COMPUTATIONAL MODELING AND THERMODYNAMIC ANALYSIS OF COMBINED CYCLES USING BLACK LIQUOR GASIFICATION

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Abstract. *Black liquor gasification is being studied in several countries, including United States, Finland and Sweden. The main motivations for these studies are related to economic, energetic and environmental issues. Simulations accomplished considering "Black Liquor Gasification Combined Cycle-BLGCC" indicate that it is possible to duplicate electric power generation in pulp and paper industry using this system. There are pressurized (~2MPa) or atmospheric (~200kPa) gasification systems. The operation temperatures are between 700ºC and 950ºC. Air, oxygen and steam can be used as oxidizers. The objective of this work is to present a thermodynamic analysis of two BLGCC configurations and to compare them with the typical cogeneration configuration used in the pulp and paper industry. This configuration uses a "Tomlinson" recovery boiler and a Rankine steam cycle. The configurations of BLGCC were modeled considering two conditions: (1) air at 200 kPa pressure and temperature of 700ºC and (2) air at a pressure of 2,5 MPa and a temperature of 950ºC. Computational programs were implemented for the modeling of the studied configurations. A thermodynamic analysis of the configurations was accomplished using the obtained results, identifying the components and flows that contribute with the most significant irreversibilities. It was done a comparative analysis about the BLGCC configurations and the typical cogeneration configuration.*

Keywords: *computational modeling, gasification, black liquor, thermodynamic analysis, exergy.*

1. Introduction

The black liquor is a residue of the industrial processing of cellulose, used as source of energy for the production of thermal energy and power in the pulp and paper industry. Using this resource in a cogeneration system, the industry supplies its thermal demand and part (40 to 55%) of the electric power demanded by the process. The typical configuration uses a thermal recovery boiler “Tomlinson” and a Rankine steam power cycle.

The pulp and paper industry is looking for alternatives to reach the energy self-sufficiency, motivated by the instability of the energy sector and by the lack of warranty of supply of electric power, besides the need of substitution of the Tomlinson boilers older than 30 years. The Tomlinson boiler is expensive, and it offers explosion risks, mainly when water is in excess in the black liquor. The recovery boiler requests sophisticated cleaning systems to avoid the emission of acid gases and it presents maintenance difficulties due to corrosion problems in the tubes. Those are some of the factors that motivate the great paper makers, located in Finland, Sweden and United States, to develop new recovery technologies and to develop the power generation, with the objective of improving the process of cellulose and paper production, of assisting the rigid environmental laws, as well as increasing the productivity with lower energy consumption.

Among the several existent proposals, the black liquor gasification system is one of the projects that could make possible the recovery of calcium carbonate and calcium oxide to decrease the capacity of the calcination system and the separation of hydrogen sulfide (H2S), avoiding the use of gases washing systems (Sadowski et al., 1999). With the need to reduce the energy costs, the need of improvement of the power supply quality, and the need of increasing the power self-sufficiency, the proposal of using the black liquor gasification in combined cycle becomes increasingly important.

Several studies indicate that, using the same amount of black liquor, the gasification system coupled to a combined cycle can generate a power increment higher than 100% in relation to the current system that uses Tomlinson boiler. The gasification system can operate with concentration variations of the black liquor, can also decrease the emission of nitrogen and sulfur oxides and the explosion risks are lower.

2. Black liquor gasification

The gasification of black liquor is a process of partial oxidation of this liquid mixture that, starting from the reaction of the organic and inorganic substances contained in the liquor, produces fuel gas. The heating value of the produced gas allows its use as fuel in boilers, gas turbines, or as a source for hydrogen extraction. Black liquor gasification is a technology that can be used in the pulp and paper industry as form of substituting the Tomlinson recovery boiler.

The gasification can be used as a technology for the increase of the energy use efficiency. Due to that possibility, the U.S. government, with the support of the forest products industry, founded an incentive program to the development of the gasification technology, and the American Forest & Paper Association (AF&PA) defined approaches and objectives related to the gasification of black liquor. That definition was elaborated starting from approaches established in 1994 by the industrial community and from the “2020 Agenda” implanted by the U.S. Department of Energy. That department established the main goals that should be reached starting from the development of more efficient energy utilization and also the reduction of environmental impacts (Hood and Henningsen, 2000).

Some reasons for the use of the gasification system as substitute of the recovery boiler are: the high cost of the Tomlinson recovery boiler; the low flexibility of the recovery boiler with the composition and concentration variations of the black liquor; the explosion risks due to the presence of water in excess in the black liquor; emission of acid gases and corrosion problems. Larson and Consonni (1997) highlight that the black liquor gasification is an interesting proposal for the industries located in United States, because there are many recovery boilers older than 30 years old, near the end of their useful life.

