TECHNICAL EVALUATION OF IGCC SYSTEM FOR BRAZILIAN COAL AND PETROLEUM COKE

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Abstract: The trend and the increase in global production of petroleum coke are the result of multiple and innovative industrial applications. From this point of view and also considering the actual situation of the traditional energy reserves worldwide, it is important to conduct studies in this area through the analysis of the main components of the plants utilizing this fuel (petroleum coke). The main target of this study is to realize a technical evaluation of different variants of the IGCC (Integrated Gasification Combined Cycle) technology, using as fuel petroleum coke and coal. The gasification process and the combined cycle power plant are analyzed considering their potential of implementation in Brazil.

Keywords: Gasification, Integrated Gasification Combined Cycle (IGCC), Petroleum Coke, Coal, Carbon Capture Sequestration (CCS), Gasifiers.

1. Introduction

Nowadays, Integrated Gasification Combined Cycle (IGCC) is one of the most important and promising clean technologies for power generation, when using coal, petroleum coke (petcoke) and biomass as energy sources. The environmental benefits and the higher energy conversion efficiency distinguish this technology from the traditional ones.

The IGCC power plants performance is affected by different technological and operational aspects, e.g. gasifier agent, gasification technology, environmental conditions, coal quality and power demand. This group of variables conduces necessarily to the use of thermodynamic simulation tools to analyze the different process and equipments used in this technology. In this paper the analysis are carried out considering the gasifier simulation in the software CSFBM version 24.9 [1] (Comprehensive Simulator of Fluidized and Moving Bed equipment) to determinate the synthesis gas (syngas) composition. In a following stage, the syngas composition is used in GateCycle™ version 5.51 [2] to analyze power plant performance.

The methodology used for thermodynamics simulation of IGCC plants, as well the results obtained through CSFBM and GateCycle interaction, are discussed in this paper. The results for gasification process simulation using different fuels are also presented. The results of GateCycle IGCC model were evaluated considering the gasification behavior and the energy efficiency of combined cycle. As a preliminary analysis, the results were compared with the operating parameters of ELCOLGAS Puertollano IGCC power plant in Spain.

Nowadays, there is a tendency in using thermodynamic simulations to estimate the performance of gasification process as a function of the available energetic resources, operational and environmental conditions. Several commercial software can be used to perform these simulations [3-4]. Through the integration of the software results it is possible to analyze different generation capacities, and its behavior under different fuel, air, oxygen, nitrogen, steam and water flow rates [5].

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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 1, 2 and 3 show the elemental fuel analysis that will be considered in the gasification technologies simulation [6-7].

Table 1. CANDIOTA COAL Elemental fuel analysis [6]

Ultimate analysis		Proximate analysis (wt. %)	
Carbon (%)	34.0	Moisture (%)	15.0
Hydrogen (%)	2.6	Volatile	16.4
Nitrogen (%)	0.7	Fixed Carbon	24.4
Oxygen (%)	8.5	Ash (%)	44.2
Sulphur (%)	1.2		
Ash (%)	53.0		
HHV (MJ/kg)	13.8		

Table 2. PETCOKE Elemental fuel analysis [7]

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 3. CANDIOTA COAL / PETCOKE MIXTURE, Elemental fuel analysis

Ultimate analysis		Proximate analysis (wt. %)	
Carbon (%)	62.5	Moisture (%)	9.2
Hydrogen (%)	3.0	Volatile	18.6
Nitrogen (%)	1.1	Fixed Carbon	51.5
Oxygen (%)	4.5	Ash (%)	20.7
Sulphur (%)	3.9		
Ash (%)	25.0		
HHV (MJ/kg)	25.1		

2.1. Coal

In the Brazilian energy matrix, the coal corresponds to only slightly more than 1% of total primary energy produced [8]. However, it is the most abundant fossil resource in Brazil. Considering the estimated reserves it is projected that there are sufficient reserves for 200 years of supply (against 40 years for oil and 60 years for natural gas).

