ENERGY ANALYSES OF COAL-FIRED RANKINE CYCLE AND INTEGRATED GASIFICATION COMBINED CYCLE (IGCC) POWER PLANTS

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Abstract. *Clean abundant energy is a major challenge for this new century. IN this scenario, coal, despite being a fossil fuel, is still an important resource, since large economies in the world have considerable coal reserves and intend to exploit them in the near future. However, because of deterioration of the environment due to man-made pollution, it is imperative to seek manners to improve the efficiency of coal usage and diminish its environmental impacts. One area for research is power generation. Today coal is burned in Rankine cycle plants to produce over 40% of the electricity in the world. Integrated Gasification Combined Cycle (IGCC) is an alternative process that can also be used to generate power from coal. A considerable number of reports can be found with energy indicators and cost comparisons for these cycles. Comparative exergy analyses, however, have not been found. Exergy analyses are important to conceive ideal performance of each cycle and determine entropy generation patterns. To perform an exergy analysis of a plant efficiently, it is mandatory to be able to simulate it. The purpose of this ongoing study is to replicate in a process simulator the process data of the Rankine and IGCC plants described in detail in a reference study. The simulation models include not only the power cycles, but also all the auxiliary processes required to meet emissions regulations. This is a key aspect when comparing IGCC and Rankine cycles, since the performance penalties to meet these environmental restrictions are different from one cycle to the other. Results for the energy analyses are consistent with those of the reference study, and indicate energy efficiencies on a lower heating value basis of 38.5% and 42.0% for the Rankine and IGCC cycles, respectively.*

Keywords*: Coal, IGCC, energy, efficiency, power plants*

1. INTRODUCTION

Coal is an important resource for countries worldwide to assure energy security. Among fossil fuels, it is the one with the largest and least concentrated reserves. If current levels of consumption were to be maintained, coal reserves would last for 155 years, whereas oil and gas would last for 65 and 41 years, respectively (Higman and Burgt, 2008). Major energy consumers such as USA, China and India have large domestic coal reserves that are vital to their energy security, for it can reduce their dependence on imported oil and gas.

Coal, however, is a fossil fuel and when burned, it releases large quantities of carbon dioxide, a greenhouse gas that can presumably intensify global warming effects. Therefore it is imperative to seek manners to improve coal usage and diminish associate environmental impacts.

Most of the coal produced in the world today is used for power generation purposes. Efforts to increase the efficiency of such application are justified, since even small process improvements can have large benefits due to the scale of coal usage. Traditionally, power is obtained from coal through Rankine cycle plants, in which the fuel is burned in a boiler to generate high pressure steam, that is then expanded in a steam turbine. A competing technology is the Integrated Gasification Combined Cycle (IGCC), in which coal is burnt with substoichiometric quantities of oxygen. The process yields a gas composed mainly of carbon monoxide and hydrogen, named syngas. The syngas has a lower heating value than coal, but still high enough to be used as fuel for a gas turbine. The gas turbine operates in a combined cycle, with the heat content of its exhaust gases used to raise steam for a bottoming steam tubine.

Beér (2007) conducted a study reviewing efforts to reduce greenhouse gas emissions through the improvement of the efficiency of fossil fuels power plants. With respect to coal, he presented comparative performance data from Rankine and IGCC cycles. The study showed that advanced Rankine plants can reach a thermodynamic efficiency of 43.4% on a HHV basis, while IGCC plants can reach efficiencies up to 38.4%. Similar findings were presented in a report by the Massachusetts Institute of Technology (2007). Christou *et al.* (2008), on the other hand, presented an IGCC competitiveness study in which it was considered that this cycle could reach efficiencies between 40% and 55% (on a HHV basis), while Rankine plants could reach 36.2%. In its study for baseline performance of fossil fuels, the United States Department of Energy (2007) considered that IGCC has higher efficiency than Rankine cycle under certain operating conditions.

From the foregoing scenario, it is plausible to conclude that further research and understanding of the performance of the coal-fired IGCC and Rankine cycles are needed. Exergy analysis is a very important thermodynamic tool for such a task, since it allows the comparison of a process to an ideal path – an upper bound reference –, identifying entropy generation patterns which make real processes deviate from their ideal paths. Erdem *et al.* (2009) presented exergy analyses of nine coal-fired Rankine plants. The authors found that the greatest entropy generation occurred in the boiler, and the plants presented exergy efficiencies between 30% and 40%. Sengupta *et al.* (2007) also carried out such analyses, and verified the impact of operating parameters, such as the condenser pressure and load factor, in the overall performance of the cycle. They encountered an efficiency of 36%, with the greatest exergy destruction in the boiler.

