas has a lower LHV than natural gas, for which the gas turbine was designed. Therefore, in order to keep high gas turbine performance and a sufficient stall margin, the same pressure ratio and TIT of the natural gas fired case are kept by regulating air mass flow rate by means of the VGVs [4].[4]. The calculated net electrical efficiency for the IGCC plant without CO_2 capture is about 47.5% with specific CO_2 emissions in the range of 720 g_{CO2}/kWh_{el}. This result is on the high side of IGCC published in literature. It can be explained by (i) the high combined cycle efficiency, (ii) the adoption of a saturator after AGR and (iii) the assumption of TIT equal to NG case (the model adopted for plant simulation, GS [5], accounts for larger blade cooling flows to maintain the same metal temperature on NG case, [5], which taking into account gas composition).

In the IGCC reference case with CO_2 capture (SELEXOL), the capture is carried out with a two-stage Selexol process. The gasification section comprises of the scrubber as well as the air separation unit are modelled as in the reference case previously presented, thus achieving the same cold gas efficiency at scrubber outlet. After scrubbing, syngas is mixed with steam bled from turbine in order to reach the desired steam-to-carbon ratio for the shift reaction: a Steam-to-CO ratio of 1.9 is set at WGS inlet [3]. Sour water gas shift reaction is performed into two reactors. In the first one, the majority of CO is converted and the reaction heat is recovered by producing high pressure steam in a waste heat boiler; in the second one, shift reaction is almost completed due to the lower temperature which enhances products formation increasing CO conversion to about 85%. Compared to reference case without CO_2 capture, COS hydrolysis is directly carried out in the WGS avoiding any additional reactor and thermal cycling. Because of the high water content in syngas necessary for shift reaction, water condensation occurs at higher temperature compared to the IGCC without capture, thus condensation heat can be more efficiently recovered for syngas saturation and water economizers. Carbon dioxide is removed from the syngas by a Selexol process. A two-stage Selexol process is adopted where H_2S is removed in the first stage and CO_2 in the second stage of absorption. The process results in three product streams: (i) the rich fuel gas, (ii) a CO_2 rich stream and (iii) an acid gas feed to the Claus plant. The CO_2 stream is purified before the final compression, while the rich fuel gas is recycled back to the process. The overall electricity consumption for the Selexol process is 58.85 kWh/tonCO_2; the heat requirement for the sour H_2S reboiler is 67.62 kWh/tonCO_2. After the dilution with nitrogen from ASU for NO_x control, the hydrogen-rich fuel gas is saturated by low temperature heat available from syngas cooling and then preheated to 200°C. The hydrogen rich fuel gas is finally sent to the power island and burned in the gas turbine combustor. As in the previous case, the VGV control at gas turbine compressor must be adopted to compensate lower LHV of syngas. The resulting net electric efficiency is 36.5% with a CO_2 avoided of about 88%.

3. "SEWGS integration in IGCC"

To integrate SEWGS into the IGCC, two different lay-outs are investigated: the first called “Sweet SEWGS” is characterized by sulphur removal upstream SEWGS, while the second one, “Sour SEWGS”, can deal with sulphur. A critical parameter of the SEWGS process is the dynamic sorbent capacity because it determines the flows required for rinsing and purging the reactors. Within the CAESAR project, experimental and modeling work has been carried out in parallel to this study to characterize promising sorbent materials and allow to estimate SEWGS unit performance. Lay-out investigated and results presented in this work will be updated in future publications according to more accurate data based on experiments and modeling work ongoing.

3.1 SWEET SEWGS

For a no-sulphur tolerant sorbent, the reactor must be placed downstream of a sulphur separation process; as for the reference case, Selexol^{TM} is selected for AGR. Water gas shift reaction can be either carried out before and after AGR. As shown in Figure 1, the latter option is preferred because limits (i) CO_2 captured within AGR process and (ii) steam condensation losses. The resulting layout ahead of the sulphur removal section is therefore identical to the base case without CO_2 capture (IGCC). The syngas is then saturated, pre-heated and mixed with steam to achieve a 1.9 Steam/CO ratio before entering a conventional high temperature shift reactor (HTS). Syngas saturation is fundamental to limit efficiency penalty because allows heat recovery at low temperature and reduces the amount of steam bled from the steam turbine. The adiabatic HTS is necessary to convert as much CO as possible into CO_2 and consequently minimizing the detrimental temperature rise inside the SEWGS vessels due to reaction heat.

