

THERMODYNAMIC EVALUATION OF THE REHEATING EFFECT IN COGENERATION SYSTEMS FOR BRAZILIAN SUGAR AND ALCOHOL INDUSTRY

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Abstract. This paper develops a thermodynamic evaluation of the implementation of the reheating in cogeneration systems of the Brazilian sugar and alcohol sector. It is aimed to establish actions focused on the overall performance increased to provide greater availability of surplus bagasse. Four scenarios were analyzed, considering the cogeneration system of a sugar and alcohol plant divided into two groups. Group I has fixed power and his objective is to obtain a higher index of surplus bagasse; Group II uses a consumption fixed rate of bagasse, employing all its availability to generate steam. Each grouping consists of a base case (Basis I e II) and a scenario with reheating (A, e B_r), which in turn was obtained by an optimization of the vapor pressure extraction pressure. It was used GateCycle™ software for simulation of different schemes. It was established as the main parameters the milling capacity of 500 tc / h, specific steam consumption of 450 kgv / tc and operation with condensing/extraction steam turbines. Whereas cogeneration systems produce electricity and useful thermal energy simultaneously, the case studies for the scenarios are now based on the analysis of two indicators, the exergetic efficiency, and surplus bagasse index. In addition to the observed increase efficiency in each group and increases the quality turbine outlet, there was obtained additions of exergetic efficiency of 1.78% and 1.55% for the groups I and II, respectively.

Keywords: cogeneration, reheating, Rankine cycle, sugar and alcohol.

1. INTRODUCTION

The interest in to diversify the energy matrix is common to several segments, as social groups, the academic community and other decision makers as dependence on fossil fuels exposes the energy supply to various risks, such as exhaustion prospects, appointed by recent publications on the reduction of oil production in the coming decades; volatility of costs and adverse impacts on the climate and air pollution. In this scenario, renewables assume their importance and that its expansion is harnessed to economic competitiveness against the conventional model and technology.

Brazil achieves to stand out in the international scenario as its renewable sources, so that in 2014 obtained a market share of 39.4% of resources in its energy mix, up about three times the world average; in this context, the sugarcane biomass has a decisive role, both for the production of ethanol and the rational use the form of bagasse that, of this amount, answered by a 15.7% stake, superior even to water sources, 11.5% (EPE, 2015).

It is observed, from the economic point of view, the importance of the sector remains high; we have the gross domestic product (GDP) in the sector is estimated at US \$ 43.36 billion, equivalent to nearly 2% of the national GDP in 2013, generating a financial transaction, the sum of all sales of the various links in the chain and services provided by the facilitators of the order of US \$ 107.72 billion (Markestrat, 2014). It is importante to consider that Brazil accounts for more than half of the sugar sold in the world, with an average rate of increase in production of 3.25%, projected to 2018/19 (BRAZIL, 2015).

The year of 2006 was marked by a world gasoline consumption of 1.22 trillion liters and it is estimated that by 2025 is expected to be 1.70 trillion liters (IEA, 2009). In this scenario, Brazil can play a decisive role in order to meet the global demand for bioethanol to replace 10% of global gasoline consumption (CGEE, 2009). Added to these factors the growth prospects of chemicals based on renewable sources, a segment that hold average growth estimates of 23% per year (2013-2018) and a penetration in the Brazilian scenario evolving from 0.12% (2012) to 10% (2022) (BCC, 2014; Abiquim, 2014 apud Bain & Company and Gas Energy, 2014). Following this trend, it is possible to add value to bagasse as a supply, also, to various other sectors such as pulp and paper industry, production of lignocellulosic ethanol and others.

Finally, it is clear that the use of the biomass from sugar cane focuses on expanding production of ethanol and sugar, and increasing the value added to by-products, such as bagasse. Accordingly, the present study intends to evaluate thermodynamically incorporating reheat systems in sugarcane mills, in order to increase the overall efficiency of the plant and increase the availability of surplus bagasse.