Despite being an abundant resource in Brazil (reserves are $32x10^9$ ton [9]), its low quality, due to high ash and sulfur contents, and the related environmental impacts, makes it underutilized. The most important deposits of Brazil are located in the states of Rio Grande do Sul, Santa Catarina and Paraná.

Coal is classified according to its quality as: peat, low-content coal, which is one of the early stages of coal with carbon content of around 45%, lignite, which features carbon ranging 60% to 75% bituminous coal, most used type, due to its advantages in the generation of electricity and the production of cement, iron and steel, and contains between 75% and 85% carbon, and anthracite, the purest of coal, containing 90% of coal or higher.

The high ash content of the Brazilian coal can influence negatively the performance of a generation system based on its combustion [10]. For this reason, in many applications, it is recommended to mix the coal with petcoke to improve the properties of the fuel.

2.2. Petroleum coke

Petcoke is a byproduct of the petroleum refining industry which has a high calorific value, low cost and sulfur content determined by the type of petroleum, from which it originates [11].

Due to the increasing quantities of heavy oil that are being processed nowadays, the production of petcoke is also increasing. The biggest potential of petcoke is obtained when it is used in production processes for the industrial sector, mainly in electricity generation [12] and cement production.

The Brazilian petcoke is produced in parks steel and this product is considered as LSC (low sulfur content) because it is produced during the processing of oil with low sulfur content (0.8% sulfur [13]), 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. Therefore, the advantage of using petcoke is the possibility of poly-generation when it is gasified to produce syngas, that can be burned in gas turbines.

3. Gasification process simulation with the CSFBM software

CSFMB 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 [15]. The proposed model uses 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 CSFMB program, taking into account the power ranges that they can achieve. Figure 1 shows the CSFMB 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 coal used in Candiota, a power station located southern Brazil.

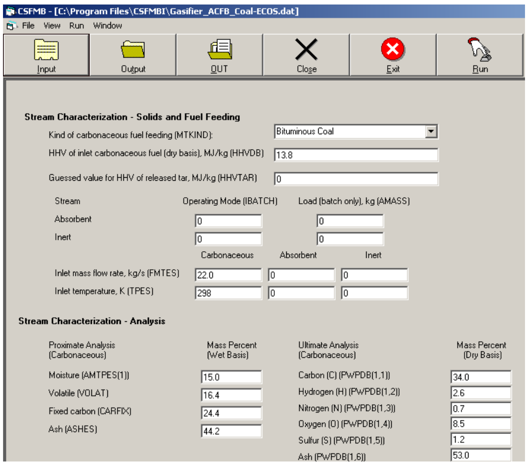

Fig. 1. CSFMB interface

Nowadays, there are several software available for chemical process simulation, such as Chemcad, Aspen Hysys and Aspen Plus, which have the capability of estimating the final composition of syngas, using ideal reactors and the knowledge of the initial composition of the fuel. Recently simulation schemes with the use of Aspen and Fortran were also developed, and are being employed in the gasification process, in order to analyze commercial gasifiers [4]. Among these software one can find CSFBM, which is capable of dealing with the major components of a gasifier into the model gasification process simulation.

The kinetic parameters for homogeneous reactions, illustrated in the equations (1) to (4), were identified and specified during the modeling and simulation of the gasification process.

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{1}$$

$$2CO + O_2 \leftrightarrow 2CO_2 \tag{2}$$

$$2H_2 + O_2 \leftrightarrow 2H_2O \tag{3}$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{4}$$

Among the many reactions involved in the gasification process, the main determinants parameters of the kinetic coefficient of the most important reactions [1] are shown in the Table 4.

