

Thermodynamic Performance of IGCC with Oxy-Combustion CO₂ Capture

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ABSTRACT

This paper discusses the relevant thermodynamic aspects of IGCC plants with CO₂ capture, mainly focusing on oxy-combustion techniques. The following plant configurations were considered here, all based on a dry-feed oxygen-blown entrained-flow gasifier with syngas quench (Shell type) and a FB class gas turbine: (i) two reference cases, one without CO₂ capture and one with ‘conventional’ pre-combustion capture, (ii) three oxy-combustion cases, the first one with today’s technology and the other two with advanced technology, including CO₂/SO₂ co-sequestration or, alternatively, Hot Gas Desulfurization.

It is concluded that oxy-combustion techniques in IGCC cycles may deserve some attention in the near future, because they have the potential of achieving better thermodynamic and environmental performance, in comparison with more conventional capture concepts: in the best case, 45% net efficiency and near-zero emissions were predicted. However, some technological challenges are an obstacle to their development, especially as far as the re-design of the gas turbine is concerned.

INTRODUCTION

CO₂ capture from fossil fuel power plants is increasingly proposed for greenhouse gases emission mitigation. However, when applied to conventional coal power stations, by means of post-combustion amine capture or by means of boiler oxy-combustion, severe loss of efficiency and larger investment costs can be predicted. To mitigate these drawbacks, CO₂ capture coupled to IGCC can be considered. Up to now, the most appealing solution, often quoted by the literature as the one showing the lowest possible cost of avoided CO₂, is based on the syngas decarbonization concept: CO is converted into CO₂ (water-gas shift) and CO₂ is removed from syngas before its combustion by means of physical or chemical solvents. This concept brings to an hydrogen-rich syngas (typically 90% H₂), then burned in a rather conventional gas turbine. The carbon capture cannot exceed 90% and some NO_x emission problems may be encountered due to elevated flame temperature.

An alternative concept for IGCC plants, providing better environmental performance, is represented by the oxy-combustion technique: the CO-rich syngas is basically burned by high purity oxygen in a semi-closed Joule cycle, exhausting a high purity CO₂ stream after water condensation. To moderate the combustor outlet temperature, combustion products are diluted by CO₂ re-circulated by a CO₂ compressor, in a semi-closed Joule cycle. The CO₂ stream exiting the power cycle, after water condensation, is compressed and liquefied for final storage: any release to the ambient of combustion gases, including any type of pollutant, is virtually eliminated, approaching ‘zero-emission’. Such an approach requires deep modifications to existing gas turbine machines, not requiring unproven technologies but calling for a large development effort, whose extent will be discussed in the paper.

PLANT CONFIGURATIONS

To understand the potential of IGCC with oxy-combustion capture, we theoretically estimated the performance of some optimized plant configurations, including two reference cases (without CO₂ capture and with ‘conventional’ pre-combustion capture) and three oxy-fuel configurations, the first one with today’s technology and the other two with advanced technology, including CO₂/SO₂ co-sequestration or, alternatively, Hot Gas Desulfurization. With more detail, fig.1 shows the plant configuration of the reference case with pre-combustion capture by means of water-gas shift (WGS) and physical absorption of CO₂. The scheme for the no-capture plant is strictly similar, of course not showing WGS and CO₂ separation/compression.