2. GENERAL ASPECTS

The Brazilian sugar and alcohol sectors commonly are characterized as cogeneration systems with sugarcane bagasse as the primary fuel and operated in the Rankine thermodynamic cycle. It is important to note that the increasing mechanization, as well as legal changes on restricting the burning of straw harvesting, makes the straw stand out as fuel to generate steam or as lignocellulosic feedstock to several other processes. In general, biomass sugarcane consists of approximately equal amounts of juice, bagasse and straw (CGEE, 2009).

The actual Rankine cycle differs from the ideal due to the presence of heat loss to the environment, non-isentropic processes of compression/expansion and other kinds of irreversibilities.. Therefore, it is possible to increase the cycle efficiency by reducing the irreversibility either by raising the average temperature of heat addition or reduction of the average temperature of heat rejection (Panosso, 2003). The concept of average thermodynamic temperature is necessary since this parameter governs most of the cases in this work. Souza (1980) suggests that in a reversible process between two states, the average temperature is given by the ratio between the heat portion divided by the change in entropy; so that in a theoretical cycle efficiency varies inversely to the ratio between the average temperature of rejection by the average temperature of addition.

A medium average temperature of adding heat is through the reheating; steam expands in a first phase to a certain pressure, so it is taken back to the steam generator to raise its energy and temperature. After reheated, the expansion continues in a second stage until the condenser pressure (Moran et al., 2011). This method aims in addition to an improvement in cycle efficiency and increasing steam quality at the end of expansion, avoiding accelerated wear of the turbine palettes caused by erosion; usually the stages of reheating is limited to two (Badr et al., 1990). Since the average temperature of heat addition is a key parameter in the reheating, how bigger than the difference between the temperature of the reheated fluid and the temperature of the primary fluid in the boiler (fuel gas), will be obtained lower thermal efficiency cycle; ideally, it takes to reheat temperature equal to the generation (Nag, 2008).

Several studies directed to define the reheating procedure, establishing a relationship between the reheating temperature and the thermal efficiency of the cycle. Among these works, there is an analytical proposition de Souza (1980) and the computational analysis of Badr (1990).

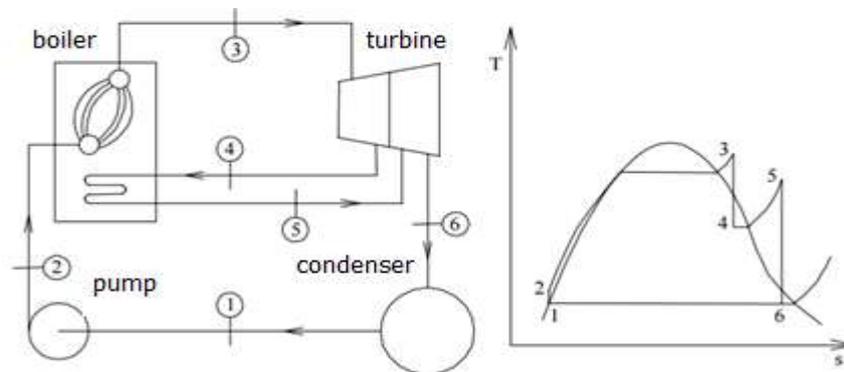


Figure 1. Diagram T-s for an ideal Rankine reheat cycle.

Souza (1980) examines the effect of reheating step insertion and proposes that the average temperature of heat addition to the cycle can be described by Eq. (1).

$$T_m = \frac{T_{mc}(s_3 - s_2) + T_{ma}(s_5 - s_4)}{s_5 - s_2} \quad (1)$$

where s , T_{mc} , T_{ma} represent, respectively, the entropy, average temperature of heat addition in the steam generation phase and in the reheating stage for Fig. 1.