Table 4. Kinetic coefficients

Reaction	rate of reaction ($k_{0,i}$)	Circulating Fluidized Bed	T (K)
COAL	2.78×10^{3}	$kmol^{-1}\ m^{3}\ s^{-1}$	1510
PETCOKE	1.3×10^{17}	$kmol^{-0.75}\ m^{2.25}\ s^{-1}$	34740
MIXTURE	5.159×10^{13}	$kmol^{-1.5}\ m^{4.5}\ K^{1.5}\ s^{-1}$	3430

On the other hand, due to the complexity of the gasification process, this is usually carried out by considering the balance of a reactive system under reasonable suppositions [16-18], but the various gasification technologies employed prevent identifying their effects on the composition of the gas produced [5]. Even though there are underway many research projects and some experiences been reported on combined cycle plants around the world, still remain uncertainties about some of the variables involved in the simulation of the gasification processes.

3.1. Results and analysis of gasification process simulation

Gasification process simulation was carried out using different types of fuels (Tables 1 – 3) and a circulating fluid bed as gasifier. Table 5 lists the main parameters required by CSFMB software for the gasifier simulation using coke as fuel. In the tests carried out, the feed mass flow rates, the feed gas though distributor (Gasification Agent) 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)	740	kg/m^3
True density, Carbonaceous	RORES(1)	1750	kg/m^3
Inlet mass flow rate, Carbonaceous	FMTES(1)	40	kg/s
Inlet temperature, Carbonaceous	TPES(1)	298	K
EQUIPMENT DATA - BASIC GEOMETRY Gasifier			
Bed - equivalent hydraulic internal diameter	DD	3.0	m
Freeboard - equivalent hydraulic internal diameter	DF	3.0	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	33000	-
Diameter of orifices for gas/steam injection through distributor	DOD	0.003	m
EQUIPMENT DATA - CYCLONES AND RECYCLING Ciclone			
Internal diameter of cyclones	DCY	0.7	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	Air		
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

Figures 2 to 4 show the mass flow (kg/s) gases for each kind of fuels presented in Table 6. This table described the main compounds in mass percentage of the synthesis gas produced from coal, pet coke and a mixture or both, using the CSFMB software without taking into account the low percentage of H_2, H_2S, NH_3 and SO_2 compounds.

Table 6. Synthesis gas composition

	COAL	PETCOKE	MIXTURE (50:50w)
CO_2	6.19	3.97	4.07
CO	13.25	12.85	19.12
CH_4	0.05	0.07	0.04
H_2O	7.58	6.83	6.05
H_2	11.46	12.24	16.08
N_2	59.97	61.95	53.41
HHV (MJ/kg)	3,95	4,30	4,19

