TECHNICAL ASSESSMENT FOR IGCC SYSTEM USING BRAZILIAN COAL AND PETROLEUM COKE MIXTURE: Environments impacts, challengers and possibilities to CCS

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ABSTRACT

Coal is abundant, cheap and widespread fossil fuels. Therefore, it represents an energy source that contributes around to 39% of the world's electric power generation [1]. The BP Statistical Review of World Energy 2009 predicts a considerable growth of the world's primary energy demand and states that fossil fuels will remain the dominant source of primary energy [2]. Among fossil fuels, coal has vast reserves, relatively even worldwide distribution and low prices compared to oil and gas. One of the factors that limit the massive utilization of coal is its environmental impact. Coal combustion emits larger quantities of CO_2 than oil and gas. As CO_2 is the leading cause [3] for global warming, the use of coal for power generation demands a clean coal technology, preferably with carbon capture and storage systems (CCS).

Integrated Gasification Combined Cycle (IGCC) systems are considered a very promising technology for next generation coal-fired power plants, especially when it uses coal and petroleum coke (petcoke) mixtures to improve the properties of the fuel. IGCC systems can enhance the thermal efficiency and strongly reduce pollutant emissions with respect to state-of the- art power plants based on coal-fired boilers. In order to evaluate IGCC technology, an analysis of coal gasification process in a combined cycle power plant is presented in this paper. The combustion of the synthesis gas (syngas) from coal gasification was simulated using CeSFaMBi™ software. In the next part, the syngas composition is used to analyze power plant performance through GateCycle™ software.

A model of a 350 MW IGCC plant using Parana coal, petcoke and a mix of 50% coal and 50% petcoke as fuel presented. A technical assessment of the gasification process is conducted, considering its integration with the combined cycle. High Heating Value (HHV) and combined cycle global efficiency were obtained when using petcoke as fuel, with values of 12.40 MJ/kg and 45%, respectively.

1.- Introduction

Current regulation is being amended to integrate the systems of power generation and fulfil the limits imposed to the emission in the environment of heavy metals, dioxins, unsaturated hydrocarbons, aromatics and carbon dioxide in the environment. Moreover, the limitations for gas turbines in filtering and cleaning gases are more restrictive in some cases, even than the environmental regulation [4]. The fact that environmental laws are becoming stricter worldwide encourages the implementation of IGCC systems, particularly because this technology offers a solution for the treatment of waste generated by the refining of crude oil. In this context the article deals environments impacts, challengers and possibilities to CCS in IGCC systems. At first was analyzed the gasification process using CeSFaMBi software to determine the composition of syngas. After that, is using GateCycle to analyze the power plant cycle. The results obtained through CeSFaMBi and GateCycle interaction, are discussed in this paper.

2.- Integrated gasification combined cycle technology (IGCC)

IGCC is one of the most efficient, environmentally effective means of producing electricity. IGCC technology convert an often “dirty” fuel, such as coal, biomass, or refinery residues that cannot be directly used in gas turbines, to a clean gaseous fuel that meets engine specifications and environmental emissions standards. Figure 1 shows the basic structure of the IGCC systems.

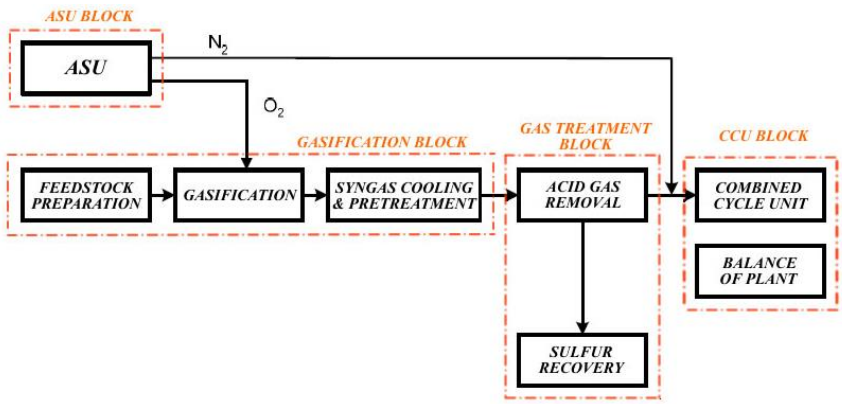

Figure 1. Diagram of IGCC power plant [adapted to 5].