Fewer similar studies are found for IGCC plants, probably because it is a more recent technology. Kim *et al.* (2001) conducted an exergy analysis of this cycle and obtained an efficiency of 42%. They indicated that the gas turbine is the equipment responsible for the greatest exergy destruction.

The energy efficiency figures, however, do not provide an accurate comparison between the cycles, since each study has been conducted separately under different basis, which can affect the calculated values. The United States Department of Energy (2007) carried out a baseline performance study for different coal power cycles (including IGCC and Rankine), operating under the same conditions – similar power output, same type of coal as feedstock and same site characteristics. The plants included not only the power generation equipment, but all the apparatuses necessary to meet US regulations for emissions of NOx, sulfur, mercury and particulates. Exergy analyses of such data would in principle allow adequate comparison of IGCC and Rankine power cycles. To perform an exergy analysis of a plant efficiently, it is mandatory to be able to simulate it thermodynamically. The purpose of this ongoing study is to replicate in a process simulator the process data of the Rankine and IGCC plants described in detail in the aforementioned study, as a first step towards a comparative exergetic analysis to be carried out in the future.

2. METHODOLOGY

In order to model and simulate the cycles in the present work, the process simulator customized for power generation applications IPSEpro program (Simtech, 2003) has been used. The software has specific libraries which contain model equations describing the behavior of typical equipment found in the power industry, such as boilers, heat exchangers, pumps, steam and gas turbines. The Advanced Power Plant Library (APP) of IPSEpro has been used to simulate the Rankine and IGCC power cycles for the present work. The Flue Gas CleanUp Library (FGC) of IPSEpro has been used to simulate specific processes required for emissions control. The module PSE of IPSEpro includes the interface, which allows the user to set up the process, by specifying globals, selecting units and establishing the connections between them, and setting input data. The connections will result in mass and energy balance equations, configuring a system of nonlinear algebraic equations, to be solved through a Newton method. The IPSEpro-module MDK allows the user to write and compile custom models for specific applications not covered by the standard libraries. For the IGCC cycle (see section 2.2), MDK has had to be used to develop models for components that are not so common in the power industry.

The reference study for the present simulations (US Department of Energy, 2007) includes process data for five coal powered cycles. The coal cycles replicated in the present study are the pulverized coal Subcritical Rankine Plant and the General Electric Energy (GEE) IGCC process. Bituminous coal has been considered as feedstock, with composition indicated in Tab.1. The original composition presented in the reference study had approximately 0.3% of chlorine. This chemical constituent has not been considered here, because, first, the APP library did not support it in the coal description. Second, this minute amount has a negligible effect on the heat and mass balances calculations. The weight of chlorine has then been proportionally distributed among the other constituents. Site conditions considered an average ambient temperature of 15 ºC, pressure of 0.1 MPa and relative humidity of 60%. The cycles are described in detail in the following two sections.

Table 1 – Composition of the bituminous coal, as received.

Chemical constituent	Weight (%)
Carbon	63.94
Hydrogen	4.51
Nitrogen	1.25
Oxygen	6.90
Sulfur	2.52
Water	11.15
Ash	9.73
Total	**100.00**

