# ANALYSIS OF COGENERATION SYSTEMS WITH GASIFICATION OF BLACK LIQUOR IN THE PAPER AND CELLULOSE SECTOR

**Elzimar Tadeu de Freitas Ferreira, elzimar@feg.unesp.br**

**José Antonio Perrella Balestieri, perrella@feg.unesp.br**
UNESP – Campus of Guaratinguetá
Faculty of Engineering
Av. Ariberto P. Cunha, 333 – Pedregulho – Guaratinguetá, SP

***Abstract.*** *The pulp and paper sector is intensive in the use of energy, and presents a high participation in the industrial context, specially based in renewable source generated in the pulp process. Although the black liquor gasification (BLG) is not still completely dominated, it has the potential of becoming an important alternative for the pulp and paper sector, once the burning of BLG in gas turbines should guarantee higher efficiencies, better use of the available renewable resources, also allowing the chemical recovery, just as is done nowadays with Tomlinson chemical recovery steam generators. In this article, it will be developed an analysis of the pulp and paper sector identifying its energy and environmental participation in the context of the national matrix. Based on the Rankine cycle, taken as the current state of knowledge, an energetic and exergetic analysis of a cogeneration system based on BLG system associated to gas turbine, heat recovery steam generator and backpressure steam turbine with extractions will be developed. The proposed scheme will be developed to produce electric/mechanical power and two pressure steam for guaranteeing better operational conditions comparatively to the traditional system.*

***Keywords****: Cogeneration, black liquor, gasification*

## 1. INTRODUCTION

Currently, the pressing concern related to the environment and reduction of fossil fuels has led researchers to focus on new technologies for the energy conversion for minimizing the impacts on nature and warranting the human survival on Earth. Renewable energy sources may be a solution to the offering of alternative energy because the greenhouse effect and global climate change are minimized.

There are several renewable energy sources to be considered, and Brazil stands out for having environmentally-friend resources in abundance, such as hydropower, biomass, solar and wind. However, the water resources are already being affected by climate change, which means that rain dynamics is changing. Vegetal and agricultural biomasses are a source of energy obtained from the sun, a renewable and inexhaustible source in the long term, through the natural photosynthesis process. The use of this fuel is enabled to have a neutral $CO_2$ emission balance and also there is a great absorption of this gas by the biomes. The great advantage for Nature is the reduction of greenhouse effect, as a consequence of $CO_2$ emissions decrease.

Biomass is available in so many ways, as in the large surpluses of timber forests, agricultural waste and organic fractions of municipal solid wastes. The importance of energy obtained from biomass is dependant of its availability in natura; the conversion of solid biomass to gas is also important to be proposed because some more efficient additional technologies (other than steam thermal power plants, based on steam generators and incinerators), such as gas turbines, can be employed.

Biomass is easier to gasify than fossil fuels because biomass contains its oxygen and water in its chemical structure, crucial elements in the gasification process. The gasification allows the conversion of solid material into combustible gases, generating energy to be processed to mechanical and/or electrical energy, as well as the production of synthetic fuels and chemicals.

In this paper, an energetic and exergetic analysis of a black liquor-integrated gasification combined cycle is presented. Based on the integrated gasification combined cycle scheme proposed by Larson *et al.* (2000), a black liquor and a green liquor compositions were established, according to the literature; mass, energetic and exergetic balance equations were then applied to each component and the available data were considered for validating the analysis. Gas turbine energetic and exergetic analysis are presented in details, and data relative to the energetic and exergetic analysis of black liquor-integrated gasification combined cycle scheme is then presented.

## 2. GAS TURBINE - ENERGETIC AND EXERGETIC ANALYSIS

The thermodynamic analysis of a gas turbine is based on the scheme proposed in Fig. 1. Table 1 registers the physical properties of points relative to inflows and outflows; Table 2 presents the composition of synthesis gas that is burnt in the gas turbine's combustion chamber, as the result of chemical equilibrium calculations (Gordon and McBride, 1971); the black liquor composition (Consonni *et al.*, 1998) was due to Phyllis (2007).