Reductions of emissions of SOx, NOx, CO, volatile metals, and particulates can be significantly better than those obtained by scrubber equipped pulverized, as well as circulating fluidized bed coal combustion plants [6]. IGCC's economic benefits will become more significant as air emission standards are made more stringent, since this technology can achieve greater emissions reductions at lower incremental costs. IGCC systems can be designed to approach zero emissions, including CO_2 emissions [7] Carbon is captured as CO_2 from syngas, such that a gas that is mostly H_2 is burnt in gas turbines. This pre-combustion capture may be combined with syngas desulfurization and may be accomplished in a physical solvent acid gas removal process.

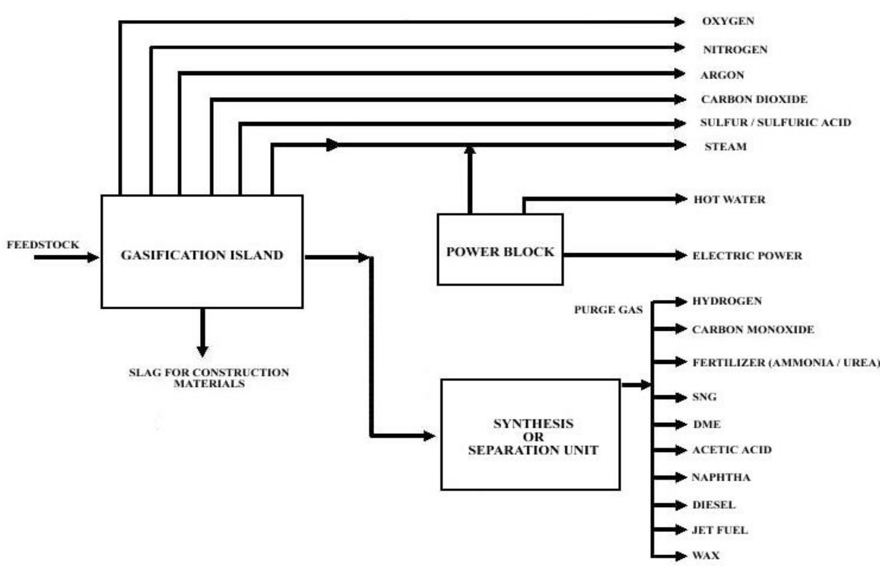

Figure 2. Coproduction alternatives in IGCC systems [adapted to 4].

One of the major advantages of IGCC systems is that a number of co-products may be produced to improve process economics. Figure 2 shows various products and co-products which may be produced. It may include the following advantages:

- Efficient use of steam in a single large steam turbine,
- Opportunity for load following,
- Economies of scale of larger plants,
- Advantages specific to products such as methanol or F-T liquids:
    - Reduced synloop recycle rate with unconverted purge gas fired in gas turbines,
    - Higher reactor throughput due to lessened buildup of inerts,
    - Reduction in diluents addition to gas turbines for NOx control due to low heating value of purge gas.

2.1- Environmental impact of IGCC systems

In IGCC systems the sulfur oxides emissions become limited, due the reduced concentrations of H_2S and COS in the exhaust gas after desulphurization process to 25-70 ppmv [8]. The content of nitrogen compounds in the syngas is practically zero, so the production of nitrogen oxides is controlled through the design of burners and combustion chambers, besides the saturation and dilution gas. Table 1 shows a comparison of IGCC plants with conventional thermal power systems, where the former have higher efficiency and lower emissions [9].

Table 1. Comparison of emissions and waste production from different technologies.

Technology	Emissions (g/kWh)				Sub-products /Solid residues (g/kWh)
	SO_2	NOx	Particles	CO_2	
IGCC	0.10	0.20	0.02	725	Slag: 21, Ash: 2, Sulfur: 4
PC Subcritical	2.50	2.30	0.30	852	Slag: 27.4, Plaster: 19.6
PC Supercritical	2.15	1.10	0.27	774	Slag: 25.0, Plaster: 18.8
AFBC	1.40	0.80	0.10	852	mix ash limestone plaster: 52.9
NGCC	0.54	0.02	350	-	-

To achieve the reduction of emissions to the environment, IGCC systems require more complex structures than the conventional steam power plants, what means they require higher capital costs [7]. In the other hand, IGCC systems result in higher efficiency, reducing the cost with fuel supply.