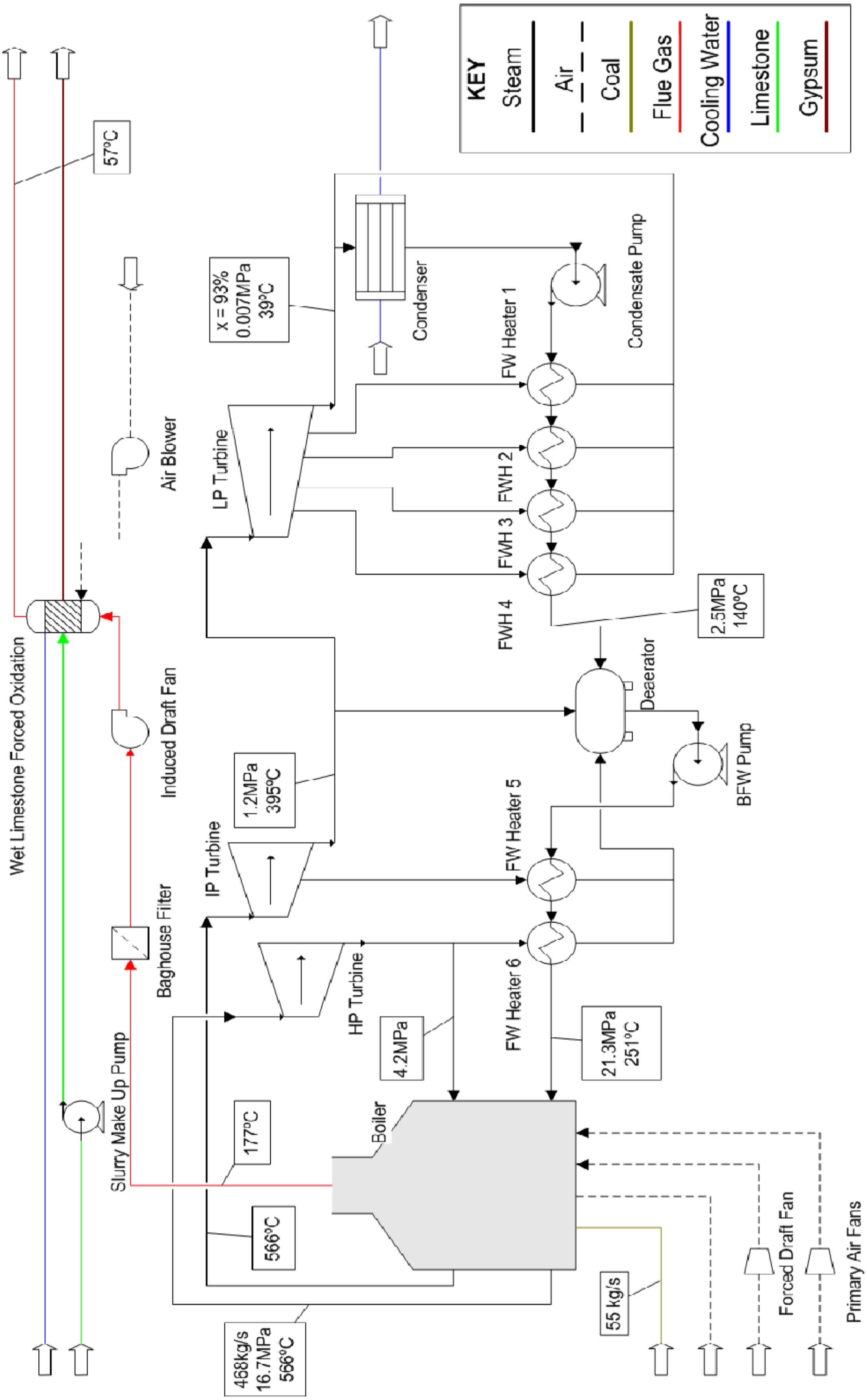

Figure 1 – Subcritical Rankine coal power plant.

2.1. Subcritical Rankine

The Rankine cycle with operating data for selected points is shown in Fig. 1. The actual simulation is complete, accounting for relatively small streams, such as turbine leakage and sealing, and steam needed for mechanical drive applications. For the sake of clarity, not all cycle streams are shown in Fig.1. Approximately 55 kg/s of coal is burned in the boiler, which generates steam for the turbine. The boiler consists of the economizer, evaporator, steam drum, superheater, reheater and air pre-heater. It is equipped with primary and forced draft fans. The exhaust gases leave the boiler at a temperature of 177 ºC, and are conducted first to a filter in order to remove particulate matter, and second to a flue gas desulfurization unit (FGD). This unit promotes the reaction of the sulfur present in the exhaust gases with limestone, thus forming gypsum, a plant byproduct. The boiler generates 468 kg/s of high pressure steam, at a temperature of 566 ºC and pressure of 16.7 MPa. This stream is directed to the high pressure (HP) turbine, where it expands to 4.2 MPa. It is then redirected to the boiler, where it is reheated to 566 ºC and fed to the intermediate pressure (IP) turbine. Exhaust steam at 1.2 MPa and 395 ºC then follows to the low pressure (LP) turbine, and expands until it is wet (steam quality of 93%), at the condenser pressure of 0.007 MPa and temperature of 39 ºC. After the main stream is totally condensed, it is pumped through the first array of feedwater (FW) heaters. Extractions from the low pressure turbine are used as heat sources. At the end of the array, the water is at a pressure of 2.5 MPa and temperature of 140 ºC, and is sent to the deaerator to remove any air infiltrated in the condenser. The heat source for this equipment is an extraction from the intermediate pressure turbine. At the exit of the deaerator, the water pressure is increased through the steam-driven boiler feedwater (BFW) pump, and the temperature is increased further in the second array of heaters. For these, heat is supplied by an extraction from the intermediate pressure turbine and a diverted stream from the exhaust of the high pressure turbine. The water at 251 ºC and 21.3 MPa is finally fed back to the boiler.