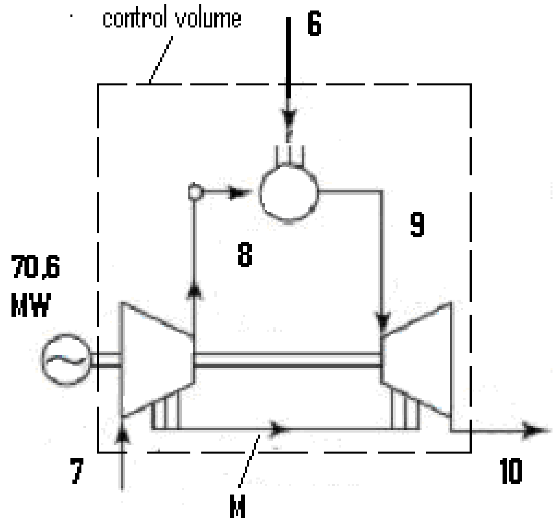


Figure 1 – Gas turbine

Table 1 - Properties of the entrances and exits of the gas turbine

| | Description | $\dot{m}(kg\ /\ s)$ | $T(°C)$ | P (MPa) |
|---|---|---|---|---|
| 6 | entrance of fuel | 62.3 | 130 | 2.31 |
| 7 | entrance of air (15°C) | 190 | 15 | 0.101 |
| 8 | entrance of air (423°C) | 105 | 423 | 1.71 |
| 9 | combustion gas exit | 167.3 | 1280 | 1.66 |
| 10 | exhaust gas exit | 202 | 585 | 0.104 |

Table 2 - Composition of the synthesis gas in the gasifier exit

| Composition of the gas | $n_{i1}$ | $n_{i2}$ | $\%vol_{i1}$ |
|---|---|---|---|
| $H_2$ | 0.1549 | 0.155305 | 15.53 |
| $H_2O$ | 0.088793 | 0.088985 | 8.90 |
| $H_2S$ | 0.0025588 | - | - |
| $NH_3$ | 0.0000074359 | - | - |
| CO | 0.1909 | 0.191399 | 19.14 |
| COS | 0.00010092 | - | - |
| $CO_2$ | 0.07531 | 0.075507 | 7.55 |
| $N_2$ | 0.4875 | 0.488774 | 48.88 |
| Total | 1.0230993559 | 0.999935 | 100.00 |

Based on the synthesis gas composition, the exhaust gas composition at the combustion chamber exit is modeled according to the Eq. (1). Considering a reasonable 10% air excess in the combustion process, the exhaust gas composition is presented in Tab. 3.

$$(0.1553\ H_2 + 0.08899\ H_2O + 0.1904\ CO + 0.07551\ CO_2 + 0.4888\ N_2) + m(O_2 + 3.76\,N_2) \rightarrow\ a\,CO_2 + b\,H_2O + c\,N_2 + d\,O_2 \quad (1)$$

Table 3 - Composition of the gas that leaves the combustion chamber

| Composition of the gas | $n_{i3}$ | $\%vol_{i2}$ |
|---|---|---|
| $CO_2$ | 0.26691 | 15.3900 |
| $H_2O$ | 0.24429 | 14.0857 |
| $N_2$ | 1.205776 | 69.5248 |
| $O_2$ | 0.017335 | 0.9995 |
| Total | 1.734311 | 100.0000 |

**2.1 Energetic analysis of the gas turbine**

The specific heat of the exhaust gas ( $c_{p_g}$ ) was calculated according to the Tab. 3 data; the specific heat equations for carbon dioxide, water (steam), nitrogen and oxygen were used (Perry and Green, 1999; Dias and Balestieri, 2003); in this way, an expression to characterize the variation of the specific heat of the exhaust gas in the gas turbine as a function of its temperature was elaborated Eq. (2).

$$c_{p_g}(T) = \frac{0.1539}{44}\bar{c}_{pCO_2} + \frac{0.140857}{18}\bar{c}_{pH_2O} + \frac{0.695248}{28}\bar{c}_{pN_2} + \frac{0.009995}{32}\bar{c}_{pO_2} \tag{2}$$