Now, in most of the pulp and paper industries, the recovery boiler pressure is limited to 6 MPa, due to possible corrosion problems in the furnace and in the super heater, to minimize safety hazards. The black liquor gasification is interesting, because it presents smaller explosion risks and corrosion problems, in comparison with the recovery boiler. It is possible to decrease the load in the multistage evaporators, because it allows the use of less concentrated black liquor, decreasing the steam consumption. When the gasification system operates coupled to a combined cycle it is possible to supply the power demand of the company, and to sell the energy surplus (Larson and Consonni, 1997).

Whitty and Baxter (2001) present the advantages of using gasification instead of the recovery boiler, highlighting the existence of a potential for increasing in at least twice the power production with the same consumption of black liquor, when compared with the conventional system. They also point the increase of the global efficiency and the improvement in the environmental performance, with lower emissions. With the increase of the power generation, modern methods and advanced systems of cellulose production can be applied.

Saviharju (1993) highlights some problems that can happen and should be avoided in black liquor gasification: corrosion problems, when the operation occurs above the fusion point of sodium salts (650-850ºC); scum and soot formation due to the low fusion point of the salts and of the formed aerosols; reduction of the sulfur to sodium sulfide (Na2S), which presents high fusion point, defaulting the recovery process, or the reduction of the sulfur to hydrogen sulfide (H2S) with low fusion point, increasing the need of gas cleaning. For a good conversion of the carbon and high efficiency of the gasification process, it is recommended a high content of dry solids in the black liquor after the concentration process. The gas generated should be cleaned to be used as fuel in gas turbines, due to the need of low content of alkaline substances; the atomization of the black liquor must be well performed due to its high viscosity. The safety system of the gasification system is important, mainly in pressurized equipment.

With the black liquor gasification the problems presented by the recovery boiler can be minimized, and several research centers are working in the development of the best processes to operate with the black liquor. Black liquor gasification can be classified according with the operation pressure (as atmospheric or pressurized); with the operation temperature: low temperature (lower than 750ºC) and high temperature (higher than 750ºC); also according with the oxidant used in the gasification process, as air, oxygen or steam systems. The combination of these parameters characterizes the project type. Several proposals concerning the gasification of black liquor are addressed to the use of this technology coupled to combined cycles with the objective of power and heat generation. The feasibility of those projects is more significant when the pulp and paper industries want to change from the current system of power generation to this new technology.

3. Studied configurations

In this section the configurations of Black Liquor Gasification Combined Cycle (BLGCC) proposals (a) and (b) and the configuration used currently in the pulp and paper industry (c) are presented (Gallego, 2004). In Fig. 1 the flow sheet of the configuration (a) of black liquor gasification coupled to combined cycle is represented. The gasifier operates with air at 200 kPa and the process occurs at 700ºC. This configuration is similar to one proposed by Asea Brown Boveri. Five groups of heat exchangers are used to superheat the steam generated by the HRSG (Heat Recovery Steam Generator); to preheat the air supplied to the gasifier; to preheat the feeding water of the biomass boiler and of the HRSG; to preheat of the fuel gas, and to preheat the air for the biomass boiler. A gases scrubber does the gas cleaning. The fuel gas is cooled and compressed before entering the combustion chamber of the gas turbine. In the gas turbine exhaust there is a HRSG that, together with the biomass boiler, generates steam for the operation of the steam turbine. The steam turbine operates at two pressure levels: 1000kPa and 400 kPa to feed the process demand. In Fig. 2 is presented the flow sheet of a black liquor gasification configuration (b) coupled to a steam power system. The combined cycle operates with air at the pressure of 2,5 MPa and gasification temperature of 950ºC. The gasifier feeding air is removed from the compressor. The air is compressed and cooled before entering the gasifier. The gasification system has a gas cooling system and the gas cleaning is a "quench cooler", similar to the system developed by Kvaerner. To improve the cycle efficiency several heat exchangers are used to preheat the air; to preheat the feeding water of biomass boiler, of HRSG, and the water that returns to the gasifier; to preheat the fuel gas and to preheat the air for the biomass boiler. The gas scrubber operates at 110ºC. The gas turbine, the HRSG, the biomass boiler and the gas turbine operate like in the previous configuration. The gas turbine is subdivided in nine control volumes. This subdivision is useful to the analysis of the influence of the operation parameters of each component in the cycle performance. In Fig. 3 the flow sheet of the configuration (c) is represented with the Tomlinson recovery boiler and the steam turbine operating at 6 MPa and 450ºC. The configuration (c) has heat exchangers with the following functions: to preheat the air for the biomass boiler and for the recovery boiler. The configuration (c) uses a biomass boiler and a steam turbine that operates in a similar way to the steam turbine in the configurations (a) and (b).