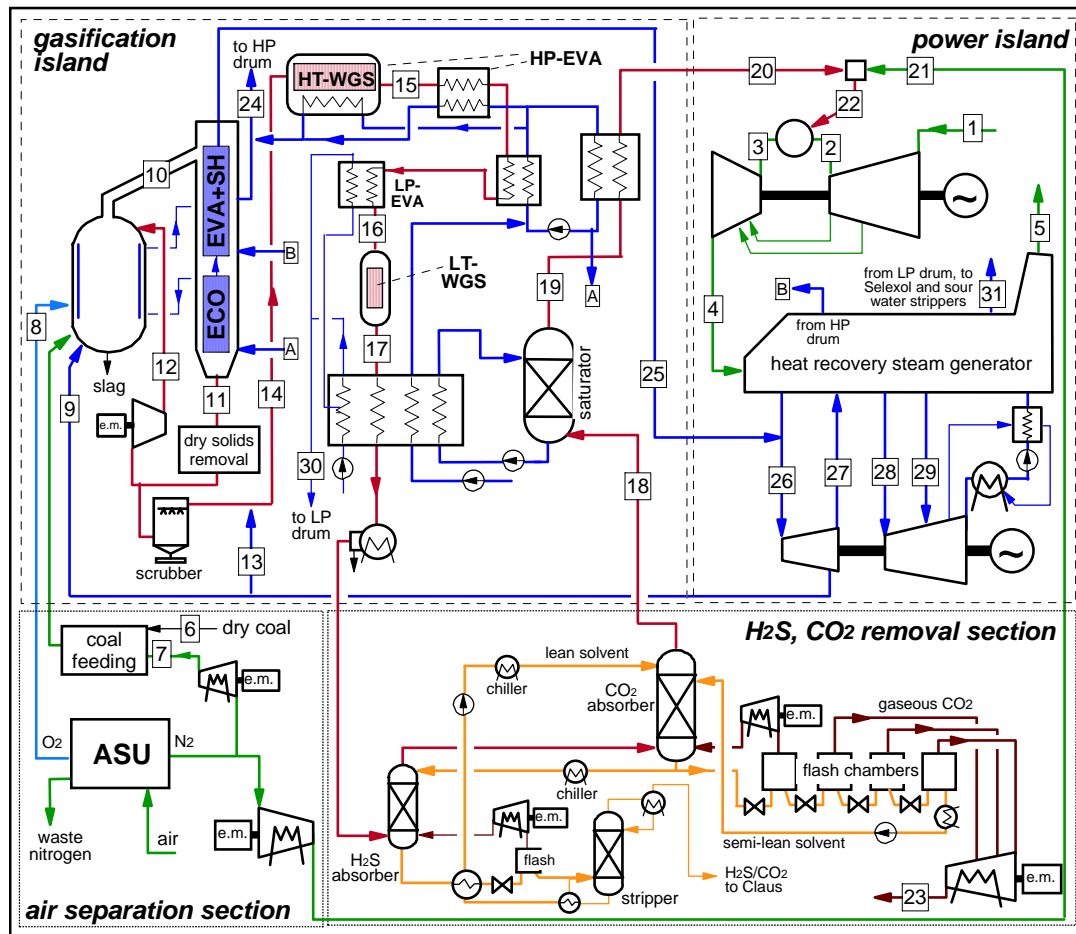


Figure 1 – Configuration of the IGCC plant with pre-combustion capture.

The plant scheme includes an oxygen-blown dry-feed entrained flow gasifier, resembling the Shell gasification process: the raw syngas at 1550°C is quenched by cooled syngas to produce HP steam in a convective syngas cooler, after slag removal. Two WGS reactors are used: an high temperature one for bulk removal (heat of reaction can be recovered to produce HP steam again) and a low temperature one to achieve a very elevated CO conversion. CO₂ is separated by means of a Selexol process with two separate absorbers: the first one, mainly removing H₂S, is fed by a semi-lean solvent regenerated in a low pressure stripper releasing H₂S to the Claus unit; the second one, using lean solvent at the top of the column, is devoted to CO₂ removal: the largest solvent fraction is regenerated by pressure-swing, within different flash chambers connected to the CO₂ compressor. The final syngas is low-purity hydrogen, with about a 10% of: (i) N₂ and Ar from oxygen impurities, (ii) CH₄ from gasifier, (iii) unconverted CO, (iv) CO₂ not separated. It is saturated by steam and then mixed with nitrogen from ASU to limit the NO formation in the combustor.

The same gasification process of the no-capture case is shared by the first oxy-combustion configuration, only modified to use CO₂ rather than N₂ for lock-hoppers pressurization, in order to avoid the presence of incondensable N₂ in the final stream exiting the cycle. The power cycle consists of a novel gas turbine machine: syngas (made of CO and H₂) is burnt in a oxy-fuel combustor and diluted by recycled pressurized CO₂ to limit the turbine inlet temperature to the typical values of today's machines. As we will discuss later, the different working fluid (mostly CO₂ with some water in the expansion) involves the selection of an higher pressure ratio and larger blade cooling flows; the excess oxygen for combustion is to be strictly controlled to limit the presence of incondensable gases in the final CO₂ stream.