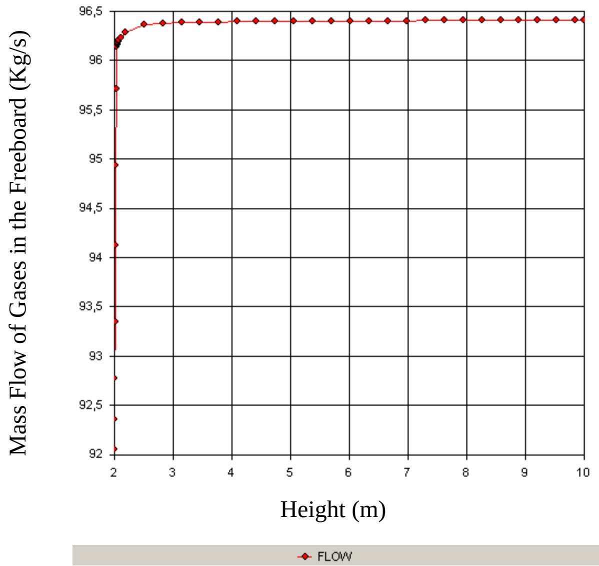

Fig. 2. Coal Case, Mass flow of gas exiting

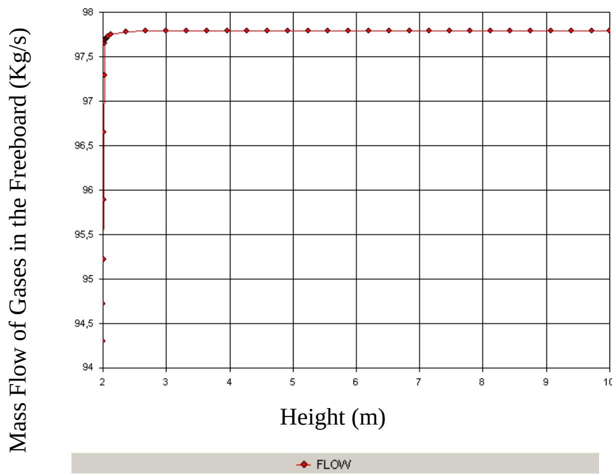

Fig. 3. Petcoke Case, Mass flow of gas exiting

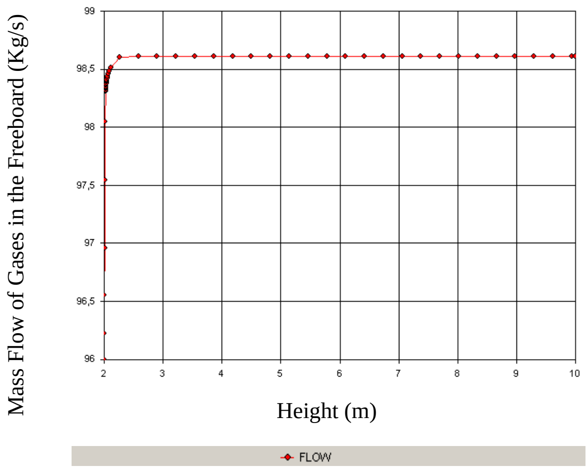

Fig. 4. Mixture Case, Mass flow of gas exiting

4. Combined cycle simulation using GateCycle software

A combined cycle in the generation of energy is defined as "The coexistence of two thermodynamic cycles in the same system", and simulation as "The process of imitating a real phenomenon with a set of mathematical formulas. In addition to imitating processes to see how they behave under different conditions, simulations are also used to test new theories" [19]. IGCC systems are one of the most efficient technologies to produce energy using coal and petcoke as fuel, and their efficiency can be as high as 45 to 50%. This technology is one of the promising options which need to be considered for future power generation possibility. Another promising possibility is the Carbon Capture Sequestration (CCS), which can be integrated to IGCC power plants [20]. Currently are efforts related with development and demonstrated CCS with IGCC technology were originally focussed on improved concepts for coal-based plants and thus on an alternative to conventional steam plants. The experience with the demonstration plants in Europe, in the United States, and now also in Japan, and the parallel development efforts for improved steam power plants resulted in a situation where coal-based IGCC (see Table 7). This technology is, in one to be considered as a commercially available technology, and in the order hand still needs further reduction in their initial costs to be fully competitive [21].

Table 7. IGCC power plants built, in operation, under design, construction or commissioning.

	Total MW_{el}	Total Operational MW_{el}	Operational Coal/Petcoke IGCC	Operational Oil/heavy residues IGCC
Europe	4.170	2.620	35 %	65 %
Asia/Australia	1.400	1.120	29 %	71 %
Americas USA, Canada	2.020	960	83 %	17 %
Total	7.590	4.700	43 %	57 %

From the 7,600 MW of global IGCC power plants which have been built or are under design, construction and commissioning, 4,700 MW are in operation. About 55 % of this operational capacity is installed in Europe (Table 7). Next generation plants of larger size, where the lessons learned from the today operational plants are implemented and co-firing of low-cost fuels, wastes or biomass is foreseen for reduction of fuel costs and to produce green electricity, could pave the way for a commercial breakthrough. This is primarily expected for IGCC applications with CCS [21]. The situation is different for refinery residues where, depending on the individual site conditions, IGCC can already today be considered as a commercially attractive solution for power generation, co-generation or co-production of power and hydrogen internal use purposes. The introduction of IGCC for refinery applications was supported by the experience gained with the technology from the coal-based plants.