3.- Gasification process

Gasification itself has been in commercial use for more than fifty years; its first applications was related to the production of "town gas", for heating and cooking purposes, before large natural gas reserves were discovered and providing syngas for production of chemicals. Valuable, such as H_2 or F-T liquids, can enhance IGCC economics. Gasification is a conversion process that involves partial oxidation at elevated temperature. It is intermediate between combustion and pyrolysis. In fact, oxygen (or air) is present but it is not enough for complete combustion. This process can start from carbonaceous feedstock such as biomass or coal and convert them into a gaseous energy carrier [10].

The overall gasification process may be split into two main stages: in the first is pyrolysis stage, where oxygen is not present but temperature is high, and here typical pyrolysis reactions take place; in the second stage is the partial combustion, where oxygen is present and it reacts with the pyrolyzed biomass or coal to release heat necessary for the process. In the latter stage, the actual gasification reactions take place, which consist of almost complete charcoal conversion into lighter gaseous products through the chemical oxidizing action of steam, oxygen, and CO_2.

Gasification reactions require temperature in excess of 800°C to minimize tar and maximize gas production. The gasification output gas, is composed by H_2 (18%–20%), CO (18%–20%), CO_2 (8%–10%), CH_4 (2%–3%), trace amounts of higher hydrocarbons like ethane (C_2H_6) and ethene (C_2H_4), H_2O, N_2 (when is used air as oxidant agent), and various contaminants such as small char particles, ash, tars, and oils. The incondensable part of syngas and it represents the useful product of gasification. Syngas has a HHV in the order of 4–7 MJ/m^3, when is used air as oxidant agent, which is exploitable for boiler, engine, and turbine operation, but due to its low energy density, it is not suitable for pipeline transportation. If oxygen is used, the syngas HHV almost doubles (approximately 10–18 MJ/m^3 HHV). However, the most common technology is the air gasification because it avoids the costs and the hazards of oxygen production and usage [10].

3.1 - Syngas applications

The range of products immediately obtainable from synthesis gas extends from bulk chemicals like ammonia, methanol and F-T products, through industrial gases to utilities such as clean fuel gas and electricity. Furthermore, there are a number of interesting by-products such as CO_2 and steam.

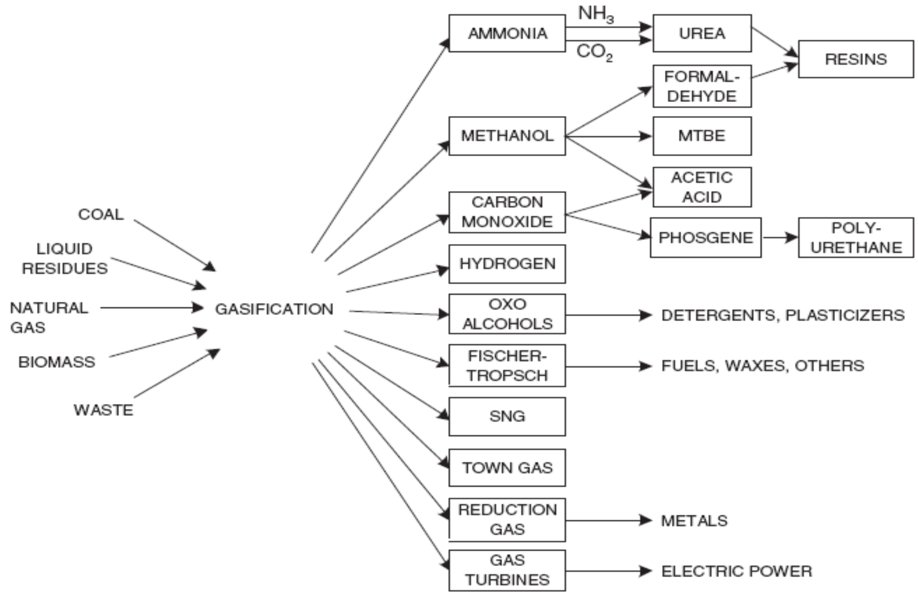

Figure 3. Applications for synthesis gas [*adapted to 11*].