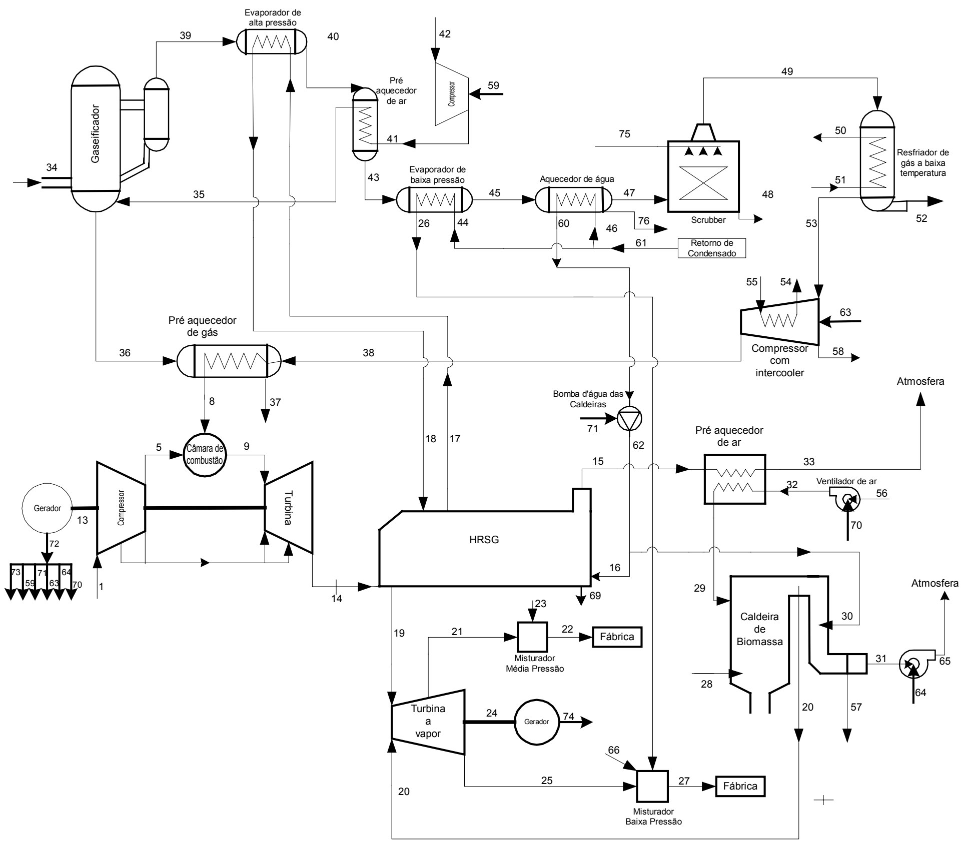

Figure 1 – BLGCC configuration (a): gasification with air, 200kPa and 700ºC.