In this paper, the IGCC system simulation was conduct using a model developed in GateCycle version 5.51 (Figure 5) and syngas composition presented in Table 6. The simulation considered the ISO standard conditions (1 atm, 15 °C and 60 % HR) and GateCycle's model was developed with the information presented in Table 6. This model is characterized by the integration of thermodynamic cycles, Brayton and Rankine, the first of them describes the workings of the gas turbine engine (power cycle) and the second describes a model of steam operated forward heat engine which converts heat into work (steam cycle).

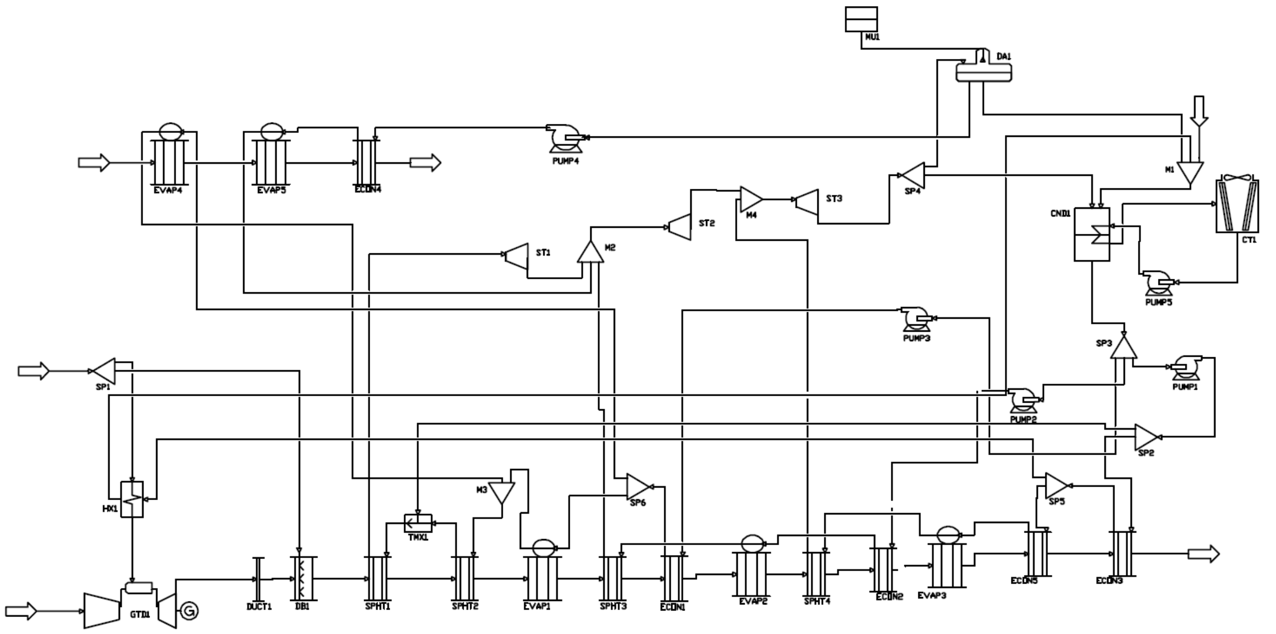

Fig. 5. IGCC power plant scheme modeled on GateCycle

The models available in GateCycle for equipments used in the combined cycle systems (steam and gas turbine, evaporators, heat exchanger, HRSG, condenser, cooling tower, etc.) taking into account operation parameters of the ELCOGAS IGCC power plant in Puertollano, Spain. This power plant has a successful industrial behavior and has been used as standard reference for the study of new technologies. Table 6 presents the technical description of this power plant [22].

Puertollano's combined cycle has a 317 MW net capacity (182 MW from gas turbine and 135 MW from steam turbine). Shell gasification technology with pure oxygen is implemented in Puertollano, the flow is ascendant and dried fuel is feeded using nitrogen. Heat recovery steam generator (HRSG) is used to recover heat from exhaust gas turbine gases and from cooling process of raw syngas [5].