Finally, in an ideal isentropic expansion cycle, the temperature reheating takes the same as the average temperature of heat addition to the cycle given by Eq. (2). Souza (1980) indicates the validity of this proposition for a real cycle, in which the main advantage lies in the improvement of the quality after expansion and a small increase efficiency.

$$T_m = T_{ma} = T_{mc} = T_4 = \frac{h_3 - h_2}{s_3 - s_2} \quad (2)$$

where s , h , T_{mc} and T_{ma} represent, respectively, entropy, enthalpy, and the average thermodynamic temperature of heat addition to the cycle.

Badr et al. (1990) proposed a computational approach which is linked to thermal efficiency of the cycle to a variable, dimensionless pressure reheating - P_R . This parameter is given as the difference from the extraction pressure to reheat and condenser pressure, divided by the difference between the pressure generation and condenser pressure. Figure 2 illustrates the behavior under thermal efficiency and P_R for a range of 0 to 1.

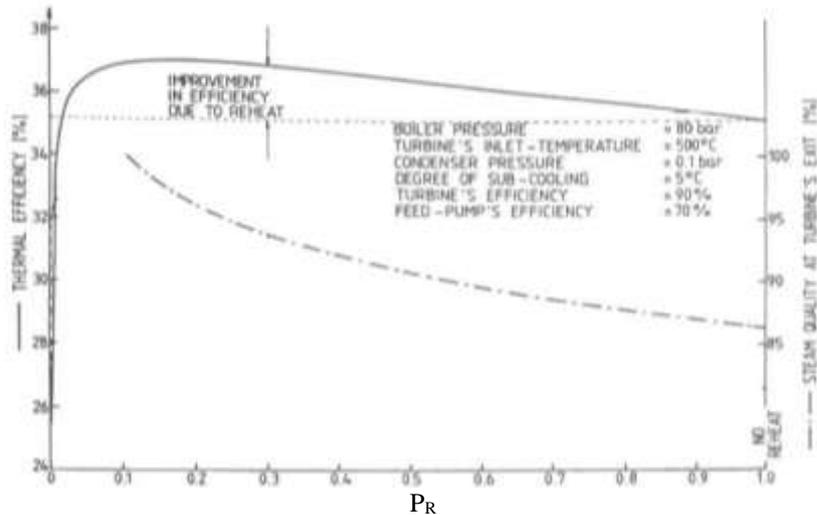


Figure 2. Effect of PR pressure on the thermal efficiency in a single-stage reheating (BADR et al., 1990).

In order to quantify the performance of insertion of reheat in cogeneration systems, the following parameters were set:

Exergy efficiency: The sum of the exergies of the cogeneration plant products divided by the fuel exergy Eq. (3).

$$\eta_{exe} = \frac{B_P + B_Q}{B_F} \quad (3)$$

where B_P is the exergy of the electricity produced (kW), B_Q is the exergy of the heat consumed by the process (kW), and B_F , exergy fuel (kW).

Bagasse surplus: The availability of bagasse consider the fiber content, initial system biomass and mass crushed of cane.

$$\beta_{exc} = \frac{(\beta_{available} - \beta_{consumed})}{\beta_{available}} \quad (4)$$

where $B_{available}$ is the amount of bagasse available in the milling sugarcane and $\beta_{consumed}$ represents the amount consumed in the boilers of the cogeneration systems.

3. CASES OF STUDY

The studies were established for the evaluation of two groups, where the distinction between them is the way that the generated residue is employed. Group I focuses on obtaining surplus bagasse, so that the owner decides to make more attractive with the residue; therefore, power was set at 50 MW. Group II considers that all generated bagasse is used for generating steam, so that increases in the overall efficiency of the plant be converted into increased power output, hence greater electrical excess. The application of the first and second laws of thermodynamic concepts allows us to measure the performance of the two indicators considered: exergetic efficiency and surplus bagasse.