In Equation (2), the numerator expresses the product of the molar fractions of each chemical substance multiplied by its characteristic specific heat in molar base, and the denominator refers to the molecular weight. They are considered the specific heats of $CO_2$, $H_2O$, $N_2$ and $O_2$ respectively:

$$c_{p_g}(T) = \frac{0.1539}{44}(10.34 + 0.00274\cdot T - \frac{195500}{T^2}) + \frac{0.140857}{18}(8.22 + 0.00015\cdot T + 0.00000134\cdot T^2) +$$
$$+ \frac{0.695248}{28}(6.5 + 0.001\cdot T) + \frac{0.009995}{32}(8.27 + 0.000258\cdot T - \frac{187700}{T^2})$$

This complete expression is then reduced and converted to the International System to generate Eq. (3).

$$c_{p_g}(T) = 1.107288 + 0.000149T + 4.39029.10^{-8}T^2 - \frac{3108.42}{T^2}\left(\frac{kJ}{kg\cdot K}\right) \tag{3}$$

For the exhaust gas temperature obtained in the Tab. 1, T=585°C=858 K, $c_{pg}$(T=858 K) = 1.263516 (kJ/kgK).

The specific heat of the air ( $c_{p_{ar}}$ ) is calculated by the equation proposed by Shieh and Fan (1982) for the air compressor entrance temperature, of T=15°C=298 K, according to Tab. 1:

$$c_{p_{ar}}(T) = 1.04841 - 0.00038372T + \frac{9.45378}{10^7}T^2 - \frac{5.49031}{10^{10}}T^3 + \frac{7.92981}{10^{14}}T^4 \tag{4}$$

$$c_{p_{ar}}(T = 298\ K) = 1.00374\ kJ/kgK$$

As there is no information about the percentage of compressor entrance air is used for its refrigeration, an estimate is done considering that ( $\dot{m}_M$ ) 34.3 kg/s of ( $\dot{m}_{ar}$ ) 190 kg/s entrance air is sent to the gas turbine via the M point of Fig. 1. As the net gas turbine power ( $\dot{W}_{liq}$ ) is of 70,600 kW, the temperature of air injection ($T_M$) can be estimated by Eq. (5). The mechanical efficiency ( $\eta_m$ ) of gas turbine is 93.5%.

$$\dot{W}_{liq} = \dot{m}_g \cdot c_{p_g}\cdot(T_9 - T_{10}) - \frac{1}{\eta_m}\cdot c_{p_{ar}}\cdot[\dot{m}_{ar}\cdot(T_8 - T_7) + \dot{m}_M\cdot(T_M - T_7)] \tag{5}$$

$$70600 = 167.3\cdot 1.263516\cdot(1280 - 585) - \frac{1}{0.935}\cdot 1.00374\cdot[155.7\cdot(423 - 15) + 34.3\cdot(T_M - 15)]$$

Therefore, $T_M$= *235.45°C*

For the available data, the compressor isentropic efficiency ( $\eta_{cp}$ ) (Bathie, 1984; Boyce, 2002; Cohen and Saravanamuttoo, 1987) can be calculated for the data of Tab. 1. In the compressor, admitting k=1.4 for the air, $T_8$=423°C, $T_7$=15°C, $P_8$=1.7 MPa and $P_7$=10 kPa, the values are calculated by using Eq. (6).

$$\frac{T_8}{T_7} = \left\{ 1 + \frac{1}{\eta_{cp}} \left[ \left( \frac{P_8}{P_7} \right)^{\frac{k-1}{k}} - 1 \right] \right\} \tag{6}$$

$$r = \frac{P_8}{P_7} = \frac{17.1}{1.01} = 16.93 \quad \text{and} \qquad \frac{423 + 273}{15 + 273} = \left\{ 1 + \frac{1}{\eta_{cp}} \left[ (16{,}93)^{\frac{0.4}{1.4}} - 1 \right] \right\} \qquad \Rightarrow \qquad \eta_{cp} = 0.8782$$

For the temperature of the point M ($T_M$), the pressure ratio ($r$) will be:

$$r = \frac{P_M}{P_7} = \left( \frac{T_M}{T_7} \right)^{\frac{k}{k-1}}, \text{ therefore corresponds to } r = \left( \frac{235.45 + 273}{15 + 273} \right)^{\frac{1.4}{1.4-1}} \quad \Rightarrow r = 7.3113$$

The thermal efficiency of the gas turbine, based on the 1st Law of Thermodynamics ($\eta_I$) is given by Eq. (7).