In this work, temperature, pressure, clean syngas composition, and mass flow are initial parameters of the gas turbine equipment, after than combusted gases goes to HRSG equipments and steam production and heat recovery are estimated. As a final point, the electric power generated is estimated and efficiency and heat rate is evaluated.

Table 6. PUERTOLLANO IGCC technical description

System	Variable		Value
Environmental conditions	Temperature [°C]		15
	Humidity [%]		0.8
	Pressure		1
Coal	Flow [kg/s]		29.7
	LHV [kJ/kg]		22550
Syngas	Flow [kg/s]		120
	LHV [kJ/kg]		4242
Gasification Island	High pressure recovering Temp. [°C]	In	800
		Out	400
	Middle pressure recovering Temp. [°C]	In	400
		Out	235
	High pressure steam	Pressure [bar]	126
		Flow [t/day]	230
	Middle pressure steam	Pressure [bar]	35
		Flow [t/day]	23
HRSG	Steam	High pressure [bar]	127
		Middle pressure [bar]	35
		Low pressure [bar]	6.5
	Exchanger area [m^2]		300000
	Combusted gas temperature [°C]	In	535
		Out	103
Gas turbine	Power [MW]		182
	Mass flow air [kg/s]		537
	Compression		15:1
	Thermal efficiency [%]		34.6

Steam turbine	Power [MW]		135
	High pressure superheated steam	Pressure [bar]	122
		Temp. [°C]	509
	Reheated steam	Pressure [bar]	29
		Temp. [°C]	517
Air splitter unit	Air flow [kg/s]		80
Combined cycle	Net power [MW]		317.7
	Efficiency [%]		47.44
	Heat Rate [kJ/KWh]		7589

Figures 6 to 8 shows the results obtained for simulations of IGCC power plant using syngas resultant for different types of fossil fuels. The simulations were performed considering Siemens V94.3A (1999 GTW) gas turbines, in the power plant of Figure 5.

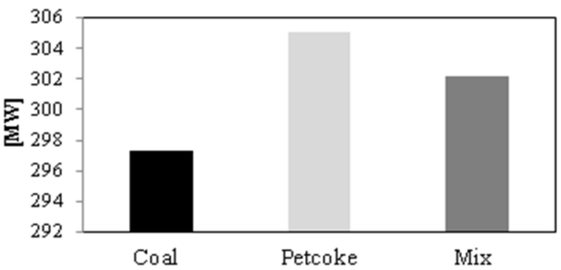

Fig. 6. Combined Cycle Net Power

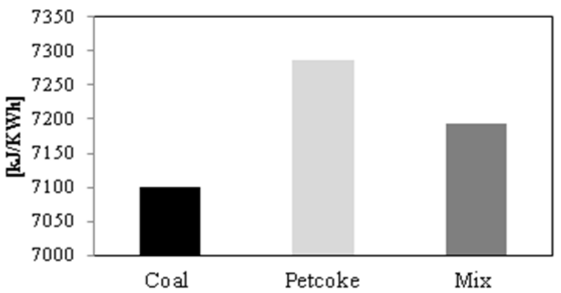

Fig. 7. Combined Cycle Heat Rate

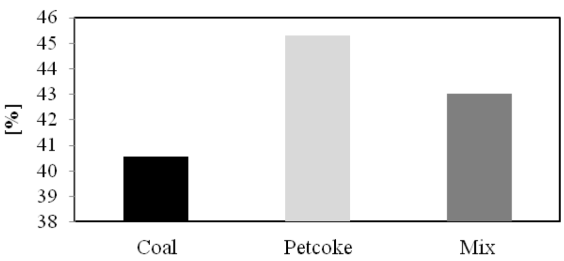

Fig. 8. Combined Cycle Global Efficiency

5. Brazilian potential for implementation of IGCC systems

The viability of implementing IGCC technology using Brazilian coals or petcoke depends basically on the following factors: the initial investment for the plant built-up, the investment return and the analysis of potential factors that could appear and avoid a proper operation of the plant due to the low quality of Brazilian coals.