The IPSEpro combustor model calculates complete combustion only, of carbon, sulfur and hydrogen components in the fuel. Heat losses are modeled in a separate component. IPSEpro also requires that each component of the boiler be modeled separately. In the reference study, only the temperatures of the boiler's incoming and outgoing water streams and outlet temperature of the exhaust gases are shown. There is no information regarding the temperature profiles in each component of the boiler. Therefore, it has been necessary to consider reasonable temperature differences between the flue gases and steam in each heat exchanger, while still satisfying the overall heat balance. Figure 2 indicates such temperature profiles in the cooling curve for the boiler.

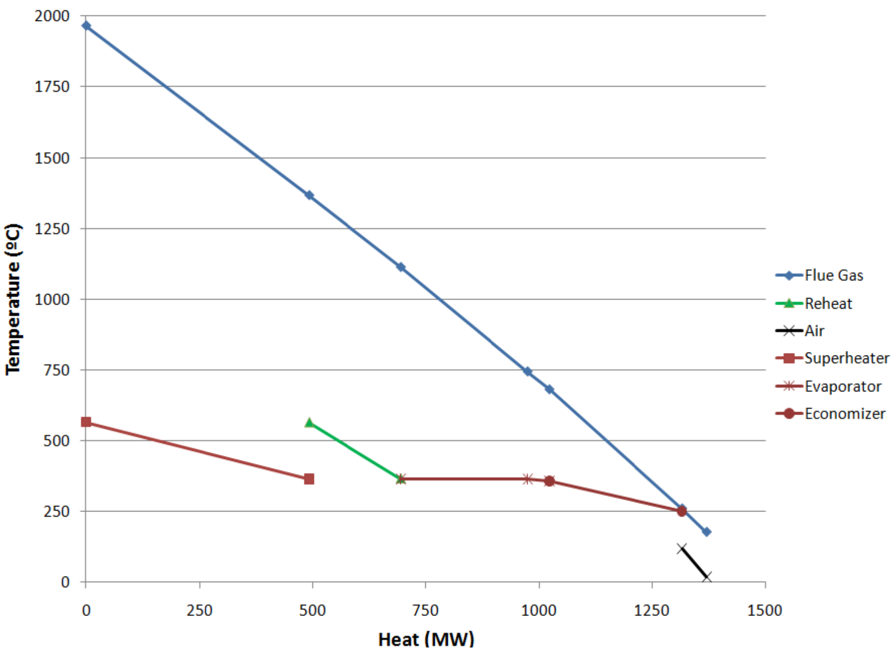

Figure 2 – Cooling curve for the HRSG of the Rankine cycle.

The isentropic efficiencies of the turbines have been obtained from the exhaust temperatures informed in the study, while the mechanical efficiencies have been adjusted to yield the final electrical power of the generator. A similar procedure is adopted for the pumps and fans. The heat exchanger models are calculated only to comply with the mass and heat balances, therefore data such as heat transfer areas and global heat transfer coefficients are not available.

The flue gas desulfurization model calculates the output stream composition according to the reactions presented in Eqs. (1) and (2),

$$CaCO_3 + H_2O \Leftrightarrow Ca(OH)_2 + CO_2 \quad (1)$$

$$Ca(OH)_2 + SO_2 + ½ O_2 \rightarrow CaSO_4 + H_2O \quad (2)$$

The limestone mixed with water ($CaCO_3$+H_2O) will form lime, $Ca(OH)_2$, and carbon dioxide. Lime will react with the sulfur dioxide present in the flue gas and the oxygen present in the air stream, forming calcium sulfate ($CaSO_4$) and water. The dihydrate of calcium sulfate is gypsum ($CaSO_4 \cdot 2H_2O$). The extent of the reactions is an input; therefore, chemical equilibrium is not calculated for this reaction model.