One aspect of gasification technology which has attracted recent attention is its ability to produce gaseous hydrogen. If an energy economy based on hydrogen ever evolves, then coal gasification could provide one source of the fuel. Figure 3 shows many of these direct products are only intermediates towards other products closer to the consumer market, such as acetates and polyurethanes. The syngas is an intermediate that can be produced by gasification from a wide range of feedstocks and can be turned into an equally wide range of products. This inherent flexibility associated with syngas production and use provides a multitude of choices that is increased by the variety of utility systems, in particular the broad possibilities for steam system configuration.

3.2 - Fuel characterization

Initially it will be presented the main characteristics of the fuels (coal, petcoke and a mix between 50% coal with 50% petcoke) used in this analysis. Tables 2, 3 and 4 show the elemental fuel analysis that will be considered in the gasification technologies simulation [12-13]. This characterization corresponds to samples of Brazil fuel, including petcoke and coal type Paraná coal one of the most important deposits of Brazil coal located in Paraná states.

Table 2. Paraná coal, Elemental fuel analysis [12]

Ultimate analysis		Proximate analysis (wt. %)	
Carbon (%)	56.6	Moisture (%)	5.8
Hydrogen (%)	3.1	Volatile	35.4
Nitrogen (%)	0.8	Fixed Carbon	49.8
Oxygen (%)	15.73	Ash (%)	9.0
Sulphur (%)	2.0		
Ash (%)	21.76		
HHV (MJ/kg)	26.54		

Table 3. Petcoke, Elemental fuel analysis [13]

Ultimate analysis		Proximate analysis (wt. %)	
Carbon (%)	86.3	Moisture (%)	7.0
Hydrogen (%)	3.5	Volatile	19.2
Nitrogen (%)	1.6	Fixed Carbon	73.5
Oxygen (%)	0.5	Ash (%)	0.3
Sulphur (%)	7.5		
Ash (%)	0.6		
HHV (MJ/kg)	33.6		

Table 4. Paraná Coal / Petcoke Mixture, Elemental fuel analysis

Ultimate analysis		Proximate analysis (wt. %)	
Carbon (%)	71.5	Moisture (%)	6.4
Hydrogen (%)	3.3	Volatile	27.3
Nitrogen (%)	1.2	Fixed Carbon	54.5
Oxygen (%)	8.1	Ash (%)	11.8
Sulphur (%)	4.8		
Ash (%)	11.0		
HHV (MJ/kg)	25.1		

The high ash content of the Brazilian coal can influence negatively the performance of a generation system based on its combustion. On the other hand, the Brazilian petcoke is considered as LSC because it is produced during the processing of oil with low sulfur content (0.8% sulfur), while some imported petcoke, which may come from Venezuelan oil refining, presents sulfur content in the order of 3% by weigh [14], has a low market value and a great chance of becoming an economically viable fuel for thermal generation. According to the World Energy Council (2007), it is for this reason that in many applications it is recommended to mix the coal with petroleum coke (with a content of around 20-50% of coke) to improve fuel properties [15].

3.3 - Gasification process simulation with the CeSFaMBi software

The proposed model for the gasification process uses CeSFaMBi software, which is a comprehensive mathematical model and simulation program for bubbling and circulating fluidized-bed, as well as downdraft and updraft moving-bed equipment. Among these equipments, there are furnaces, boilers, gasifiers, dryers, and reactors [16]. In the gasification process simulation was selected a circulating fluidized bed as gasifier, this technology has been successfully used in many fields, including combustion, biomass/coal gasification and oil catalytic cracking, which is the type that best fits within the possibilities of simulation gasifiers in the CeSFaMBi program, taking into account the power ranges that they can achieve.