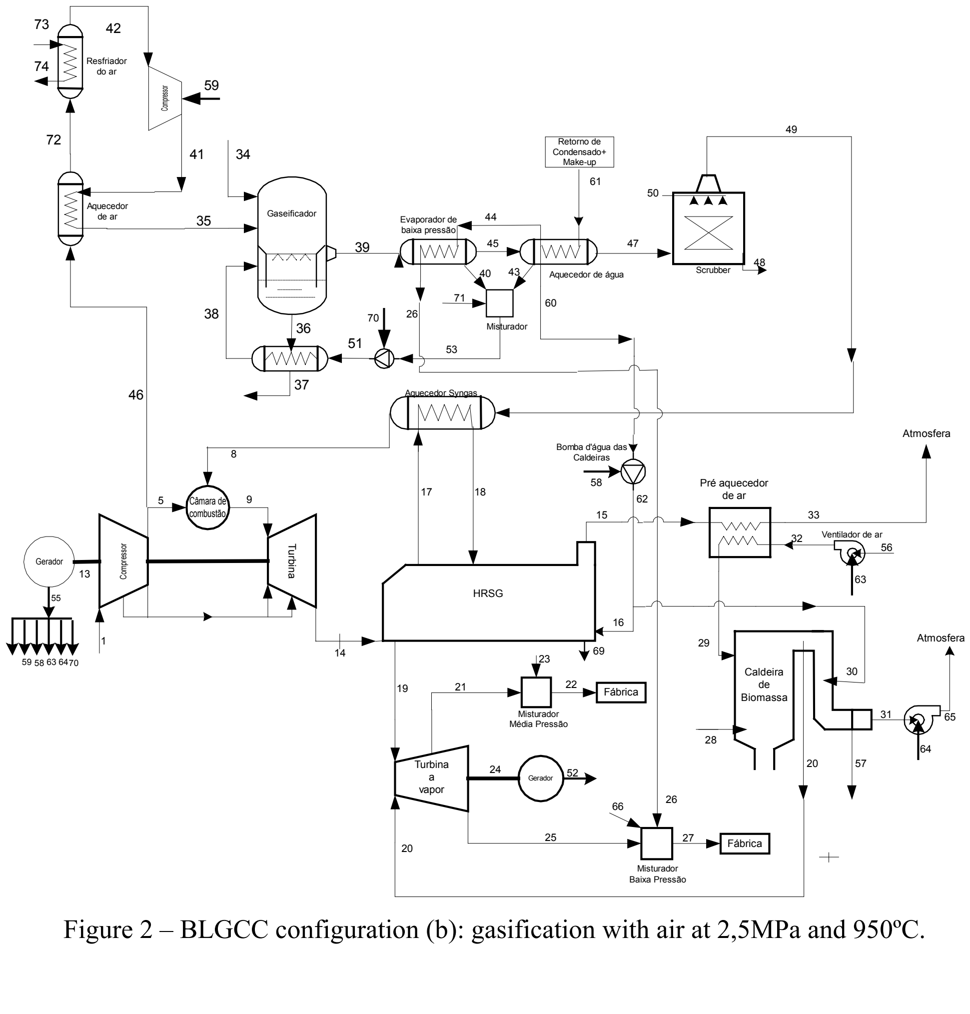

Figure 2 – BLGCC configuration (b): gasification with air at 2,5MPa and 950ºC.

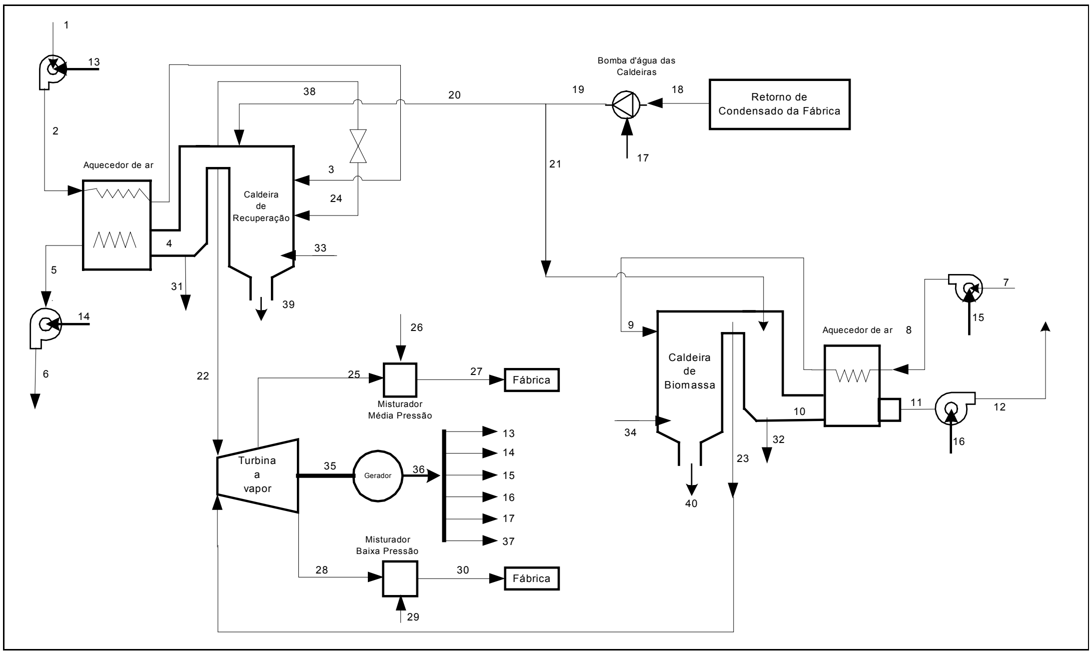

Figure 3 – Configuration (c) with Tomlinson recovery boiler and steam turbine cycle.