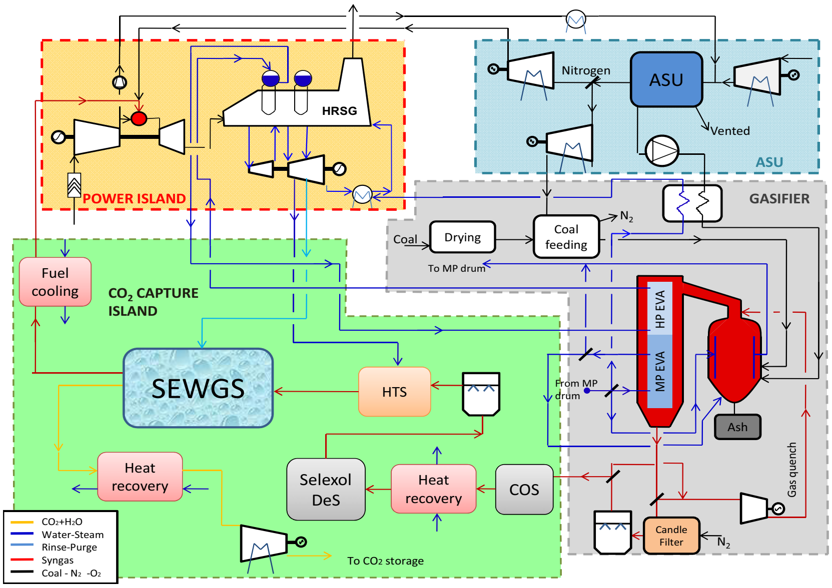

Figure 1 Layout of the IGCC power plant with CO_2 capture by SEWGS with sorbent intolerant to sulphur

The syngas stream enters the SEWGS unit completing CO conversion: simultaneous conversion and separation can achieve a 99% CO conversion with advantages in terms of CO_2 capture. SEWGS produces two streams: a high purity CO_2 stream and a hydrogen rich stream to feed the gas turbine. The resulting CO_2 stream, is cooled to ambient temperature and then compressed in a intercooled compressor up to 110 bar for storage. From a thermodynamic point of view, this solution takes advantage of (i) the high fuel temperature at the gas turbine inlet and (ii) of the water gas shift reaction excess steam that is expanded in the gas turbine instead of cooled and condensed as in the IGCC reference case with capture. It must be outlined that the hydrogen rich stream is produced at about 450°C and, before feeding the GT, it is cooled to 350°C because of combustor constraints. Thus, advantages of CO_2 separation at high temperature can be further exploited. Although this solution does not save equipment, the main advantage can come from lower SEWGS investment costs compared to Selexol for CO_2 capture.

3.2 SOUR SEWGS

Even more promising is the SEWGS process based on a sulphur tolerant sorbent and, in particular when sulphur is adsorbed together with CO_2 [6]. This sorbent property minimizes exergy losses and simplifies the lay-out. The gasification section up to the scrubber is the same of previously described cases, steam is added to the syngas to achieve a Steam/CO ratio of 1.9 and a first water gas shift reaction can take place upstream of the SEWGS unit. The adoption of an adiabatic WGS upstream SEWGS is necessary for the same reasons stated previously. After CO_2 and sulphur separation in the SEWGS unit, the hydrogen rich syngas produced at about 450°C is sent to the gas turbine. However, fuel temperature is limited to 350°C, so a cooling step between SEWGS and combustor is introduced. During the desorption process, CO_2 and sulphur are released at the same pressure. Since the CO_2-steam mixture results similar to geothermal fluids, the sulfur removal process can be based on systems developed for geothermal power plants that consists of a catalytic oxidation of H_2S and then conversion to elemental sulfur in a commercial FGD. In this solution, sulphur separation process affects overall efficiency of about 0.2% points. However, further sulfur removal processes will be investigated in future works. This layout, compared to the previous SEWGS integration and reference IGCC with CO_2 capture, has the significant advantage of avoiding syngas cooling to ambient temperature.