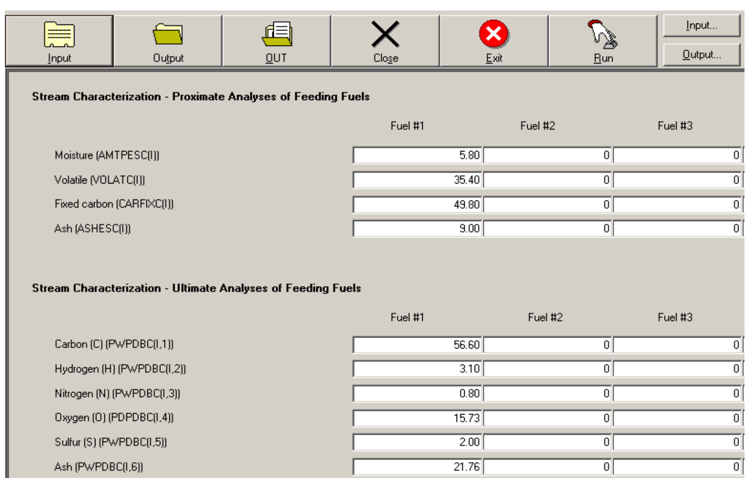

Figure 4. CeSFaMBi interface

Figure 4 shows the CeSFaMBi interface, where is introduced the stream characterization and fuel composition, in wet basis, for proximate analysis, and in dry basis, for ultimate analysis. The data shown is this figure refers to used in Paraná coal.

3.4 - Results and analysis of gasification process simulation

Gasification process simulation was carried out using different types of fuels (Tables 2 – 4) and a circulating fluid bed as gasifier. Table 5 lists the main parameters required by CeSFaMBi software for the gasifier simulation using coke as fuel. In the tests carried out, the feed mass flow rates, the feed gas though distributor and the granulometry of the fuel fed to the gasifier were modified in order to achieve the conditions above the second turbulence limit, allowing for increased contact between particles and gases.

Table 5. Key input parameters of the gasifier design

Parameter	Variable	Value	Units
STREAM CHARACTERIZATION SOLIDS AND FUEL FEEDING			
Apparent density, Carbonaceous	ROPES(1)	700	kg/m^3
True density, Carbonaceous	RORES(1)	1650	kg/m^3
Inlet mass flow rate, Carbonaceous	FMTES(1)	30	kg/s
Inlet temperature, Carbonaceous	TPES(1)	298	K
EQUIPMENT DATA - BASIC GEOMETRY ***Gasifier***			
Bed - equivalent hydraulic internal diameter	DD	3.50	m
Freeboard - equivalent hydraulic internal diameter	DF	3.50	m
Position of main gas withdrawal	ZF	10.0	m
Position of carbonaceous fuel feeding	ZFEED(1)	1.0	m
Distributor			
Number of orifices for gas/steam injection (0=porous plate)	NOD	3000	-
Diameter of orifices for gas/steam injection through distributor	DOD	0.004	m
EQUIPMENT DATA - CYCLONES AND RECYCLING ***Ciclone***			
Internal diameter of cyclones	DCY	0.8	m
Height of the cylindrical part of cyclones	HCY	1.000	m
Height of the conical part of cyclones	HCYC	1.000	m
Position of recycling injection	ZRCY	2.00	m
STREAM CHARACTERIZATION GASES THROUGH DISTRIBUTOR			
Gasification agent	Mixture Oxygen (85%) + Steam (15%)		
Inlet gas through distributor, Temperature	TEGID	435	K
Inlet gas through distributor, Pressure	PEGID	160	kPa (abs.)
ADDITIONAL OPERATIONAL CHARACTERISTICS			
Average pressure in the bed	POPER	150	kPa (abs.)
Local Ambient Conditions			
AVG surrounding air temperature	TAMB	290	K
Wind velocity	VV	2	m/s

Table 6. Synthesis gas composition (dry basis) and gasifier efficiency

	COAL	PETCOKE	MIXTURE (50:50w)
CO_2	14.72	12.99	13.11
CO	42.22	41.57	43.02
CH_4	0.05	0.06	0.04
H_2	42.11	44.24	43.05
N_2	0.53	0.67	0.73
H_2O	38.51	39.85	40.16
HHV (MJ/kg)	10.85	12.40	11.79
Cold efficiency 57%		Hot efficiency 81%	

Table 6 describes the gasifier efficiency and the main compounds in volumetric percentage of the synthesis gas produced from coal, pet coke and a mixture or both, using the CeSFaMBi software without taking into account the low percentage of H_2, H_2S, NH_3 and SO_2 compounds.

4.- Combined cycle simulation using GateCycle software

The IGCC system simulation was conduct using GateCycle software (version 5.51). It software is a powerful tool for both the gas and steam sides of power plant design and analysis. For model a gas turbine, it was select from the library the Siemens V94.3A (1999 GTW) gas turbine. For the steam side, it was include all of the component icons needs to built the model HRSGs accurately with multiple pressure levels, parallel sections and pressure losses.