4. Computational modeling

The computational programs were developed in Pascal Object language, and among the parameters used as data are the cellulose production, the extraction desired in the steam turbine and the amount of biomass added to obtain the desired supply of thermal energy when the steam production in the Tomlinson recovery boiler and in the HRSG is not enough. The calculation procedure is sequential, and there is a subroutine for each type of component that includes iterative processes to observe the mass conservation and the first law of Thermodynamics. After the calculation for the last component it is done a successive substitution process to converge the results for the mass and energy flows.

In all the subroutines, including the compressor and the gas turbine procedures, the temperature dependence of the thermodynamic properties was considered and specific heat averaged values were not used. The thermodynamic steam properties and gases properties are calculated at each point by means of specific procedures that use a modified Newton-Raphson method to solve the non linear equations system. The steam properties are calculated using the procedures developed by Llagostera (1994), based on the correlations developed by Keenan et al. (1978). The gases properties are determined using the correlations presented by Rivkin (1988), and other polynomial correlations based on the JANAF tables (Chase, 1986) or on the thermo chemical tables organized by Barin (1993).

The computational programs are composed by a group of modular procedures, each one associated to a cycle component, such as: air compressor, combustion chamber, gases generator, power turbine, HRSG, steam turbine, dryer, gasifier, pumps, scrubber, compressors, heat exchangers, mixers and flow distributors. The thermal systems modeling was accomplished using classic modeling methods as described by Franks (1972). The analysis of thermodynamics parameters, as the exergetic efficiency, was performer several components of the integrated systems. Each one of the procedures executes mass conservation and first law calculations for the respective control volume. For the combustion chamber and for the gasifier, the conservation of chemical species is also imposed. The calculation for the total installation is developed in sequential and iterative modes, seeking the convergence values for the operation parameters. Finally, the program calculates the enthalpy and exergy flows for the important lines. The group of components associated to the gas turbine includes the air compressor, gas generator turbine, the combustion chamber and the power turbine. The mixture process of air and combustion gases is represented by a fictitious component denominated "mixer" in order to model the mixture process by means of a specific control volume.

A basic element of the program and also of the subroutines is the numerical procedure used for the approximate solution of non linear equations systems. It was utilized a modified Newton's method (Burden and Faires, 1988) to solve the non-linear systems. In that procedure the Jacobian matrix was calculated by numeric derivation of the corresponding functions. Since the initial estimate is adequate, the convergence of calculation process is quite fast, given the quadratic characteristic of the convergence obtained by Newton's method. The proposed system was modeled to approximate the operational characteristics presented by Consonni et al. (1998). For the thermodynamic analysis it was assumed: steady state operation, negligible variations of kinetic energy and potential energy, atmospheric pressure of 101,325 kPa and temperature of 15ºC. The thermodynamic properties were determined at the inlet and at the outlet of all the control volumes. The nomenclature presented by Moran and Shapiro (2002) was used to represent the equations of mass conservation (Eq. 1), the first law Thermodynamics (Eq. 2), and the second law of the thermodynamics (Eq. 3), the exergy analysis (Eq. 4) and the global efficiency (Eq. 5). The exergetic analysis was done using a reference temperature of 298,15K. The rational efficiency defined by Kotas (1995) was also used (Eq. 6).

$$\sum \dot{m}_s = \sum \dot{m}_e \quad (1)$$

$$0 = \dot{Q}_{VC} - \dot{W}_{VC} + \sum\left(\dot{m}_e . h_e\right) - \sum\left(\dot{m}_s . h_s\right) \quad (2)$$

$$0 = \sum_j \left(\dot{Q}_j \big/ T_j\right) + \sum\left(\dot{m}_e . s_e\right) - \sum\left(\dot{m}_s . s_s\right) + \dot{\sigma}_{VC} \quad (3)$$

$$0 = \sum_j \left(1 - \left(T_0 / T_i\right)\right)\dot{Q}_j - \dot{W}_{VC} + \sum\left(\dot{m}_e . e_e\right) - \sum\left(\dot{m}_s . e_s\right) - \dot{E}_d \quad (4)$$

$$\eta_{\text{cog}} = \left(\dot{W}_{liq} + \dot{Q}_{process}\right) \Big/ \left(\sum \dot{m}_{fuel} \times PCI_{fuel}\right) \quad (5)$$

$$\Psi = \sum \dot{E}x_{prod} \Big/ \sum \dot{E}x_{fuel} \quad (6)$$

The physical and chemical exergies of the gases mixtures were calculated according to Kotas (1995). The exergy of the black liquor and the exergy of the biomass were calculated according to Szargut, Morris and Steward (1988). The gasifier modeling was done applying the mass conservation and the first law of Thermodynamics, assuming that the composition of the gas generated in the gasifier is the calculated chemical equilibrium concentration (Berglin, 1996). In the simulations, the values presented by Consonni et al. (1998) were used. These values are shown in the Tab. 1.