$$\eta_I = \frac{\dot{W}_{lig}}{\dot{m}_{comb} \cdot PCI} \tag{7}$$

for which $\dot{m}_{comb} = 62.3 kg/s$ is the flow of clean synthesis gas that enters in the combustion chamber and PCI=3,780kJ/kg is the clean synthesis gas lower heating value (PCI).

$$\eta_I = \frac{70600}{62.3 \cdot 3780} \qquad \Rightarrow \qquad \eta_I = 0.2998$$

**2.2 Exergetic analysis of the gas turbine**

The exergetic analysis of gas turbine system is described below according to the flow numbers described in Fig.1.

**a) Exergy of the entrance air ($ex_{ar}$) in the compressor (flow 7) (Kotas, 1985)**

$$ex_{ar} = c_{p_{ar}} [(T - T_0) - T_0 \ln \frac{T}{T_0} + (\frac{\gamma - 1}{\gamma}) T_0 \ln \frac{P}{P_0}] \tag{8}$$

From the Table 1 it is obtained the data for the air; polytrophic index is assumed to be $\gamma = 1{,}4$. Reference state is given for temperature $T_0 = 298K$ and pressure $P_0 = 101 kPa$. The specific heat of the air for the temperature of entrance of the air in the entrance of the compressor T=15°C=288K was previously calculated and its value is $c_{p_{ar}} (T = 298 \text{ K}) = 1.00374 \text{ kJ / kgK}$.

In this way, the specific exergy of entrance air ($ex_{ar}$) is:

$$ex_{ar} = 1.00374[(288 - 298) - 298 \ln \frac{288}{298} + (\frac{1{,}4 - 1}{1{,}4}) 298 \ln \frac{101}{101}] \qquad \Rightarrow ex_{ar} = 0.1723 \text{kJ / kg}$$

and consequently the exergy of the air ($\dot{E}x_6$), for the mass flow obtained from Tab. 1 is finally calculated.

$$\dot{E}x_6 = \dot{m}_{ar} \cdot ex_{ar} = 190 \cdot 0.1723 = 32.73 kW$$

**b) Exergy of clean synthesis gas that enters in the combustion chamber (flow 6)**

The exergy of clean synthesis gas is calculated for the combustion chamber entrance temperature, at T=130°C=403K, according to Tab. 1; it is calculated according to physical and chemical components (Balestieri, 2002) represented by Eq. (9) and Eq. (10). The corresponding values are obtained of the Tab. 4.

- Physical exergy:

$$ex_g{}^F = \sum_{i=p} a_i\{\bar{h}(T) - \bar{h}(T_0) - T_0[\bar{s}(T) - \bar{s}(T_0) - \bar{R}\ln\frac{x_i \cdot P}{P_{00}}]\} \tag{9}$$

with $a_i$ coefficient for balancing the equation of combustion;
$\bar{h}$ enthalpy at the base molar;
$\bar{s}$ entropy at the base molar;
$x_i$ mole fraction of each component of the equation of combustion;
$\bar{R} = 8.3144\ kJ/kmol, \mathrm{P} = 2.31\,\mathrm{MPa}, \mathrm{T} = 403\,\mathrm{K}, \mathrm{P}_{00} = 101\,\mathrm{kPa}$ and $\mathrm{T}_0 = 298\,\mathrm{K}$.

- Chemistry exergy:

$$ex_g{}^Q = \Sigma x_i \bar{e}_i{}^Q + \bar{R}T_0\Sigma x_i \ln x_i \tag{10}$$

Table 4 – Thermodynamic properties of clean synthesis gas that enters in the combustion chamber, referred to Tab. 2.

| | $CO$ | $CO_2$ | $H_2$ | $N_2$ | $H_2O$ |
|---|---|---|---|---|---|
| $a_i$ | 0.191399 | 0.075507 | 0.155305 | 0.488774 | 0.088985 |
| $x_i$ | 0.1914 | 0.0755 | 0.1553 | 0.4888 | 0.089 |
| $\bar{h}$ (kJ/kmol) T(403K) | 11732.2 | 13495.5 | 11513.6 | 11727.6 | 13458.9 |
| $\bar{h}$ (kJ/kmol) $T_0$ | 8669 | 9364 | 0 | 8669 | 9904 |
| $\bar{s}$ (kJ/kmolK) T(403K) | 206.3425 | 225.5325 | 139.32 | 200.29 | 198.93 |
| $\bar{s}$ (kJ/kmolK) $T_0$ | 197.54 | 213.69 | 130.57 | 191.50 | 188.72 |
| $\bar{e}^Q$ (kJ/kmolK) | 269419 | 14175 | 235250 | 640 | 8635 |