GateCycle software included CycleLink utility, allow it to run analyses from within the Microsoft® Excel spreadsheet application. In addition to these tools has been widely used SteamTable supplement, in the use of steam and water tables properties. The simulation considered the syngas composition presented in Table 6 and ISO standard conditions (1 atm, 15 °C and 60 % HR). Figure 5 shows a model developed in GateCycle software.

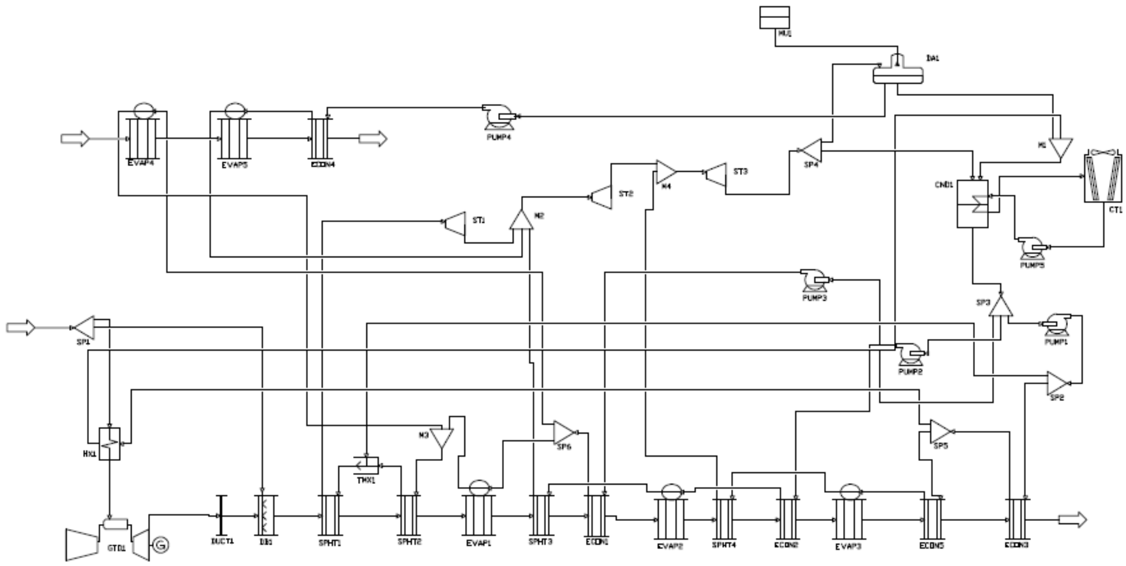

Figure 5. IGCC power plant scheme modeled on GateCycle software

GateCycle's model is characterized by the integration of thermodynamic cycles, Brayton and Rankine. In the first is describes the workings of the gas turbine engine (power cycle) and in the second describes a model of steam operated forward heat engine which converts heat into work (steam cycle).

4.1 - Assumptions on plant configuration

Normally the thermal sizing of an IGCC plant depends on the gas turbine model selected. In this work was propose a plant of 350 MW, it was decided to determine the thermal input for a given net power cycle power output, which allows a better comparison of the necessary turbomachinery sizes. For the steam cycle of the IGCC plant, a dual-pressure reheat cycle instead of the conventional assumption of a triple-pressure cycle is modeled for simplicity reasons. In order to reduce the heat losses of the gasifier, gasification and power plant are closely connected, with heat transferred between both units. The fuel supply to the gasifier is determined by the request of a net electrical output of the plant.