Table 1 - Gases concentrations and composition of the melted material.

Reactor	BLGCC – Configuration (a)	BLGCC – Configuration (b)
Temperature and Pressure in the reactor	700 ºC and 200 kPa	950 ºC and 2500 kPa
Relation dry air/liquor and air temperature	1,67 and 268 ºC	1,91 and 390 ºC
Gases		
Relation gas/black liquor	2,543	2,784
Molar composition of the gases generated in the gasifier (molar %)		
CH_4 / CO / CO_2 / H_2 / H_2O / H_2S / N_2	0,921 / 11,619 / 12,424 / 19,083 / 13,005/ 0,637 / 42,322	2,324 / 10,532 / 11,480 / 10,307 / 17,585 / 0,594 / 41,179
Melted material that leaves the gasifier		
Melted material/black liquor	0,463	0,461
Mass composition of the melted material (% in weight)		
Na_2SO_3 / Na_2CO_3 / Na_2S / NaOH / K_2CO_3 / K_2SO_4 / C	0,000 / 81,873 / 7,668 / 0,084 / 9,578 / 0,000 / 0,801	0,004 / 79,945 / 8,005 / 1,606 / 9,630 / 0,005 /
Lower heating value (kJ/kg)	3771	3002

The biomass boiler and HRSG are designed to supply the steam turbine at the temperature of 450ºC and pressure of 6 MPa. The heat transfer equipment is designed using the pinch method or the NTU method. In Tab. 2 are presented the main parameters used in the simulation of the biomass boiler, of the HRSG and of the heat exchangers. The value of "pinch" and "approach" temperature differences were obtained from Ganapathy (1991).

Table 2 – Parameters used in the modeling of HRSG, biomass boiler and heat exchangers.

Component	HRSG	Biomass Boiler	Heat exchangers (gas/gas)	Heat exchangers (gas/liquid)
Pinch Point and Approach	10 ºC and 25 ºC	-----	-----	-----
Pressure losses (gases)	2%	2%	2%	2%
Heat losses (external)	1%	1%	0	0
Minimum temperature difference (ºC)	-----	-----	25	10
First law efficiency (LHV)	-----	46%	0	0

The thermoeconomic analysis consists of a detailed exergetic analysis, the determination of the exergetic costs, an economic analysis and an exergoeconomic evaluation of the sub systems. The identification of the exergetic costs (Ex*) is important for the thermoeconomic analysis, to quantify the irreversibilities occurring in the subsystems and to determine the contribution of these irreversibilities in the total system. The method of determination of the unitary exergetic costs is based on the calculation of the irreversibilities occurred during the process of formation of each flow.

Lozano and Valero (1993) define the unitary exergetic cost (k) as a form of identifying the amount of exergy necessary to obtain one unit of exergy, this is another form of characterizing the conversion efficiency (η), Eq. 7.

$$k = \frac{Ex^*}{Ex} = \frac{exergetic\ cost}{exergy} = \frac{1}{\eta} \tag{7}$$

The determination of the exergetic cost (Ex*) is done using the incidence matrix (A) and the vector of exergetic external valoration (Y*). The incidence matrix (A) is composed of three sub matrices: the sub matrix that represents the inlets and outlets of the subsystems; the sub matrix that represents the inlets in the complete system; and the sub matrix that represents the bifurcations. The vector of external exergetic valoration (Y*) is composed of three sub-vectors: the sub-vector composed of null components, that represents the conservative properties of exergetic costs; the sub-vector that represents the exergetic flows that present external value, including the inlet and the outlet flows; and the sub-vector of values for the bifurcation equations, also formed by null components.

For the determination of the exergetic cost of all the flows, it was necessary to solve a system of 76 equations for the configuration (a) - BLGCC with atmospheric air; 74 equations for the configuration (b) - BLGCC with pressurized air; and 39 equations for the configuration (c) - with Tomlinson recovery boiler. Initially, the input flows ("fuel") and product flows ("product") were defined for each one of the control volumes, considered in the analyzed configurations. After the definition of the input and the product flows of each component, the equations of exergetic cost of each one of the components, junctions and divisions that compose the configurations. The adopted definitions follow the methodology proposed by Lozano and Valero (1993). They point out that the more detailed the exergetic analysis it becomes easier to identify the irreversibilities associated to each one of the components or subsystems, and how the exergy is being used by each component or sub system. The methodology can be used as an auxiliary instrument for the selection of components of power generation systems. Gallego (2004) presented a detailed description about the methodology application for the configurations studied here.