The second oxy-fuel plant configuration, shown in fig.2, is more interesting, being based on advanced technologies and on some novel concept, due to the mid-long term time frame for its realization. The gasification process is similar, but a larger pressure was selected to join the larger cycle pressure ratio. An hot gas filtration by means of ceramic filters, operating at 550°C, was supposed to be available. H₂S is not removed from syngas: it is burnt in the GT combustor, eliminating the power and heat requirements of the desulfurization systems and making use of the H₂S heating value; SO₂ produced is co-sequestered together with CO₂. At present, it is not clear if co-sequestration is a viable practice: however, the thermodynamic benefits are quite relevant and they will be predicted here.

In the advanced configuration, some attention was deserved to optimize the blade cooling system, to obtain an elevated turbine inlet temperature. The CO₂ coolant for the first three rows is taken from the compressor outlet and then cooled to 250°C to limit the coolant needs.

Fig.2 also shows the CO₂ compression/liquefaction section, common to all the oxy-fuel plants here considered. It includes a separation process of the inert incondensable gases (O₂, N₂, Ar). The low purity CO₂ stream is liquefied at an intermediate pressure of 23 bar, where gases are separated from liquid CO₂. Liquefaction is obtained by evaporation of purified CO₂, after a flash at 16 bar to obtain a suitable ΔT in the heat exchanger. The CO₂ stream is compressed and liquefied at 90 bar, and then pumped to the final pressure of 150 bar. The last oxy-fuel configuration is very similar to the one of fig.2, but it includes an hot-gas-desulfurization process (HGD), following the hot gas filtration. This

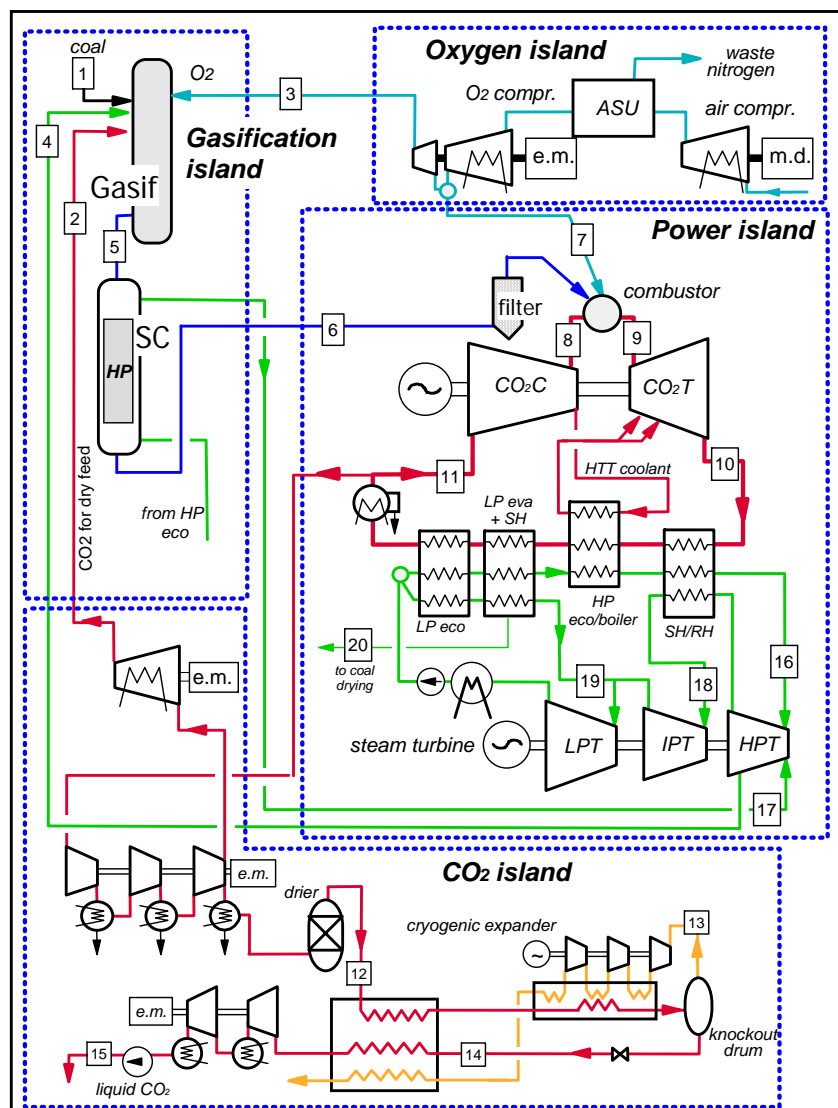
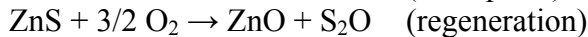
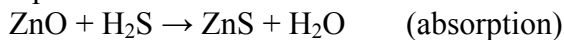