One proposal is to perform the characterization of different types of petcoke, its constituents, concentrations and volume of production, in a way that it is possible to make an effective model of a gasification system for specific use of petcoke in refineries. Through this thermodynamic modeling it is possible to evaluate the technical feasibility of the system using pieces of market equipment and its implications. Additionally, the modeling allows the verification of several possible alternatives such as generation of steam, hydrogen production and CCS. This modeling will also serve as a basic tool to understand the structural theory of the cycle that allows the application of exergoeconomic optimization techniques and besides it will facilitate the economic and financial analysis of the entire system.

This type of technology that is being adopted in Texaco, Exxon and Shell refineries using General Electric gas turbines for ten years, can also be applied to cases in Brazilian refineries, such as Landulpho Alves refinery (RLAM) located in São Francisco do Conde, in the state of Bahia, which has a capacity installed of 323 thousand barrels per day. The hydrogen produced could be sent to the nitrogenous fertilizer plant of Petrobras (FAFEN-Ba) for the production of ammonia and the CCS would be injected into mature oil fields in the vicinity.

Other interesting option would be to build a pilot plant that can be extremely important for the evaluation of the feasibility of the use of Brazilian's coal in IGCC, making it possible to evaluate the impact of the large amount of ash and moisture existing in coal on the fluidized bed and to integrate the various components of an IGCC.

The pilot plant proposal will allow a better conception of Brazilian's coal with IGCC showing different characteristics of this technology. For example:

- An important alternative to be considered is the construction of a raw coal treatment plant, making in it a cleaning until it achieves an ash content of about 25% becoming a coal of better quality, maybe a coal like the Parana or Rio Grande do Sul region [23]. Thus, doing the use of coal received could result in a gas of better quality even when using the air as gasifying agent.
- The use of oxygen as a gasifying agent allows generating a fuel gas with better calorific value free of particles and tars as a result of high operating temperatures and also enables the conventional treatment of the gas which is a proven technology. The use of oxygen improves the efficiency of IGCC power plants.
- There is also the development of hot gas cleaning and that could be used in a gasification system to oxygen resulting in a good efficiency of this equipment.

Conclusions

CSFBM software is an adequate tool for gasification process using 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. It is evident that the composition of the carbonaceous material being fed, such as the technology and the parameters of operation influence greatly the composition of the syngas obtained from the gasification process.

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. In this model was using air as gasification agent given that the particle content and tar of the syngas resulting is low levels to the gasifier type selected.

In general, the use of air in the gasification process is a low cost and can be considered as the most economical gasification agents. In addition, used mixture of air and oxygen as gasification agent, for example, mixtures of 80% oxygen and 20% air, can be obtained a decrease in the nitrogen percentage present in the syngas, increasing its calorific value.

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.

The IGCC technology has been used experimentally by developed countries as a consequence of the importance of coal as a fossil fuel and the recent concern about the damage to the environment by direct combustion of coal. It necessary to await a major advance and tends of this technology to be less expensive, together with new studies and if appropriate, deploy it in Brazil.

Theoretically it is possible the efficient operation of an IGCC using Brazilian's coal but the high cost makes it unfeasible for implementation at least temporarily the development of this technology in Brazil, unless there is a government decision to its deployment. Research centers and universities, private companies and government National, considers important for the development of the country the use of Brazilian coal and sets a target a larger share of the national energy matrix, as suggested methods to use the combustion of fossil fuel in fluidized bed reactor and its gasification in IGCC. Research experience in this area exists, i.e. CIENTEC developed a pilot plant for combustion and gasification used Brazilian's coals and should be extremely important to use the training and experience gained by those involved in studies in this area, even if use of imported coal for electricity generation always looking to minimize our dependence on foreign.

References

[1] CSFMB©, Marcio L. de Souza-Santos, 2010. Tuturial of Comprehensive Simulator of Fluidized and Moving Bed Equipment Series 24, Versions 24.7 and above.

[2] GateCycle™, 2003. Getting started v.5.51 and GateCycle for Windows Training Seminar Notes. General Electric Power Systems.