2.2. General Electric Energy (GEE) IGCC

The IGCC cycle is shown in Fig. 3, with operating data for selected points. This IGCC cycle is considerably more complex than the Rankine cycle, since it has different process sections with heat integration between them. The actual simulation model comprises all sections and equipment. For the sake of clarity, Fig. 3 shows only the main process equipment and streams. Approximately 61 kg/s of coal is mixed with process water and fed as a slurry to the gasifier. The gasifier also receives oxygen at a pressure of 6.8 MPa, which comes from an air separation plant. The reactions occur at a temperature of 1315 ºC, generating 132 kg/s of raw syngas. The gasifier reactor has a radiant cooler, where the product gas is cooled to 593 ºC, while generating 147 kg/s of saturated steam at a pressure of 13.8 MPa and temperature of 317 ºC. The gas then passes the final section of the gasifier, where it is quenched with process water, to ensure that any molten ash will solidify and be separated from the main stream. The saturated syngas is then directed to a scrubber in order to wash out chlorines and particulate matter. The fuel gas follows to a cooling section, where the temperature is further reduced and water is removed. The condensate from this section flows to a sour stripper, which recycles the liquid flow to the scrubber and coal slurry. The syngas, now with less moisture and at approximately 42 ºC, is then treated in the sulfur recovery plant, by passing through a sulfur removal unit, which operates under a process referred to as Selexol. In the latter, the hydrogen sulfide (H_2S) present in the raw syngas is removed to an acid gas stream that is treated in another unit. The fuel gas without sulfur, referred to as sweet gas, will generate power by expansion to 3.2 MPa, which is the operating pressure of the combustor of the gas turbine. A byproduct gas stream from the sulfur removal unit – mostly nitrogen and carbon dioxide – is compressed and mixed to the sweet fuel gas. In total, the gas turbine combustor will receive 118 kg/s of preheated fuel gas at a temperature of 193 ºC. In addition, it will receive compressed air from the air compressor and nitrogen from the Air Separation Unit (ASU), to serve as a diluent. Part of the flow from the air compressor is diverted to the ASU, in order to reduce the power requirement from that unit.

The combustion of the fuel gas reaches a temperature of approximately 1240 ºC. The flue gases then expand in the turbine, generating power. The exhaust temperature from the turbine is 602 ºC and the heat content of the gases is used for the Rankine part of the combined cycle. The heat recovery steam generator (HRSG) operates in two pressure levels, and is comprised of the economizer (ECO), evaporator (EV), steam drum and superheater (SH), in addition to having a reheater (RH) and an integral deaerator. The high pressure (HP) turbine admits 194 kg/s of steam at 12.5 MPa and 566 ºC generated in the first level of the HRSG. As mentioned, part of the load in the HRSG is handled by the syngas radiant cooler. The steam leaves the HP turbine at 3.1 MPa and 362 ºC. It is then reheated in the HRSG to 566 ºC and fed to the intermediate pressure (IP) turbine. An extraction of 5.7 kg/s at 1.7 MPa is directed to a feedwater system, to serve as a heat source for heat integration. The remaining flow is then expanded to 0.4 Mpa, at a temperature of 303 ºC, and mixed with 19.3 kg/s of low pressure steam generated in the second level of the HRSG at a temperature of 287 ºC. The combined stream enters the low pressure (LP) turbine, where it is expanded until it is wet, to a pressure of 0.007 MPa. After the condenser, the water is pumped to the deaerator, which is heated by an evaporator in the last section of the HRSG. The deaerator also receives the condensate used in the feedwater system. The water leaves the deaerator at a pressure of 0.3 MPa and 134 ºC. The low pressure (LP) and high pressure (HP) pumps supply feedwater to the HRSG at the pressures of 2.6 MPa and 15.5 MPa, respectively. An intermediate pressure (IP) pump will discharge 3.2 kg/s of water at 4.1 MPa to be used in the feedwater system.

A separate part in the IGCC cycle is the sulfur recovery plant, also known as Claus plant. The acid gas formed in the sufur removal unit is first burned in a furnace, generating a gas flow of composition with varied amounts of H_2S, SO_2 and elemental sulfur. The top stream of the sour stripper used in the gas cleaning section is also burnt in this furnace. The furnace will generate a flue gas stream of 6.5 kg/s, at a temperature of 343 ºC. The stream follows to a condenser, where the elemental sulfur is separated and stored as a plant byproduct. The exiting gas goes through repeated heating stages, and the remaining H_2S and SO_2 present in the gas is converted to elemental sulfur to be removed in a condenser. After two stages, the final gas stream with only traces of sulfur flows to a hydrogenation reactor to be converted back to H_2S, compressed and recycled to the Selexol Unit.