Figure 2 – IGCC plant with advanced oxy-fuel capture

is intend to avoid the need of co-sequestration of CO₂ and SO₂. The HGD block is shown in fig.3: it includes two circulating beds of zinc titanate where the following reactions take place:



Since the process operates at the gasification pressure, the mixture of air and nitrogen needed for regeneration must be compressed and therefore expanded for a proper management. It must be noted that the regeneration process cannot be carried out with air, to minimize the formation of zinc sulfate (ZnSO₄), deteriorating the system performance. An oxygen content as low as 2% in the regeneration agent was here used. The regeneration reaction is strongly exothermic: the reactor is kept at 750°C with a proper control of the circulating solid mass flow rate. A more detailed description of the process will be given in an upcoming authors' paper.

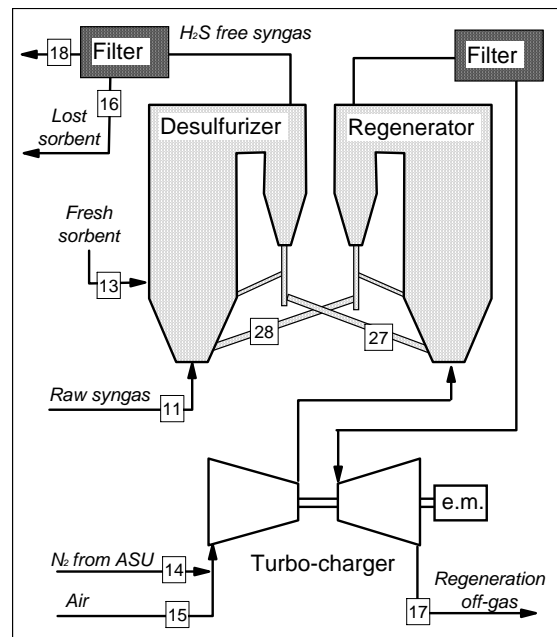


Figure 3 – Hot Gas Desulfurization

METHOD OF CALCULATION AND ASSUMPTIONS

The thermodynamic performance of the power plants here discussed were calculated by means of GS, which is an in-house computer code developed in the past years at the Department of Energy of Politecnico di Milano. The code is a powerful and flexible tool that can be used to accurately predict the performance of a very wide variety of chemical processes and systems for electricity production. GS was originally designed to assess the performance of gas-steam cycles for power production and has been progressively developed and improved to calculate complex systems including coal gasification, chemical reactors, fuel cells and essentially all the processes present in advanced plants for power generation from fossil fuels. As a brief reminder, the main features of the code are: (i) capability of reproducing very complex plant schemes by assembling basic modules, such as turbine, compressor, combustor, steam section, chemical reactor, heat exchanger, etc., (ii) built-in correlations to predict turbomachines efficiency (gas and steam turbine stages and compressors) as a function of their operating conditions, (iii) built-in correlations to predict gas turbine cooling flows, (iv) gas composition at reactors' outlet can be determined by assuming chemical equilibrium.

The calculated plant performance are dependent on a large number of assumption, defining the various processes and qualifying the characteristics of the components (i.e. efficiency of turbomachines, ΔT and pressure losses in heat exchangers and so on). The main assumptions are reported in Tables 1-5, derived from the analysis of a large number of power plants, carried out in the last two decades, both from literature and from industrial practice. More details can be found in authors' previous papers¹.

For all cases, the coal considered has the following composition (% by weight): 64.4 C, 3.95 H, 7.40 O, 1.49 N, 0.85 S, 9.20 humidity, 12.67 ash, with lower and higher heating values of 24.62 and 25.71 MJ/kg.

¹ See for instance references quoted in: (1) Chiesa P., Kreutz T., Lozza G. "CO₂ Sequestration from IGCC Power Plants by Means of Metallic Membranes", J.Eng. for Gas Turbines and Power, Vol.129, pp.123-134, Jan.2007, or in (2) Chiesa, P., Macchi, E. "A Thermodynamic Analysis of Different Options to Break 60% Electric Efficiency in Combined Cycle Power Plants", J.Eng. for Gas Turbine and Power, Vol.126, No.4, pp. 770-785, 2004.