Table 7. Technical description IGCC plant

<table>
<tr><td>System</td><td colspan="2">Variable</td><td>Value</td></tr>
<tr><td rowspan="3">Environmental conditions</td><td colspan="2">Temperature [°C]</td><td>15</td></tr>
<tr><td colspan="2">Humidity [%]</td><td>0.6</td></tr>
<tr><td colspan="2">Pressure [atm]</td><td>1</td></tr>
<tr><td rowspan="5">HRSG</td><td rowspan="3">Steam</td><td>High pressure [bar]</td><td>130</td></tr>
<tr><td>Middle pressure [bar]</td><td>40</td></tr>
<tr><td>Low pressure [bar]</td><td>7.5</td></tr>
<tr><td rowspan="2">Combusted gas temperature [°C]</td><td>In</td><td>535</td></tr>
<tr><td>Out</td><td>103</td></tr>
<tr><td rowspan="4">Gas turbine</td><td colspan="2">Power [MW]</td><td>200</td></tr>
<tr><td colspan="2">Mass flow air [kg/s]</td><td>550</td></tr>
<tr><td colspan="2">Compression</td><td>15:1</td></tr>
<tr><td colspan="2">Thermal efficiency [%]</td><td>35</td></tr>
<tr><td rowspan="5">Steam turbine</td><td colspan="2">Power [MW]</td><td>150</td></tr>
<tr><td rowspan="2">High pressure superheated steam</td><td>Pressure [bar]</td><td>120</td></tr>
<tr><td>Temp. [°C]</td><td>500</td></tr>
<tr><td rowspan="2">Reheated steam</td><td>Pressure [bar]</td><td>30</td></tr>
<tr><td>Temp. [°C]</td><td>515</td></tr>
<tr><td>Air splitter unit</td><td colspan="2">Air flow [kg/s]</td><td>90</td></tr>
<tr><td>Combined cycle</td><td colspan="2">Net power output [MW]</td><td>350</td></tr>
</table>

The model available in GateCycle for equipments used in the combined cycle systems (steam and gas turbine, evaporators, heat exchanger, HRSG, condenser, cooling tower, etc.) was developed taking into account the operation parameters presented in Table 7. In this work, temperature, pressure, mass flow and clean syngas are initial parameters of the gas turbine equipment, after than combusted gases goes to HRSG equipments and steam production and heat recovery are estimated. Exhaust gas from the gas turbines is fed to triple-pressure. Auxiliary losses, which could not be considered in this simplified approach, as gasifier and combustion chamber heat loss, coal treatment, operation of cooling water pumps or the syngas cleaning, are considered with 5 % of the total heat input.

4.2 - Results and analysis of IGCC model

GateCycle's model applied used two syngas streams are used in the syngas heat recovery block and to consider the feed up gas turbine. In the first one, pressure, temperature and mass flow information is provide for estimation of heat recovery and steam production from the gasification island. The second stream is feed with information associated to clean syngas composition as well pressure, temperature, and mass flow.

Moreover, the power cycle using 3-level pressure for determining heat rate and efficiency of combined cycle were used to validate our thermodynamics simulations. As a final point, the electric power generated is estimated and efficiency and heat rate is evaluated. Table 8 shows the results obtained for simulations of IGCC power plant using syngas resultant for different types of fossil fuels.

Table 8. Result of the combined cycle power plant modeling

Variable	Fuel	Value
Combined cycle net power [MW]	Coal	337.89
	Petcoke	345.61
	Mixture	342.14
Combined cycle global efficiency [%]	Coal	40.56
	Petcoke	45.92
	Mixture	43.13
Combined cycle Heat Rate [kJ/KWh]	Coal	7199
	Petcoke	7516
	Mixture	7398

5.- Challengers and advanced IGCC system designs

One of the main issues associated to power generation using coal as fuel concerns in sulfur removal. Stringent regulations about pollutant emissions control in developed countries, along with the need to protect the gas turbine from corrosion phenomena, require a deep removal of sulfur-based contaminants from coal derived syngas. For this reason, R&D programs in U.S and Europe working in improvement this topic. As a developing technology, there are opportunities for significant performance and cost improvements in IGCC systems [17]. Over the next decade or so, gains are expected in the following five areas:

- Advanced gasifier concepts with higher efficiency and reliability, plus higher operating pressure for more economic CO_2 capture.
- Advanced ASUs with better thermal integration with IGCC systems.
- Syngas clean up processes with less expensive particulate removal systems, including hot gas filtration.
- Advanced GTs with higher efficiency and ability to burn syngas and hydrogen-rich fuels.
- Optimal system integration with new technologies and components.

5.1- IGCC with CCS

Therefore innovative coal technologies are indispensable for climate protection. In this respect, carbon capture and storage (CCS) plays a key role in the future use of coal. There are three main ways to capture the carbon dioxide CO_2 in coal fired power plants:

- Removal of the CO_2 from the exhaust gas (post-combustion technology),
- Coal gasification and water-shift reaction of the syngas to produce a gas consisting mainly of CO_2 and hydrogen H_2,
- CO_2 can then be captured at relatively low costs leaving mainly H_2 for the use in a conventional combined cycle plant (pre-combustion technology) use of oxygen instead of air for combustion leading to a flue gas consisting mainly of CO_2 and H_2O, which allows an easy CO_2 capture by water condensation (oxy-fuel technology).