Specific physical and chemical exergy components are calculated below, according to Eq. (9) and Eq. (10).

$$\mathrm{ex_g}^{\mathrm{F}} = 6143.67\ \mathrm{kJ/kmol}$$

$$\mathrm{ex_g}^{\mathrm{Q}} = 86868.31\ \mathrm{kJ/kmol}$$

The molecular weight of the clean synthesis gas ($M_g$) is then calculated, and its value is used for estimating physical and chemical exergy components of synthesis gas.

$$M_g = \Sigma x_i \cdot M_i = 0.1914 \cdot 28 + 0.0755 \cdot 44 + 0.1553 \cdot 2 + 0.4888 \cdot 28 + 0.089 \cdot 18 = 24.2802\ (kg/kmol)$$

$$\dot{\mathrm{n}}_{\mathrm{g}} = \frac{\dot{\mathrm{m}}_{\mathrm{g}}}{\mathrm{M_g}} = \frac{62.3(\mathrm{kg/s})}{24.2802(\mathrm{kg/kmol})} = 2.566(\frac{\mathrm{kmol}}{\mathrm{s}})$$

$$\dot{\mathrm{E}}\mathrm{x_g}^{\mathrm{F}} = 6142.67 \cdot 2.566 = 15764\ \mathrm{kW}$$

$$\dot{\mathrm{E}}\mathrm{x_g}^{\mathrm{Q}} = 86868.31 \cdot 2.566 = 222893\ \ \mathrm{kW}$$

whose clean synthesis gas total exergy ($\dot{E}x_8$) is:

$$\dot{E}x_8 = 238657\ \ kW$$

**c) Exergy of the gas that leaves the gas turbine (flow 10)**

The exergy of gas turbine exhaust gas is calculated for thermodynamic properties collected of the Tab. 3 and by using Eq. (9) and Eq. (10): $P = 104\,kPa, T = 858\,K, P_{00} = 101\,kPa$ and $T_0 = 298\,K$. With the data of the Table 5, the physical exergy and the chemical exergy of the exhaust gas are calculated from the gas turbine.

Table 5 - Properties of the exhaust gas of the gas turbine, referred to Tab. 3.

| | CO | $H_2O$ | $N_2$ | $O_2$ |
|---|---|---|---|---|
| $a_i$ | 0.26691 | 0.24429 | 1.20578 | 0.01734 |
| $x_i$ | 0.1539 | 0.1409 | 0.6952 | 0.01 |
| $\bar{h}$ (kJ/kmol) T(858K) | 35191.4 | 30161.2 | 25546.4 | 26490.8 |
| $\bar{h}$ (kJ/kmol) $T_0$ | 9364 | 9904 | 8669 | 8682 |
| $\bar{s}$ (kJ/kmolK) T(858K) | 261.04 | 226.43 | 223.12 | 238.184 |
| $\bar{s}$ (kJ/kmolK) $T_0$ | 213.69 | 188.72 | 191.50 | 205.033 |
| $\bar{e}^Q$ (kJ/kmol) | 14175 | 8635 | 640 | 3950 |

$$ex_g^{\,F} = 10874.97\,kJ/kmol$$

$$ex_g^{\,Q} = 1744.55\,kJ/kmol$$

The molecular weight of the exhaust gas ( $M_g$ ) is then calculated, and its value is used for estimating physical and chemical exergy components of exhaust gas.