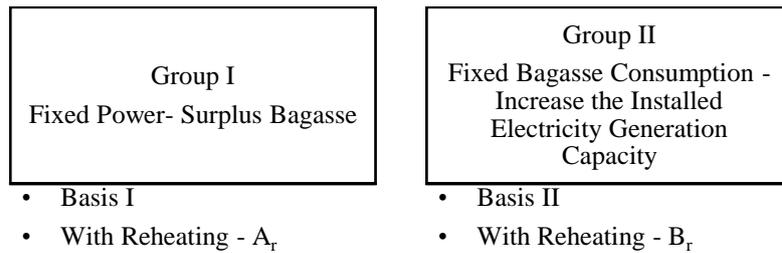


Figure 3. Structure of the groups.

The installed capacity of Group I was determined having in mind that in 85% of the plants have an installed capacity below 55 MW (ANEEL, 2015), with steam parameters of (65 bar and 480 ° C). The bagasse consumption for the Group II (65 bar and 480 ° C) was obtained considering the percentage of biomass for system startup, as well as, the generation of bagasse and operational capacity of the mills; depending on the values of Tab. 1. Figure 4 and Fig. 5 shows the layout employed in the simulations.

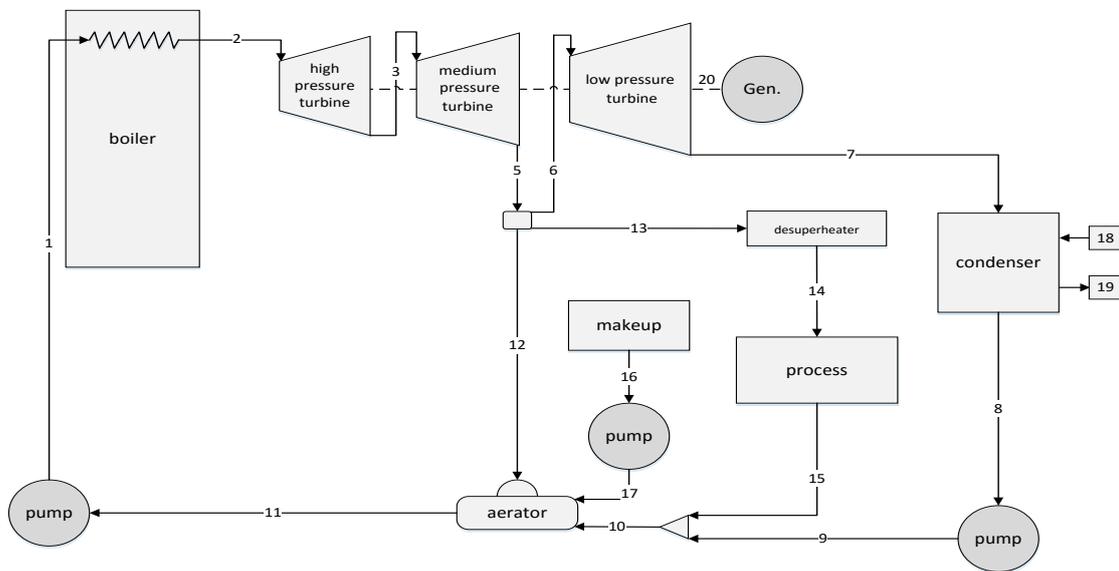


Figure 4. Layout of Cogeneration System for Group I and II.