<i>Gasification and ASU</i>		<i>Gas turbine and steam cycle</i>	
Gasification pressure, bar	44	Fuel temperature, °C	250
Gasification temperature, °C	1550	GT turbine inlet temperature, °C	1335
Heat losses, % LHV	0.7	GT pressure ratio	17
Carbon conversion	99.0	Pressure levels, bar	130/36
Temperature of O ₂ to gasifier, °C	15	SH/RH temperature, °C	565
Moderator steam, kg _{H₂O} /kg _{coal}	0.06	Pinch point/sub-cooling ΔT, °C	10/5
N ₂ to lock hoppers, kg/kg _{dry-coal}	0.22	Condensing pressure, bar	0.04
Quenched syngas temperature, °C	900	Minimum stack temperature, °C	115
Cold recycle syngas temperature, °C	200	<i>CO₂ compression</i>	
Min. ΔT in syngas coolers, °C	20	Number of inter-cooled stages	5
Oxygen purity, % mol.	95	Inter-cooling temperature, °C	25
ASU electric consumption, kWh/t _{O₂}	325	Inter-coolers pressure loss, %	1
		Compressors isentropic efficiency, %	82

Table 1 – Assumptions for the reference IGCC plants, present technology.

<i>Water Gas Shift Reactors</i>		<i>Selexol Plant</i>	
Steam to carbon at first reactor inlet	1.5	L/G ratio (wt. basis) in H ₂ S/CO ₂	
HT reactor outlet temperature, °C	400	absorption columns	1.1/11.6
LT reactor outlet temperature, °C	210	CO ₂ flash tanks pressures, bar	15/8/3.5/1.5
		Reboiler heat duty, MW _{th}	27

Table 2 – Additional assumptions for the IGCC plant with pre-combustion capture.

CO ₂ to gasifier lock hoppers, kg/kg _{coal}	0.35	Fuel side pressure loss at combustor, %	20
GT pressure ratio	40	O ₂ content at combustor outlet, % mol.	2

Table 3 – Varied assumptions for the oxy-fuel IGCC plant, present technology.

Gasification temperature, °C	1427	Syngas temperature to GT, °C	550
Gasification pressure, bar	50	Steam pressures HP/RH, bar	247/58
Carbon conversion	99.5	LP evaporation pressure, bar	4
Temperature of O ₂ to gasifier, °C	200	SH/RH steam temperature, °C	600/600

Table 4 – Varied assumptions for the oxy-fuel IGCC plant, advanced technology.

ZnO to TiO ₂ mol.ratio in fresh sorbent	1	O ₂ mol.fraction in regeneration mixture	2%
System pressure, MPa	≈ 5	Regeneration temperature, °C	750
Desulphurization temperature, °C	550	ZnS to ZnO mol.ratio in regen.sorbent	0.1
Sorbent loss, % in wt.	0.1	Pressure loss at the hot gas filter, %	3

Table 5 – Assumptions for Hot Gas Desulfurization.

DISCUSSION OF THE RESULTS

The calculated performance of the above described plants are reported in Table 6, showing the power breakdown, the efficiency and the carbon emission. The reference IGCC plant without capture shows an elevated efficiency (47.6%), consistently higher than the one of the plants now in operation. However this is obtained by a very efficient configuration, based on a dry-feed gasifier, a state-of-the-art gas turbine, an optimized heat recovery: it is representative of the performance obtained by a ‘mature’ IGCC market, rather than by ‘demonstration’ plants. The loss of efficiency due to pre-combustion capture is severe: 9 percentage points are lost due a number of factors: (i) loss of syngas heating value, due to the exothermic shift reaction (see the lower CGE – Cold Gas Efficiency), (ii) the loss of steam turbine power, caused by the steam extraction needed to achieve the required S/C ratio in the WGS reactors, (iii) the energy consumptions (pumps and LP steam) of the gas separation plant, (iv) the power re-

quirement of the CO₂ compressor. Lower loss of efficiency were encountered in other pre-combustion configurations, but starting from intrinsically lower performance: for instance with a full water quench gasification process, syngas is largely diluted with steam and a turbine extraction is not needed. However, a 38% net efficiency is a pretty elevated figure for a coal plant with CO₂ capture, compared to other solutions.