$$M_g = \Sigma x_i \cdot M_i = 0.1539 \cdot 44 + 0.1409 \cdot 18 + 0.6952 \cdot 28 + 0.01 \cdot 32 = 29.0934 (kg/kmol)$$

$$\dot{n}_g = \frac{\dot{m}_g}{M_g} = \frac{202 (kg/s)}{29.0934 (kg/kmol)} = 6.943 \frac{kmol}{s}$$

$$\dot{E}x_g^{\,F} = 10874.97 \cdot 6.943 = 75506\,kW$$

$$\dot{E}x_g^{\,Q} = 1744.55 \cdot 6.943 = 12113\ kW$$

In this way, the exhaust gas total exergy is:

$$\dot{E}x_{10} = 87619\,kW$$

**2.3 Exergetic irreversibility and efficiency of the gas turbine**

The calculation of the irreversibility ( $\dot{E}_d$ ) (Moran and Shapiro, 2002) of the gas turbine is obtained by using Eq. (11).

$$0 = \sum_e \dot{m} \cdot ex_e - \sum_s \dot{m} \cdot ex_s - \dot{E}_d \qquad (11)$$

Therefore, the irreversibility ( $\dot{E}_d$ ) of the gas turbine will be:

$$\dot{E}_d = 238690 - 158219 = 80471\,kW$$

The exergetic efficiency ($\eta_{II}$) (Kotas, 1985) can be defined by Eq. (12):

$$\eta_{II} = \frac{\Sigma \dot{E}x_s}{\Sigma \dot{E}x_e} \tag{12}$$

Therefore the efficiency of the 2nd law of Thermodynamics ($\eta_{II}$) for the gas turbine will be:

$$\eta_{II} = \frac{\dot{E}x_{10} + \dot{W}_{liq}}{\dot{E}x_8 + \dot{E}x_6} \quad \Rightarrow \quad \eta_{II} = \frac{87619 + 70600}{238657 + 32.73} \quad \Rightarrow \quad \eta_{II} = 0.6628$$

## 3. INTEGRATED GASIFICATION COMBINED CYCLE EXERGETIC ANALYSIS

The complete cogeneration scheme considered in this analysis is an air-blown black liquor integrated gasification combined cycle that is presented in Fig. 2. The results of exergetic efficiency and irreversibility for the main components are presented in Tab. 6.

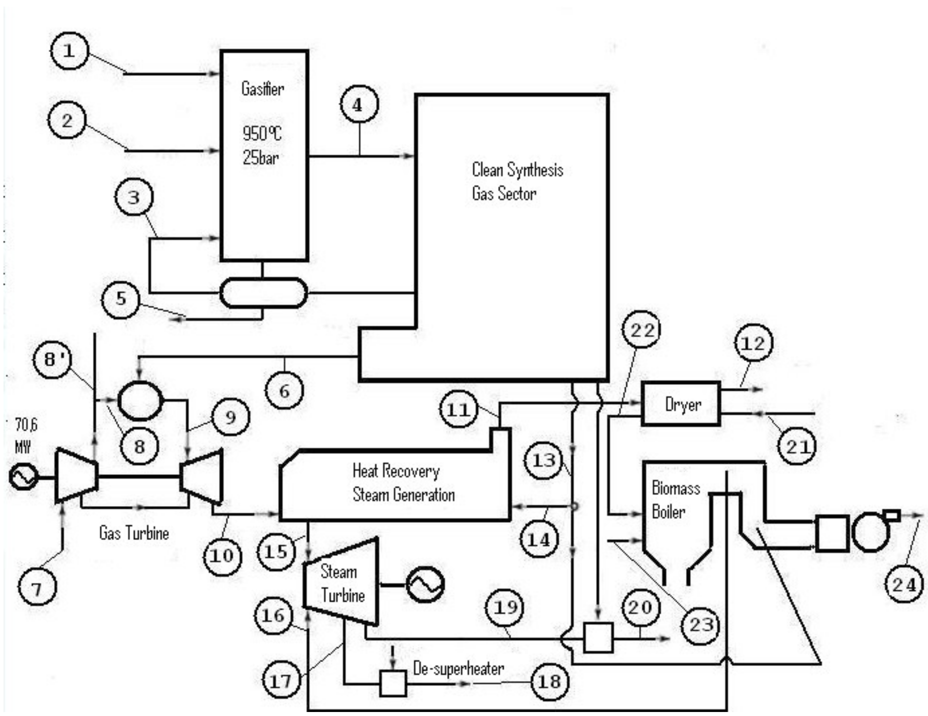


Figure 2 – Basic scheme of air-blown black liquor integrated gasification combined cycle