With IGCC now available as a commercial package, more orders could follow as utilities see the cost decreasing and availability improving. IGCC fits well with CO_2 capture and storage and there are projects planned in several countries, including Canada, Australia, Germany, the UK, in addition to the US Government FutureGen and European Commission Hypogen initiatives and the GreenGen project in China [18].

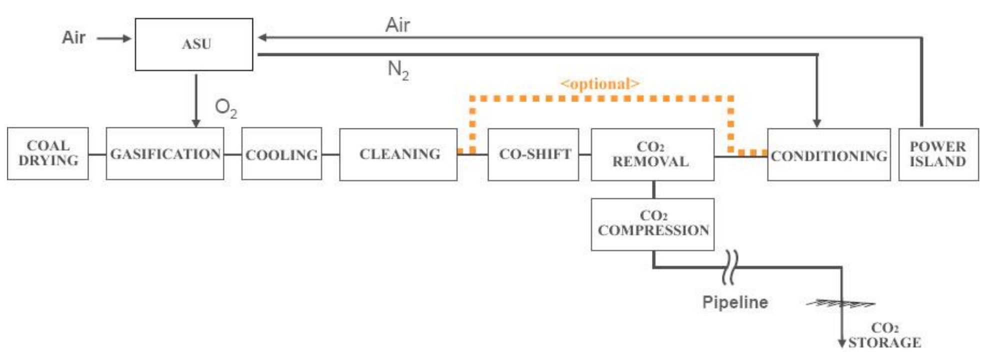

Figure 6. Flow scheme of an IGCC power plant with CCS

Figure 6 shows the principle flow scheme of the IGCC plant with pre-combustion sequestration of the CO_2. In the gasification process, before the syngas from coal gasification is fed to the absorption process or to a gas turbine combustion chamber it must be cleaned. The typical steps for a gas clean-up system are aimed at particulate, sulfur, ammonia and chlorides removal. Particulate removal is performed with cyclone and membrane filters, whereas the acid gas removal is done by chemical or physical absorption [19]. The net efficiencies of IGCC plants with CO_2 capture show an efficiency of 40 % [20].

6.- Conclusions

IGCC technology is one of the most efficient, environmentally effective means of producing electricity. IGCC systems can be designed to approach zero emissions. IGCC technology is commercially proven, and the gasification process itself has been in commercial use for more than 50 years [21]. Valuable co-products such as H_2 or F-T liquids may be co-produced to enhance economics.

In order to satisfy the world's need for energy, coal with petcoke mixture will play an important role in the future energy supply despite its detrimental effect on the world climate. Therefore 'clean coal' technologies have to be developed to protect world's climate. In the future, it is not clear, which technology will prevail but it can be expected that each technology will play a role in a future CCS market depending on the specific application. As an alternative to the pre-combustion technology demanding an energy-intensive shift reaction and CO_2 scrubbing, a combination of coal gasification with an oxy-fuel cycle of highest efficiency.

In the proposed model it is evident that GateCycle software is an adequate tool for thermodynamic simulation of power generation combined cycle. Moreover, the CeSFaMBi software used for gasification process showed to be an optimal tool for simulating a gasifier type circulating fluid bed. It makes possible to estimate composition of syngas using different types of fuel, highlighting in the obtained results the use of petcoke and the mixture coal/petcoke. The gasifier model was dimensioned based on the gas turbine power requirements of the combined cycle, resulting a gasifier with a geometry and a design conditions that involve a technical, economic and financial assessment, in order to determine the feasibility of implementation in IGCC systems.

7.- Nomenclature

ASU: Air separation unit	COS: Carbonyl sulfide
AFBC: Atmospheric fluidised bed combustion	CO_2: Carbon dioxide
NGCC: Natural gas combined cycle	F-T: Fischer-Tropsch process
CCS: Carbon capture and storage	PC: Pulverized coal
CeSFaMBi: Comprehensive simulator of fluidized and moving bed equipment	HRSG: Heat recovery steam generators
CO: Carbon monoxide	IGCC: Integrated gasification combined cycle

8.- Acknowledgments

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