5. Results

To model the configurations it was calculated the averaged production cellulose, the thermal and electric energy consumption of pulp and paper industries. According to a study accomplished in medium and large companies, the consumption of thermal energy was 14 GJ/ton of dry cellulose, and the consumption of electric energy was 657 kWh/ton of dry cellulose. The cellulose production considered in the simulations was 1275 tons of dry cellulose per day and relation black liquor/dry cellulose was 1,74 (Gallego, 2004). In the Tab. 3, the parameters used in the simulations are presented, and in the "Tab. 4", the main results obtained are presented.

Table 3 – Parameters used in the modeling of studied configurations.

Nº	Information about the process	Atmospheric Gasif. Configuration (a)	Pressurized Gasif. Configuration (b)	Tomlinson recovery Configuration (c)
1	Heat required (GJ/day)	206657		
2	Thermal energy generation (GJ/day)	206657		
3	Power required (MW)	34,90		
4	Black liquor consumption	92,44 ton/day (368,80 MW)		
5	Medium pressure steam	1000 kPa; 190 ºC; 4,65 GJ/ton dry cellulose		
6	Low pressure steam	400 kPa; 100 %; 9,36 GJ/ton dry cellulose		
7	Condensate recovery	1500 kPa; 90ºC		
8	Lower heating value of black liquor and of biomass	12409 kJ/kg; 16222 kJ/kg		

In the Tab. 4, it is shown that the lower heating value of the gas at the gasifier outlet, and at the inlet of the combustion chamber of the gas turbine, is larger for the atmospheric BLGCC configuration (a) than for pressurized BLGCC configuration (b). That fact was due to smaller molar fraction of water in the gaseous mixture and, consequently, the more significant hydrogen concentration in the atmospheric BLGCC configuration (a). It was verified that all the configurations needed to consume biomass to assist the steam demand of the industrial process. In the case of the configuration with Tomlinson boiler the combustion of the black liquor is destined to the steam generation to supply the steam turbine, and to the steam supply of the process. In the case of the BLGCC configurations (a) and (b), the energy contained in the black liquor is used initially to generate power in the gas turbine, being the steam a by-product of this system, and it is necessary to burn supplementary fuel to assist the steam demand. All the configurations generate sufficient power to satisfy the electric demand, existing in all the cases the possibility of sale of the energy surplus. In the case of the energy sale at prices that justify the investments, all the configurations of BLGCC can be interesting alternatives for the industry. The configuration (a) - BLGCC with atmospheric air - presented the lowest CO_2/work rate. That is due to the highest heating value of the gas produced in this gasifier. Another factor that contributed to the best results of the configuration (a) was the highest gas turbine power generation, starting from the same amount of black liquor. It should be considered in this analysis that the carbon dioxide obtained from biomass and black liquor combustion, will be absorbed in the future by the trees in growth, considering an appropriate forest handling. The BLGCC configurations (a) and (b) presented a rate work/biomass rate higher than the configuration (c) equipped with Tomlinson boiler.

Table 4 – Results obtained for the studied configurations.

Nº	Information about the process	Atmospheric gasif. Configuration (a)	Pressurized gasif. Configuration (b)	Tomlinson recovery Configuration (c)
1	LHV – gasifier outlet (kJ/kg)	3703	2560	-----
2	Biomass consumption (ton/day)	9,83	7,98	2,00
3	Specific energy (biomass/dry cellulose) - GJ/ton	145,08	117,78	29,52
4	Biomass/cellulose rate (kg/kg)	7,97	6,47	1,62
5	Steam turbine power (MW)	41,54	24,57	43,22
6	Gas turbine power (MW)	109,00	68,44	-----
7	Total power generated (MW)	150,54	93,01	43,22
8	Auxiliary power consumption (MW)	26,20	4,81	4,52
9	Net power generation (MW)	124,34	88,20	38,26
10	Specific net power (kWh/ton dry cellulose)	2340,46	1660,23	720,28
11	Net power for sale (MW)	89,43	53,30	3,36
12	Specific electric energy (kWh/ton dry cellulose)	1683,46	1003,23	63,28
13	Global efficiency (% LHV basis)	68,72	63,75	63,04
14	Exergetic efficiency (% Liquor + Biomass)	27,61	22,37	20,50
15	Electrical energy/steam	0,60	0,43	0,19
16	CO_2 produced/electricity (g/kWh)	955	1279	2941