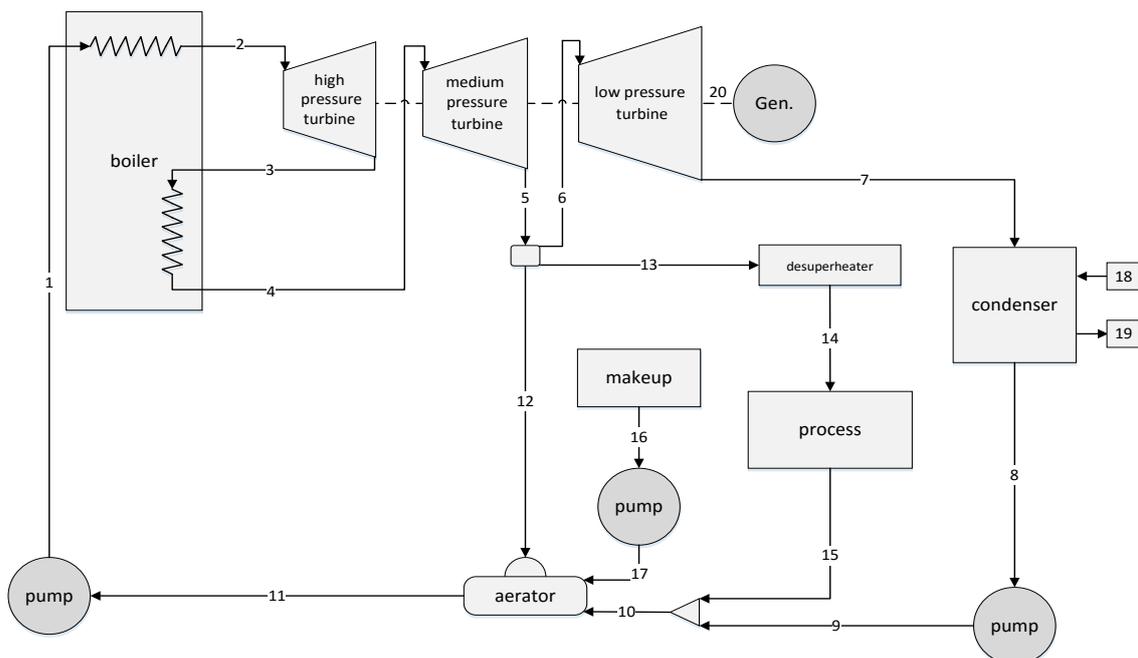


Figure 5. Layout of Cogeneration System with reheating for Groups I and II.

It is important to note that in this configuration, there is presence of a desuperheater before the process plant (see flows 13 to 14 based Fig. 4). This is due to the fact that many processes require a controlled temperature for the the steam process (Nag, 2008).

The dimensionless pressure reheat, P_r , was applied in a range of 0.15 to 0.92 in order to obtain maximum high efficiency point. The simulations were made using the GateCycle™ software.

The main parameters considered in the simulations are summarized in Tab. 1.

Table 1. Main common operating parameters to Groups I and II

Air atmospheric temperature	25°C
Atmospheric pressure	1 bar
Condensing pressure (CGEE, 2009)	0.12 bar
Bagasse moisture (Camargo et al. 1990)	50%
Sugarcane fiber content (CGEE, 2009)	14%
Bagasse LHV (CGEE, 2009)	7524 kJ/kg
Bagasse exergy (RENÓ, 2011)	9842 kJ/kg
Boiler thermal efficiency (CGEE, 2009)	85%
Steam turbines isentropic efficiency (Alves, 2011)	84%
Pump isentropic efficiency (CGEE, 2009)	65%
Electric generator efficiency (Souza, 2013)	95%
Biomass for system startup (CGEE, 2009)	10%
Plant operation Days (CGEE, 2009)	167
Mills capacity (Souza, 2013)	500 t/h
Power demand of electric drives of mills (CGEE, 2009)	16 kWh/t
Process electric power consumption (CGEE, 2009)	18 kWh/t
Process steam consumption (BNDES; CGEE, 2008), (HASSUANI et a., 2005)	450 kg/t
Process steam pressure (CGEE, 2009)	2.5 bar
Return temperature of the process (CGEE, 2009)	79°C

4. RESULTS AND DISCUSSION

The simulation results for Groups I and II are shown in Tab. 2 where P_E , \dot{m}_{bag} , \dot{m}_{vap} , P_{el} , P_r correspond to pressure extraction for reheating, bagasse used in boilers, electrical power and dimensionless pressure reheating, respectively.