Case	Reference IGCC	Pre-combustion IGCC	Oxy-IGCC	Advanced oxy-IGCC	Advanced oxy-IGCC + HGD
TIT, °C	1335	1335	1335	1400	1400
Sulfur co-sequestration	-	no	no	yes	no
Electric/mechanical power MW					
Gas turbine (2 units)	659.4	597.7	609.6	656.5	653.2
GT auxiliaries	-2.34	-2.12	-2.16	-2.30	-2.32
Steam Turbine	420.6	354.0	454.7	510.8	513.6
Steam cycle pumps	-6.53	-6.92	-6.51	-11.60	-11.01
ASU	-72.15	-72.17	-178.17	-188.2	-187.0
Lock hoppers N ₂ compress.	-9.11	-9.11	-	-	-
Syngas recycle fan	-2.4	-2.41	-2.42	-	-
Syngas compressor	-	-	-10.79	-	-
N ₂ compressor for fuel dilution	-69.13	-51.34	-	-	-
Aux. for H ₂ S / CO ₂ removal	-0.69	-26.16	-0.69	-	-3.40
CO ₂ compression	-	-40.80	-83.05	-83.30	-83.30
Auxiliaries for heat rejection	-5.86	-5.18	-8.88	-11.03	-11.03
Miscellaneous BOP	-7.40	-7.38	-7.40	-7.47	-7.45
Net power output, MW _{el}	904.4	728.2	764.2	863.5	861.3
Fuel input LHV, MW _{th}	1897.6	1897.6	1897.6	1897.6	1897.6
Cold Gas Efficiency, %	78.14	69.63	77.36	83.85	83.31
Net LHV efficiency, %	47.66	38.38	40.27	45.50	45.39
CO ₂ captured, %	0	90.76	97.38	97.38	97.38
CO ₂ specific emissions, g/kWh	732.1	82.3	25.1	22.2	22.3

Table 6 –Performance of the plants considered in the paper.

The oxy-fuel IGCC with present technology shows a somewhat better efficiency (40.3%) and a much better carbon capture, compared to the previous case. The CGE efficiency is not varied from the no-capture case, but, as easily predictable, the consumption of the ASU is largely improved: as much as 180 MWe out of 1060 gross produced are required for oxygen production and compression. Any variation of the ASU performance will largely affect the overall plant balance. Also the CO₂ compression power is much higher than for pre-combustion, even for similar CO₂ mass flow, due to many reasons: (i) CO₂ impurities increases the mass flow to be compressed, (ii) compression begins at near-atmospheric pressure for the whole stream, (iii) the separation of incondensable gas brings about a significant pressure loss. The power cycle has been optimized, as a consequence of the different fluid composition (mainly CO₂) and molecular complexity: a much larger pressure ratio (40 rather than 17) is required to have a similar temperature history of the Joule cycle, in order to optimize the cycle efficiency. This calls for a re-design of the axial compressor and expander, but the performance are rather brilliant.

The advanced oxy-fuel case, intended to predict the performance of a mid-term configurations, is very efficient (45.5%). In particular, the hot-gas-cleaning simplifies the plant scheme and eliminates the losses connected to cooling and re-heating of the syngas. Into addition, the heating value of the H₂S is here used in the gas turbine for power production. The cycle performance was improved: a turbine inlet temperature of 1400°C was adopted with comparable or lower cooling flows, thanks to some foreseeable technological improvements, mainly con-

sisting in the cooling of the coolant flow. A better insight of this configuration is given by Table 7, showing the main characteristics of the relevant streams in the process.

However, co-sequestration of CO₂ and SO₂ poses some big question marks, mainly related to the compatibility of sulfur compounds with the selected long-term storage strategy, but also regarding the possibility of acid corrosion in the transport pipeline and in the low temperature components of the power plant. Sulfur can be removed by a limestone wet scrubbing process applied to the final CO₂ stream or, in a more innovative fashion, by means of HGD. The last column of Table 6 shows that the loss of efficiency due to HGD is very limited: the turbo-charger shown in fig.3 just requires 3.4 MWe to be driven and it is the only relevant difference. It must be reminded that, even if H₂S is no longer burnt in the gas turbine, its heating value is not wasted: both desulfurization and regeneration reactions are exothermic, improving the heat available from the gaseous streams involved in the process.