The configuration (c) showed a high (heat generated)/(biomass quantity) rate, in comparison to the BLGCC configurations (a) and (b). When analyzing the system efficiency based on the Second Law of the Thermodynamics, it is verified that BLGCC configurations (a) and (b) are more efficient than the Tomlinson configuration (c), due to the largest amount of work produced per quantity of added fuel. The components that presented the largest irreversibilities are those where occur combustion processes, for example, the Tomlinson recovery boiler, the biomass boiler, and the gasification process. The flows related to heat exchangers with low exergetic efficiency, as the air heaters of the biomass boiler and of the recovery boiler, presented high exergetic unitary cost (k). The exergetic cost methodology, when it attributes null exergetic cost to the flows corresponding to combustion gases that are going to the atmosphere, but that possess a great amount of exergy, increases the exergetic costs associated to the other flows related with the component. The Table 5 shows the values of the exergetic costs of the medium-pressure steam and of the low-pressure steam, and of the power generated in each configuration.

Table 5 – Unitary exergetic costs of the medium-pressure and low-pressure steam flows, of the power generated in each configuration, of the gas generated and of other selected flows.

Nº	Unitary exergetic costs	Atmospheric Gasif. Configuration (a)	Pressurized Gasif. Configuration (b)	Tomlinson Recovery Boiler Configuration (c)
1	Medium-pressure steam	4,36	5,16	4,32
2	Low-pressure steam	4,20	3,42	4,29
3	Total power generated	3,71	4,27	5,28
4	Gas generated in the gasifier	1,81	2,12	----
5	Fuel gas	2,12	2,28	----
6	Gas turbine power	3,08	3,52	----

The exergetic unitary costs of the medium-pressure and low-pressure steam for the BLGCC configurations (a) and (b) were similar to the exergetic unitary costs presented in the configuration (c), due to the lower efficiency of the biomass boiler in the BLGCC configurations (a) and (b), which was about 16%, if compared with the efficiency of 22% presented by the biomass boiler in the Tomlinson configuration (c). This is an indication that the BLGCC configurations (a) and (b) are better from the thermodynamic point of view when compared with the configuration (c). That index can still be improved if it is chosen a more efficient biomass boiler. The low exergetic cost of the gas produced in the gasifier of the BLGCC configuration (a) with atmospheric air is due to the low unitary exergetic cost of the air in this configuration when compared to the cost of the pressurized air in the BLGCC configuration (b) with pressurized air. The highest increment in the exergetic cost of the fuel gas was achieved by the BLGCC configuration

(a) with atmospheric air, due to the fuel gas compression, but in spite of that increment, this configuration still presents a smaller exergetic cost than the configurations (b) and (c).

6. Conclusion

The gasification of black liquor is an interesting proposal for the pulp and paper industry. Many industries need to change the Tomlinson recovery boilers due to their long time of operation, low thermal recovery, environmental impact and the increased process demand of electric and thermal energy. With that expectation the proposal of gasification of black liquor can be an alternative for the pulp and paper industry, mainly if it is used in combined cycles. The simulations done in this work indicated that the power generated in the systems equipped with black liquor gasification is superior to the power generated with the system using recovery boiler.

The BLGCC configurations (a) -with atmospheric air- and (b) -with pressurized air- presented a net power generation two to three times higher than the configuration (c), commonly used in the pulp and paper industry. To attend the thermal energy demand, all the analyzed configurations needed to consume biomass energy equivalent to 5 GJ/ton of cellulose. It was verified that all the studied configurations satisfy the typical power demand of Brazilian pulp and paper industry, existing in all the cases the possibility of power surplus sale for electrical utilities. The configuration with recovery boiler (c) presented the highest CO_2/kWh rate. The configurations (a) and (b) cause lower greenhouse gases emissions. The smallest exergetic cost of the gas produced in the BLGCC configuration (a) -with atmospheric air- is due to the low unitary exergetic cost of the air flow (2,95) in this case, if compared with the unitary exergetic cost of pressurized air (3,74) in the BLGCC configuration (b) -with pressurized air. From the thermodynamic point of view, the use of black liquor gasification coupled with a combined power cycle is interesting for the pulp and paper industry, because this industry can become independent of external supply of electric power, guaranteeing the power supply with high quality, as well as the possibility of power surplus sale for electrical utilities.

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