Table 2. Main results for Group I

	P_E (bar)	\dot{m}_{bag} (kg/s)	\dot{m}_{vap} (kg/s)	P_{el} (MW)	P_r
Basis I	-	33.87	75.59	50,00	-
Reheating Scenarios	60	33.77	74.78	50,00	0.92
	55	33.65	73.75	50,00	0.85
	50	33.53	72.72	50,00	0.77
	45	33.43	71.69	50,00	0.69
	40	33.34	70.66	50,00	0.62
	35	33.28	69.63	50,00	0.54
	30	33.27	68.66	50,00	0.46
	25	33.35	67.77	50,00	0.38
	20	33.55	67.02	50,00	0.31
	15	33.98	66.53	50,00	0.23
	10	34.92	66.68	50,00	0.15

For the Group II the simulation results are shown in Tab 3. For each one of the considered P_E was calculated the dimensionless pressure reheating and the P_{el} available for a fixed bagasse consumption.

Table 3. Main results for Group II

	P_E (bar)	$\dot{m}_{bag.}$ (kg/s)	$\dot{m}_{vap.}$ (kg/s)	$P_{el.}$ (MW)	P_r
Basis II	-	35.00	78.10	52.40	-
Reheating Scenarios	60	35.00	77.50	52.61	0.92
	55	35.00	76.71	52.90	0.85
	50	35.00	75.90	53.16	0.77
	45	35.00	75.05	53.40	0.69
	40	35.00	74.16	53.62	0.62
	35	35.00	73.23	53.78	0.54
	30	35.00	72.22	53.82	0.46
	25	35.00	71.13	53.68	0.38
	20	35.00	69.92	53.24	0.31
	15	35.00	68.53	52.27	0.23
10	35.00	66.83	50.18	0.15	

4.1 Exergetic efficiency for Scenarios with Reheating for Groups I and II.

With the simulation results was possible to calculate the exergetic efficiency for each one of the considered scenarios. The main results are showed in Fig. 6.

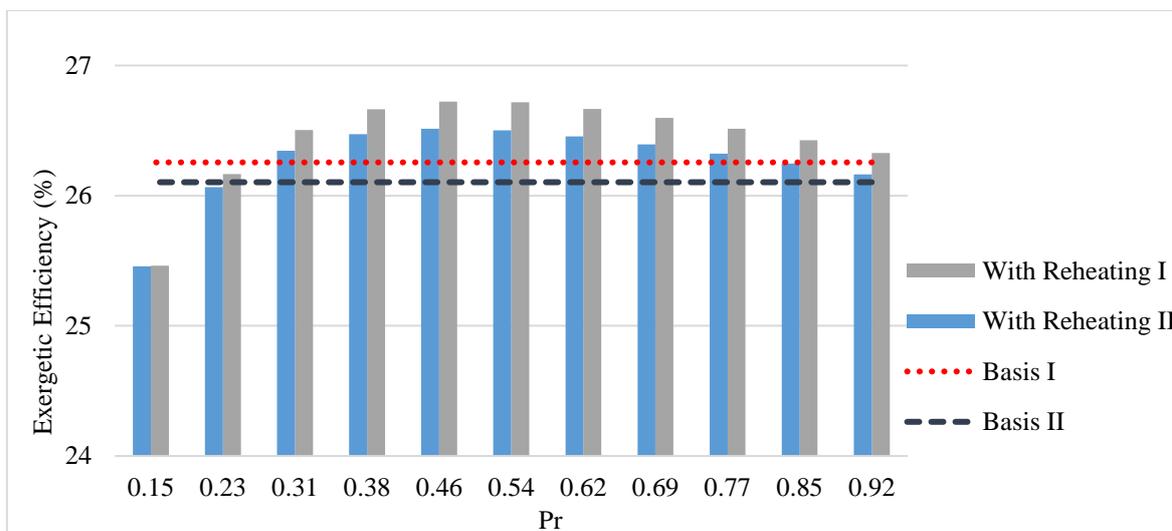


Figure 6. Variation of exergetic efficiency for the scenarios with reheating of the groups I and II.