Point	G kg/s	T °C	p bar	Composition, %mol.									
				CH ₄	CO	CO ₂	H ₂	H ₂ O	Ar	N ₂	O ₂	H ₂ S	SO ₂
1	36.83	15.0		dry coal (%wt.: 67.4 C, 4.2 H, 7.7 O, 1.6 N, 0.8 S, 5.0 H ₂ O, 13.3 ash)									
2	17.24	150.0	68.87	0.00	0.00	93.48	0.00	0.20	3.33	0.96	1.57	0.00	0.46
3	26.43	200.0	61.22	0.00	0.00	0.00	0.00	0.00	2.97	0.03	97.00	0.00	0.00
4	4.45	416.2	61.22	0.00	0.00	0.00	0.00	100	0.00	0.00	0.00	0.00	0.00
5	75.72	1426.8	51.00	0.02	65.45	5.19	21.16	5.98	1.13	0.72	0.00	0.35	0.00
6	75.72	550.0	48.00	0.02	65.45	5.19	21.16	5.98	1.13	0.72	0.00	0.35	0.00
7	49.51	200.0	40.00	0.00	0.00	0.00	0.00	0.00	2.97	0.03	97.00	0.00	0.00
8	441.6	406.9	40.00	0.00	0.00	88.51	0.00	5.51	3.15	0.91	1.48	0.00	0.44
9	566.8	1483.7	38.80	0.00	0.00	83.62	0.00	10.73	2.98	0.86	1.40	0.00	0.41
10	696.0	690.8	1.05	0.00	0.00	84.50	0.00	9.78	3.01	0.87	1.42	0.00	0.42
11	570.8	35.0	1.02	0.00	0.00	88.51	0.00	5.51	3.15	0.91	1.48	0.00	0.44
12	91.59	35.0	22.77	0.00	0.00	93.67	0.00	0.00	3.33	0.97	1.57	0.00	0.46
13	4.91	-37.0	22.09	0.00	0.00	54.88	0.00	0.00	24.20	9.86	11.04	0.00	0.02
14	86.68	-41.0	16.00	0.00	0.00	96.06	0.00	0.00	2.04	0.42	0.99	0.00	0.49
15	86.68	25.0	150.0	0.00	0.00	96.06	0.00	0.00	2.04	0.42	0.99	0.00	0.49
16	97.81	600.0	247.0	0	0	0	0	100	0	0	0	0	0
17	52.68	600.0	247.0	0	0	0	0	100	0	0	0	0	0
18	144.4	600.0	53.18	0	0	0	0	100	0	0	0	0	0
19	3.92	250.0	3.68	0	0	0	0	100	0	0	0	0	0
20	1.52	143.6	4.00	0	0	0	0	100	0	0	0	0	0

Table 7 – Mass flow, pressure, temperature and chemical composition of the relevant point of the advanced oxy-fuel IGCC (point numbers are visible on fig.2).

CONCLUSIONS

The results obtained for IGCC plants with oxy-combustion are very interesting. Better environmental performance, compared to any other realistic technology, can be obtained: (i) NO_x or SO_x are not released to the ambient, but are almost entirely solved within the CO₂ stream to be sequestered; (ii) the only carbon release to the ambient is the CO₂ contained in the incondensable gases, here estimated as a 3% of the carbon input: these low figure can be further reduced to negligible values by treating this small and concentrated gas stream.

An elevated efficiency (above 45% net) can be achieved by advanced configurations. Advancements consists of: (i) some refinement in the gasification system and in the blade cooling technology, which is fully realistic in a time frame of one decade, (ii) the adoption of an Hot Gas Clean-up system, (iii) the development of a novel gas turbine unit. The last two statements require some comments. The major obstacle is the realization of an oxy-fuel gas turbine, which must be re-designed with very large modification to existing units. However, the design of an axial compressor or turbine for a semi-closed CO₂ cycle does not require any new methodology and therefore involves costs, but not risks. An oxy-combustor is a more sensitive and novel component, but it does not pose unsurpassable barriers.

The Hot Gas Filtration is today a quite risky practice, not fully demonstrated in terms of industrial acceptability and costs. However, the oxy-fuel IGCC concept offers the possibility of obtaining the full benefits from this technology: for pre-combustion, HGF is simply not useful, because the syngas has to be cooled for CO₂ separation. Supposing that CO₂-SO₂ co-sequestration or Hot Gas Desulfuration will be viable, oxy-fuel is again the solution for taking advantage from these practices.

We can therefore conclude that oxy-combustion IGCC techniques may deserve some more attention in the R&D programs for clean power production systems in a near-mid term perspective, because they have a potential to improve the efficiency and the environmental characteristics of coal power plants.

Keywords: IGCC, CO₂, Capture, Oxyfuel, HGCU.