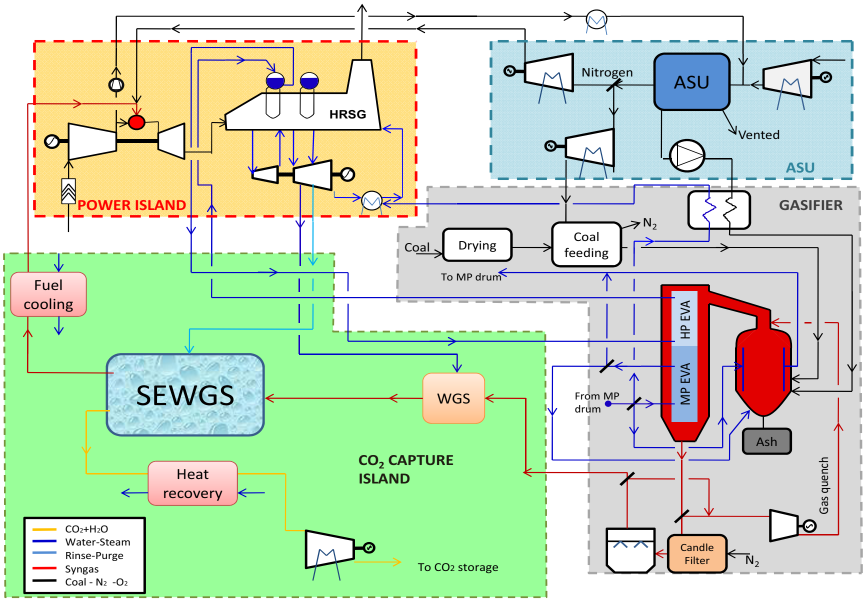

Figure 2 Layout of the IGCC power plant with CO_2 capture by SEWGS with sorbent tolerant to sulphur

4. Methodology

Heat and material balances have been estimated by a proprietary computer code developed to assess the performances of advanced power plants. The Selexol and CO_2 compression systems are simulated with Aspen Plus™. Calculation methodology and assumptions are the same used and approved in EBTF [3]. Gasifier mass and energy balances respects Shell data, with a maximum difference in compositions of less than 5%, that goes down to about 0.5% for H_2 and CO. SEWGS modeling is based on experimental activities carried out during CACHET and CAESAR project. This model can be updated according to new modeling and experimental data achieved in ongoing experiments. Main simulation assumptions are summarized in Tab.1. The mass flow rate of nitrogen sent to the GT combustor is calculated in order to have a constant inert percentage ($H_2O + N_2$) of about 50%.

A measure of the energy cost related to CO_2 capture, accounting for efficiency penalty as well as avoided carbon rate, is given by the Specific Primary Energy Consumption for CO_2 Avoided (SPECCA), which is defined as:

$$SPECCA = \frac{HR - HR_{REF}}{E_{REF} - E} = \frac{3600 \cdot \left(\frac{1}{\eta} - \frac{1}{\eta_{REF}} \right)}{E_{REF} - E}$$

where

- HR is the heat rate of the plant, expressed in kJ_{LHV}/kWh_{el}
- E is the specific CO_2 emission rate, expressed in kg_{CO2}/kWh_{el}
- REF is the IGCC reference case for electricity production without carbon capture.

Table 1 - Main assumptions adopted for plant simulations.

Ambient conditions	15 °C / 1.013 bar / 60% RH			
Air composition, dry molar fraction (%)	N_2 78.08%, CO_2 0.04%, Ar 0.93%, O_2 20.95%			
Douglas Premium coal characteristics [2]				
Ultimate analysis	C	66.52%	O	5.46%
	N	1.56%	Clorine	0.009%
	H	3.78%	Moisture	8.0 %
	S	0.52%	Ash	14.15%
Coal LHV	25.17 MJ/kg			
CO_2 specific emission	349.0 [g/kWh_{LHV}]			
Gas turbine				
Pressure ratio	18.3			
Gas mass flow rate at the turbine inlet	650 kg/s			
TIT	1360 °C			
Pressure loss at inlet	1 kPa			
Steam cycle				
Pressure levels, bar	144, 54, 4			
Maximum temperature SH e RH	565 °C			
Pinch, subcooling, approach ΔT	10/5/25 °C			
Condensing pressure	0.048 bar (32 °C)			
Turbine Isentropic efficiency (HP/IP/LP)	92/94/88 %			
Pumps efficiency	70%			
HRSG thermal losses	0.7 % of thermal input			
HRSG pressure losses, gas side	4 kPa			
Gas turbine and steam cycle				
Generator efficiency	98.7%			
Mechanical efficiency	99.6%			
Power consumed for heat rejection	0.8% of heat released			

Air Separation Unit	
Oxygen Purity	95%
Nitrogen Purity	99%
Oxygen outlet temperature	20 °C
Oxygen outlet pressure	2.5 bar
Oxygen temperature entering the gasifier	180 °C [5]
Oxygen pressure entering the gasifier	48 bar
Oxygen and Nitrogen temperature leaving ASU	22 °C
Gasifier	
Gasifier outlet pressure	44 bar
Gasifier outlet temperature	1550 °C
Selexol for CO_2 capture and H_2S removal	
Electrical energy consumption	58.85 kWh/tonCO_2
Thermal energy consumption	67.62 kWh/tonCO_2
CO_2 separation and compression	
Final delivery pressure	110 bar
Compressor isentropic efficiency	85%
Temperature for CO_2 liquefaction	25°C
Pressure drop for intercoolers and dryer	1.0%
Pump efficiency,	75%

5. Results

Overall energy balances of SEWGS integration into the IGCC plant along with the reference case are shown in Tab.2. The power output penalty related to capture is lower than the corresponding efficiency penalty, since fuel input is significantly larger for capture cases. Gas turbine net power is higher for carbon capture cases because of the lower air flow in the compression phase and different composition of the expanding gas. Steam turbine net power output is significantly lower for SEWGS due to the steam usage for shift and capture processes, while SELEXOL case is only affected by the steam extraction for the WGS. CO_2 compression power demand for SEWGS is significantly higher than Selexol because of the higher CO_2 avoided (98 vs. 89%), and of the lower CO_2 discharge pressure of the capture process.