The behavior of the exergetic efficiency is similar to the results obtained by Badr et al. (1990) in Fig. 2; a concavity the highest efficiency is obtained with a P_r equal to 0.46. Group I showed higher exergetic efficiencies in comparison with Group II; a liquid constant output power causes a reduction in the irreversibilities associated to the steam generation in the boilers. With respect to dimensionless pressure, P_r , close to 1 and close to 0, the irreversibilities generated by reheating start to compromise the cycle efficiency obtaining a smaller value than the conventional cycle. This fact is explained by the fact that this proximity reduces the average thermodynamic temperature of heat addition. For Group I, the base scenario (Basis I) has an exergetic efficiency of 26.26% and is possible to obtain an increase of 1.78% in this value through the implementation of reheating with a P_r of 0.46. For the Group II, the exergetic efficiency of the base case (Basis II) can be improved in 1.55% to pass from 26.10% to 26.51%.

Observes the data that the dimensionless pressure maximum efficiency, 0.46, diverges from the proposed value of approximately one fourth proposed by Nag (2008) and Badr et al. (1990); this fact can be attributed to the characteristics of the studied installation, in which the main factors that justify the discrepancy refer to the adopted configuration process that have a steam demand corresponding to over 80% of the generated steam.

4.2 Differences between expected Group I and II: Bagasse surplus and Electric Power Generated

Having in mind that the main purpose of the Group I is the generation of the surplus bagasse and for the Group II the increase in the electric power capacity of the plant. It was calculate for the Group I the increase in the surplus bagasse with respect to the base case (Basis I) and the results are showed in Fig. 7.

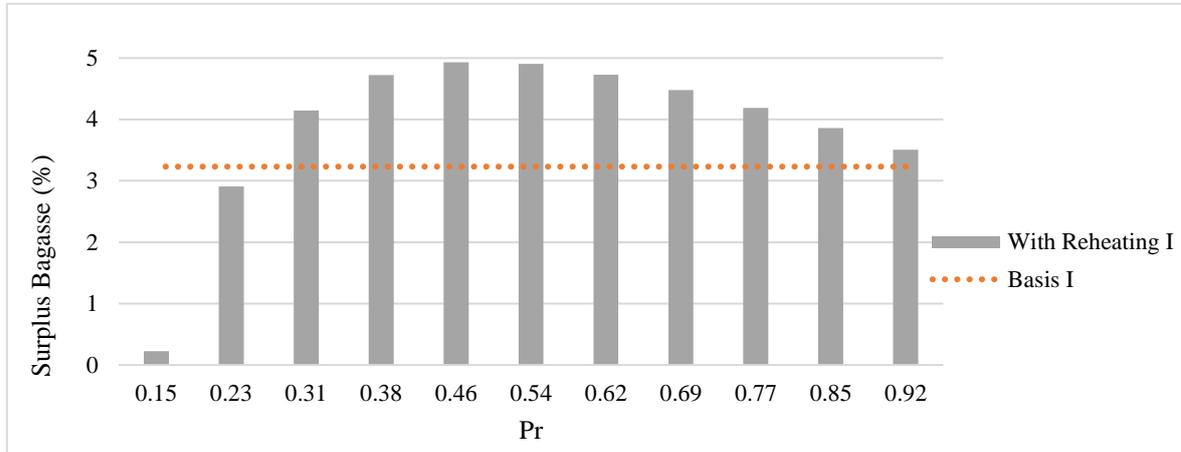


Figure 7. Variation of surplus bagasse for the Group I.

For the Group II, the electric power capacity for different Pr are presented in Fig. 8.