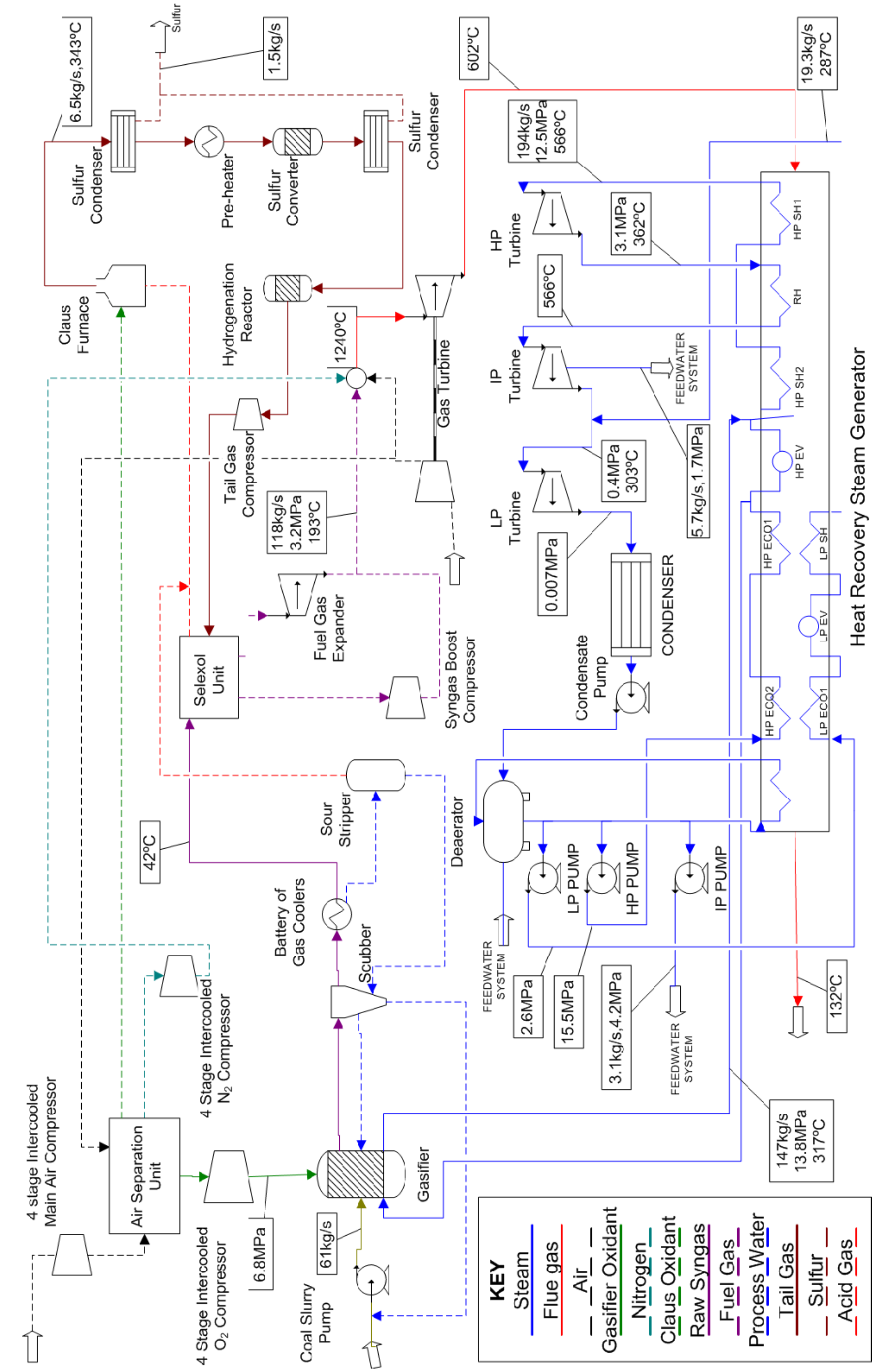

Figure 3 – Integrated Gasification Combined Cycle coal power plant.

The gasifier model in the IPSEpro program has five unknowns to be calculated in order to establish the drain gas composition: methane, carbon dioxide, carbon monoxide, water and hydrogen mass fractions. Three of the five required equations are the atom balances of carbon, hydrogen and oxygen. Methane and carbon dioxide mass fractions have then had to be set in order to solve the system. Although IPSEpro is able to calculate chemical equilibrium for homogenous or heterogeneous reactions in the gasifier, this option has not been used in the present study, to avoid convergence difficulties. All other chemical species are inert, and therefore they are solved through balance equations.