Table 6 – Exergetic efficiency and irreversibility for the scheme proposed in Fig. 2

| Description of components | $\eta_{II}$ (%) | $\dot{E}_d$ (kW) |
|---|---|---|
| gasifier | 48.05 | 521093 |
| gas turbine | 66.28 | 80471 |
| heat recovery steam generation | 48.45 | 46404 |
| steam turbine | 96.71 | 3116 |

The above results do not exactly match the ones obtained by Gallego (2004), except for the gasifier, whose gasifier second law efficiency was 53%. However, it must be noted that several differences are present: Larson *et al.* (2000) and Gallego (2004) taken specific black liquor composition that is different from the one here considered; some other thermodynamic properties differ, such as component efficiencies, and this is decisive for the results obtained.

## 4. CONCLUSIONS

The analysis of an air-blown black liquor integrated gasification combined cycle here described was developed considering the scheme proposed by Larson *et al*. (2000); however, as the authors do not present the formulation used to develop their calculation, and also some important parameters are missing, it was structured a sequence of calculations to reproduce the modeling of such cogeneration unit.

Some of the obtained values were not completely reproduced, when compared to the ones presented in the above reference, because the black and green liquor compositions had to be adopted; however, the modeling was validated and is presenting adequate values of energetic and exergetic analysis.

## 5. ACKNOWLEDGEMENTS

The first author is indebted to CAPES for his post-graduation grant. The second author is grateful to FAPESP - The State of São Paulo Research Foundation for finance research project (Process 05/03985-1). He is also indebted to CNPq-The National Council for Scientific and Technological Development, for his productivity grant (Process 301503/2005–2).

## 6. REFERENCES

Balestieri, J.A.P., 2002, "Cogeração: Geração Combinada de Eletricidade e Calor", Editora UFSC, Florianópolis - SC, 279p.

Bathie, W.W., 1984, "Fundamentals of gas turbines", John Wiley, New York, 358p.

Boyce, M.P., 2002, "Handbook for Engineering and Combined Cycle Power Plants", New York The American Society of Mechanical Engineers.

Cohen, H., Saravanamuttoo, H. I. H., 1987, "Gas Turbine Theory", England: Longman Society & Technical.

Consonni, S., Larson, E. D., Kreutz, T. G., Bergin, N. , 1998, "Black Liquor Gasifier/Gas Turbine Cogeneration", Asme Journal of Engineering for Gas Turbine and Power, v.120, n. 3, p. 442-449.

Dias, R.A. and Balestieri, J.A.P., 2003, "Energetic and Exergetic Analysis in a Firewood Boiler", Revista de Ciência e Tecnologia Vol. 12 nº 23, 15-24p.

Gallego, A.G., 2004, "Modelagem computacional e análise termodinâmica de sistemas de geração de potência utilizando gaseificação de licor negro", Tese de Doutorado, Campinas, FEM/UNICAMP.

Gordon, S., McBride B. J., 1971, "Computer program for calculations of complex chemical equilibrium compositions, rocket performance, incident and reflected shocks and Chapman – Jouguet detonations", Washington: NASA SP – 273.

Kotas, T.J., 1985, "Exergy Method of Thermal Plant Analysis", Butterworths, London, 344p.

Larson, E.D., McDonald, G.W., Yang, W., Frederick, W.M.J., Iisa, K., Kreutz, T.G., Malcolm, E.W., Brown, C.A., 2000, "A cost–benefit assessment of BLGCC technology", Tappi Journal June, vol. 83 no. 6, p. 2-16.

Moran, M.J.O. and Shapiro, H. N., 2002, "Princípios de Termodinâmica para Engenharia", 4ª edição, Rio de Janeiro, Editora Livros Técnicos e Científicos, 681p.

Perry, R.H. and Green, D.W., 1999, "Perry's Chemical Engineers' Handbook", Mc Graw-Hill.

Phyllis, "The composition of biomass and waste", available at: http://www.ecn.nl/phyllis/dataTable.asp.

Shieh, J.H. and Fan, L.T., 1982, "Estimation of energy (enthalpy) and exergy (availability) contents in struturally complicated materials", Energy Sources, Laramie, 6, 1/2, 1-46p.

## 7. RESPONSIBILITY NOTICE