Capture cases have a lower cold gas efficiency because of exothermic CO conversion into H_2. SEWGS cases achieves the lowest values because of the almost complete CO conversion into CO_2 (as already stated conventional case has a CO conversion of about 85%, while SEWGS about 99%).

Finally, the SEWGS efficiency penalties for carbon capture (CO_2 avoided of 98%) are about 10.1% and 9.3% for Sweet SEWGS and Sour SEWGS, respectively. About 40% of the efficiency penalty depends on CO_2 compression work, while most of the remaining 60% is due to steam turbine power loss, thus related to separation process. The higher efficiency of Sweet SEWGS vs SELEXOL shows that SEWGS process is less energy intensive than Selexol. About two SEWGS cases, Sweet case has a lower efficiency of about 1% point because of syngas cooling down to ambient temperature.

Table 2 - Comparison among balances of IGCC with and without carbon capture investigated

	IGCC	Selexol	Sweet SEWGS	Sour SEWGS
Gas Turbine [MW]	289.91	304.95	311.50	311.75
Steam cycle net power [MW]	193.91	175.12	138.00	142.05
Air Separation Unit and O_2 compressor [MW]	-22.53	-26.46	-25.97	-25.98
CO_2 compressor [MW]	N/A	-22.86	-32.76	-32.86
Balance of plant [MW]	-36.09	-47.61	-4.84	-0.62
Net power output [MW]	425.20	383.14	385.93	394.34
Thermal input [MW, LHV base]	883.29	1039.18	1018.13	1018.43
Thermal input for coal drying [MW, LHV base]	7.71	9.07	8.89	8.89
Cold gas efficiency [%, LHV base]	82.54	74.04	73.60	73.61
Net electric efficiency [%, LHV base]	47.7	36.5	37.6	38.4
Specific CO_2 emissions, [g_{CO2}/kWh_{el}]	719.52	89.32	14.37	14.06
CO_2 avoided [%]	N/A	87.6	98.0	98.0
SPECCA [MJ_{LHV}/kg_{CO2}]	N/A	3.66	2.89	2.59

SPECCA for the three cases are shown in Figure 3. Compared to efficiency penalty, this coefficient takes into account also CO_2 capture thus showing difference both in terms of efficiency and CO_2 avoided. It results about 2.9 MJ_{th}/kg_{CO2} and 2.6 MJ_{th}/kg_{CO2} for Sweet SEWGS and Sour SEWGS respectively, which are 20 to 30% lower than the Selexol.

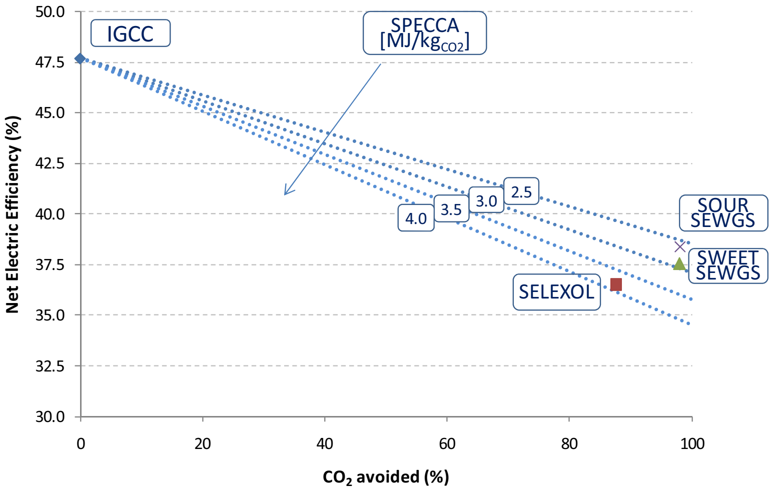

Figure 3: CO_2 avoided and net electric efficiency for the cases investigated

6. Conclusions

This paper presented an innovative CO_2 capture process, named SEWGS, applied to Integrated Gasifier Combined Cycle. Results showed the advantages of this technology compared to commercial one both in terms of efficiency penalty (up to 2% points higher) and CO_2 avoided (about 10% point higher). Moreover, SEWGS allows advantages also in term of equipment saving if the sorbent is tolerant to sulphur. Future work will focus on tight integration between capture section and gasification island in order to further decrease efficiency penalty.

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