Because the reference study does not describe the inner processes of the air separation and sulfur removal units, these components have been represented as "black boxes" in the simulation model, meaning that pressure, temperature, flow and composition of all input and output streams have had to be set. In addition, the simulation of the gas coolers downstream of the gasifier requires gas-liquid equilibrium calculations in order to determine flow and composition of the liquid that is separated from the syngas stream. IPSEpro obtains thermophysical properties through the ideal gas model and cannot perform such equilibrium calculations. Therefore for these units, the compositions of the output streams have had to be determined separately from the simulation model. This has been done in VRTherm (VRTech Tecnologias Industriais Ltda., 2009), a software suited for such calculations.

For the purposes of this study, there is no significant loss in adopting the procedures just described for the gas coolers, ASU and sulfur removal unit. The procedures will certainly allow correct calculations of the mass and energy balances and of overall performance figures for the cycle. However, they would not be suited if other operating conditions were to be investigated, such as part load operation or different feedstock.

For the Claus furnace, it has been necessary to develop a model to properly calculate the composition, mass and temperature of the flue gas stream. The model calculates the product gas composition considering chemical equilibrium of reactions, as shown in Eqs. (3) and (4),

$$H_2S + 3/2\ O_2 \Leftrightarrow H_2O + SO_2 \quad (3)$$

$$2\ H_2S + SO_2 \Leftrightarrow 2\ H_2O + 3/2\ S_2 \quad (4)$$

The model has five unknowns: hydrogen sulfide, oxygen, water, sulfur dioxide and elemental sulfur mass fractions. The five required equations come from sulfur, hydrogen and oxygen atom balances, and the remaining two come from the definition of the equilibrium constants for reactions (3) and (4).

Similarly to the Rankine cycle procedure, the temperature profiles in the components of the HRSG have had to be established considering reasonable temperature differences between the flue gases and steam, while still satisfying the overall heat balance. Figure 4 shows such temperature profiles. Pumps, turbines, compressors and heat exchangers have been modeled the same way as in the Rankine cycle.

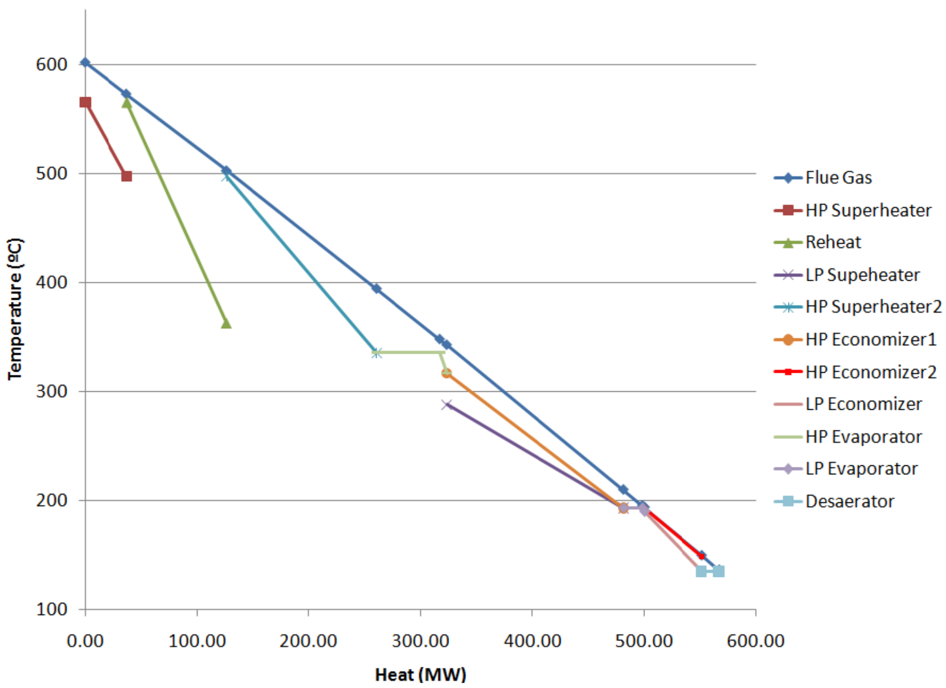

Figure 4 – Cooling curve for the HRSG of the IGCC cycle.