[3] Bassily, A. M., 2007. Modeling, numerical optimization, and irreversibility reduction of a triplepressure reheat combined cycle, Energy 32, pp. 778–794.

[4] Zheng, L., and Furinsky, E., 2005. Comparison of Shell, Texaco, BGL and KRW gasifiers as part of IGCC plant computer simulations, Energy Conversion and Management, 46, pp. 1767-1779.

[5] Nieto, C., Arenas, E., Arrieta, A., Zapata, Z., Londoño, C., Valdés, C., and Chejne, F., 2008, Simulation of IGCC technologies: Influence of operational conditions (environmental and fuel gas production), Revista Energética, 40, pp. 39-51.

[6] CIENTEC, Fundação de Ciência e Tecnologia, database for biomass and waste, [online], URL: http://www.cientec.rs.gov.br/

[7] Santos, A. R., 2007, Generation of petroleum coke in the refine of heavy oils and its use in rotary kilns of clinker production, Ph.D. thesis in mechanical engineering, Federal University of Itajubá, Brazil.

[8] EPE, Energy Research Company, 2009, BEN, Brazilian Energy Balance year 2008, [online], URL: https://ben.epe.gov.br/

[9] Carvalho, I., 2003, Estado da arte e tendências tecnológicas para energia, CTEnerg.

[10] World Energy Council, 2007, "WEC Statement". [online], URL: http://www.worldenergy.org/

[11] Speight, J.G., 2004; New Approaches to Hydroprocessing, Catalysis Today, vol. 98, pp. 55 – 60.

[12] Wang, J., Anthony E.J., and Abanades J.C., 2004; Clean and efficient use of petroleum coke for combustion and power generation, Fuel, vol. 83, pp. 1341 – 1348.

[13] Barros, F.C., Lázaro, W., Borges, C.N., 2003, Coking Considerations, Hydrocarbon Engineering, pp. 61 – 65.

[14] Salvador, S., Commandré J.M., Stanmore B.R., 2003, Reaction rates for the oxidation of highty sulphurized petroleum cokes: the influence of thermogravimetric conditions and some coke properties, Fuel, 82, pp. 715 – 720.

[15] De Souza Santos, M., 2007, A new version of CSFB comprehensive simulator for fluidised bed equipment. Fuel, 86, pp. 1684–1709.

[16] Li X., Grace J. R., Watkinson A. P., Lim C. J. and Ergüdenler A., 2001, Equilibrium modeling of gasification: a free energy minimization approach and its application to a circulating fluidized bed coal gasifier. Fuel, 80(2), pp. 195-207.

[17] Zainal Z. A., Ali R., Lean C. H. and Seetharamu K. N., 2001, Bubbling fluidized bed biomass gasification — Performance, process findings and energy analysis. Energy Conversion and Management, 42(12), pp. 1499-1515.

[18] Deiana P., Pettinau A. and Tola V., 2007. Sardinia, Hydrogen production from coal gasification in updraft gasifier with syngas treatment line, *Third international conference on clean coal technologies for our future.*

[19] Campbell, P.E, Mc Mullan J.T., y Williams B. C., 2000, Concept for competitive coal fired integrated gasification combined cycle power plant. Fuel, 79 (9), pp. 1031-1040.

[20] Karg, J., 2009, Siemens AG, IGCC experience and further developments to meet CCS market needs, *Coal-Gen Europe-Katowice, Poland.*

[21] Franco A.; and Diaz A., 2009, The future challenges for clean coal technologies: Joining efficiency increase and pollutant emission control, Energy, 34, pp. 348–354.

[22] Treviño, M., 2003, Elcogas S.A, Integrated gasification combined cycle technology: IGCC, Edited Club Español de la Energía. Spain.

[23] Da Costa Labanca, R. A., 2000, Estudo de viabilidade da utilização de carvão mineral brasileiro em usinas de IGCC. Mechanical Engineering Masters theses, Fluminense Federal University.

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