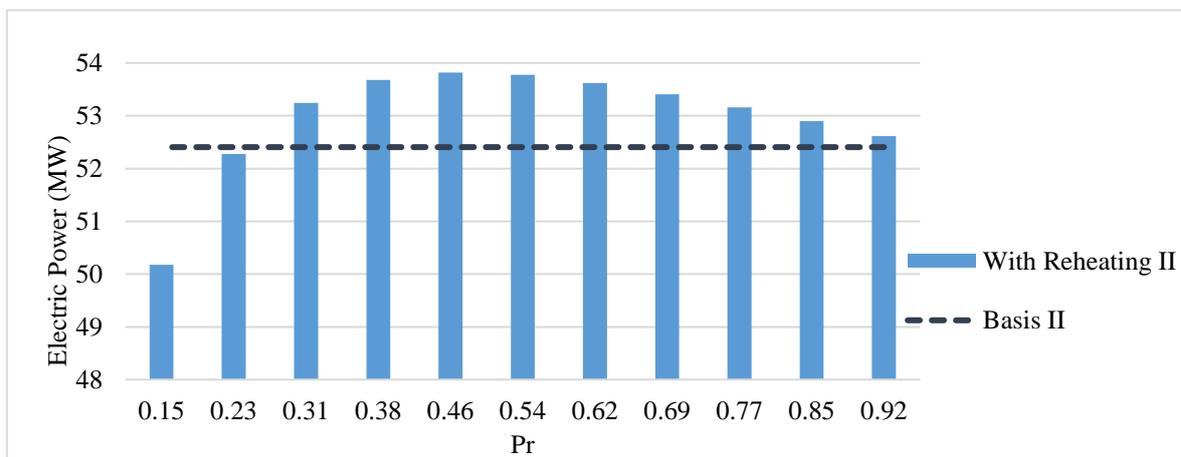


Figure 8. Variation of electric power for the Group II.

Evaluating the Group I and II it is noted that for P_R values decreasing from 1 to 0.46, the rate of surplus bagasse and electric power increase; This is due to the approximation average temperature of heat addition to the cycle, which increases the energy load and hence a higher enthalpic jump. However, it is possible to note that there is a decay in both the surplus bagasse and the electrical power after the inflection point, since from this value by reducing the extraction pressure would lead to a large temperature differential and consequently a high level of irreversibilities reducing average temperature of heat addition; P_r lower values of approximately 0.25 for Group I and Group II 0.24 to lead electric power values and surplus bagasse lower than the respective reference scenarios.

The base scenario for Group I (Basis I) has a bagasse consumption rate of 33.87 kg/s and its possible to obtain an increase of 1.79% with a P_r of 0.46. The power installed capacity in the basis scenario for the Group II is 52.41 MW and 53.82 MW for the best P_r ratio, representing an increase of approximately 2.70%.

With respect to the steam quality was obtained an increase of 0.898 to 0.943. This improves the operational conditions of the plant, preventing erosion of the turbine blades (Badr et al., 1990; Souza, 1980; Nag, 2008).

5. CONCLUSIONS

The incorporate of reheating systems in cogeneration cycles in Brazilian sugarcane mills was evidenced, since the increased surplus bagasse enables the use of this material to generate greater power surplus or as raw material in the second generation production of alcohol, in the manufacture of paper and agglomerate panels and various other processes.

The methodology enabled to view earnings, is aiming to sell the surplus bagasse or comprehensive employment generating steam. Added to this, it showed the influence of the extraction process for the dimensionless pressure reheat, Pr.

The analysis indicated improvements in cycle performance when implemented reheating; was obtained as a percentage increase over the pomace to 1.79% and 1.86% in the electrical power for reheating pressure ratio Pr equal to 0.46 in the groups I and II. Added to this one of the main advantages obtained by reheating the rise of the end title of the expansion 5.0%.

6. ACKNOWLEDGMENTS

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