3. RESULTS

The performed numerical calculations of the present Rankine and IGCC simulation models have converged and replicated each individual stream data of the reference study (US Department of Energy, 2007) with deviations smaller than 2%. Computed gas compositions (flue gas in Rankine cycle and raw syngas in IGCC) have also matched those of the reference study with deviations smaller than 2%. These results indicate that the assumptions of complete combustion for the Rankine cycle and chemical equilibrium for the IGCC cycle are adequate. Tables 2 and 3 present the performance summary of the Rankine and IGCC cycles, respectively. They show the power requirements, power generation and thermal inputs calculated by the IPSEpro process simulator. The Rankine plant has a net power generation of 550 MW and efficiency (on a LHV basis) of 38.5%, whereas the IGCC cycle has a net power generation of 640 MW and slightly higher efficiency (on a LHV basis) of 42.0%.

In the Rankine plant, it is possible to observe that the equipment part of the flue gas system (induced draft fan and flue gas desulfurization unit) are responsible for a power requirement of 10.76 MW, which represents a performance penalty of about 0.8 percentage point in the overall efficiency. The equipment is necessary to comply with sulfur emission regulation rates, but are not part of the actual power cycle. Due to this fact, they are not usually included in process simulation studies described in the literature.

In the IGCC plant, sulfur abatement is accomplished through the Selexol and Claus Plant units, which have a power requirement of 4.7 MW, representing a performance penalty of 0.3 percentage point in the overall efficiency. Considering the difference of only 3.5 percentage points in the efficiencies of the plants, the importance of simulating complete cycles to conduct a comparative study is thus clear. Although the auxiliary systems do not consume significant power, they place different demands on each process, and if they are not properly considered, deceptive conclusions may be reached.

Table 2 – Performance summary for the Rankine power cycle.

Forced Draft Fan	1,774 kW
Primary Air Fan	1,390 kW
Condensate Pump	1,390 kW
Induced Draft Fan	7,590 kW
FGD Pumps and Fans	3,170 kW
Auxiliary Loads (not simulated)[1]	17,540 kW
Steam Turbine Power	583,500 kW
Coal Thermal Heat Input (LHV)	1,430,000 kW
LHV-Based Efficiency	**38.5%**

[1]Auxiliary loads include lighting, coal handling, cooling water system and plant control system.

Table 3 – Performance summary for the IGCC power cycle.

Boiler Feedwater Pumps	4,590 kW
Condensate Pump	250 kW
Tail Gas Compressor	1,230 kW
Selexol Auxiliaries (including Syngas boost compressor)	3,420 kW
Oxygen Compressor	11,270 kW
Nitrogen Compressor	30,650 kW
Main Air Compressor	60,070 kW
Coal Slurry Pump	700 kW
Auxiliary Loads (not simulated)[2]	16,280 kW
Fuel Gas Expander	7,130 kW
Steam Turbine Power	298,920 kW
Gas Turbine Power	464,300 kW
Coal Thermal Heat Input (LHV)	1,527,110 kW
LHV-Based Efficiency	**42.0%**

[2]Auxiliary loads include lighting, coal handling, cooling water system and plant control system.

The results from the simulations also permit the investigation of the sulfur and carbon dioxide emissions for each cycle. The values calculated by the process simulator are presented in Tab. 4. The IGCC cycle leads to lower emission rates for SO_2 and CO_2 than the Rankine cycle. Both cycles emit sulfur amounts well below US regulations limits.

Table 4 – Emissions of SO_2 and CO_2 for the Rankine and IGCC cycles normalized by net power output.

Emission	Rate (kg/MWh)	
	Rankine	IGCC
SO_2	0.34	0.04
CO_2	807	662

As a final note, it is possible to anticipate that exergy analysis will contribute to identify points for improvements in each cycle, and to understand the inherent differences. An example can be observed from the analysis of Figs. 2 and 4. In the Rankine cycle, heat transfer between the flue gas and steam occurs across large temperature differences, which are sources for entropy generation. In the IGCC cycle, the temperature differences in the HRSG are smaller, indicating a more efficient heat recovery process. Exergy analysis shall thus help to properly assess and quantify such observations.

4. CONCLUSION

In the present study, simulation models for the coal Rankine subcritical cycle and Integrated Gasification Combined Cycle have been developed in the IPSEpro process simulator. It is concluded from the simulations that the models permit satisfactory duplication of the results of the reference study. Therefore, the developed models are suitable to be employed in a future exergy analysis investigation. The IPSEpro program has proved to be an adequate process simulator for coal applications. However, the use of ideal gas relations to obtain thermodynamic properties is a limiting factor for some component models, which require calculation of vapor-liquid equilibrium.

5. ACKNOWLEDGEMENT

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