EXERGY ANALYSIS OF ADVANCED COGENERATION PLANTS FOR SUGARCANE MILLS: SUPERCRITICAL STEAM CYCLES AND BIOMASS INTEGRATED GASIFICATION COMBINED CYCLES

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Abstract. *Back in 1970's and 1980's, cogeneration plants in sugarcane mills were primarily designed to consume all bagasse, and produce steam and electricity to the process. The plants used medium pressure steam boilers (21 bar and 300°C) and backpressure steam turbines. Some plants needed also an additional fuel, as the boilers were very inefficient. In those times, sugarcane bagasse did not have an economic value, and it was considered a problem by most mills. During the 1990's and the beginning of the 2000's, sugarcane industry faced an open market perspective, thus, there was a great necessity to reduce costs in the production processes. In addition, the economic value of by-products (bagasse, molasses, etc.) increased, and there was a possibility of selling electricity to the grid. This new scenario led to a search for more advanced cogeneration systems, based mainly on higher steam parameters (40-80 bar and 400-500°C). In the future, some authors suggest that biomass integrated gasification combined cycles are the best alternative to cogeneration plants in sugarcane mills. These systems might attain 35-40% efficiency for the conversion of power. However, supercritical steam cycles might also attain these efficiency values, what makes them an alternative to gasification-based systems. This paper presents an exergetic comparative study of these systems for sugarcane mills. The configurations studied are based on real systems that could be adapted to biomass use. Different steam consumptions in the process are considered, and the possibility of producing power during the whole year is evaluated.*

Keywords*: cogeneration, sugarcane mills, gasification, supercritical cycles*

1. INTRODUCTION

For more than 60 years, from the beginnings of 1930's until the middle 1990's, the Brazilian sugar and ethanol industry was strongly regulated by the government. The former Sugar and Ethanol Institute ("Instituto do Açúcar e do Álcool" – IAA) was responsible for the production volumes as well as the amount of sugarcane to be processed in each mill. With the de-regulation of the sector in the late 1990's, sugar and ethanol producers faced a competitive market, which led them to seek product differentiation strategies and/or diversification of their production sets (Vian, 2005).

In the harvest of 2006/07, almost 426 million tons of cane will be crushed in Brazil, producing 30.2 million tons of sugar and 17.6 millions of m³ of ethanol. The Centre-South region is responsible for 87% of the national production (368.7 million tons of cane), producing 25.4 million tons of sugar and 15.8 millions of m³ of ethanol (CONAB, 2006). The total capacity installed in the sector is 3000 MW, from which 2400 MW for internal use and 600 MW for commercialization. In 2006, 4200 GWh of electricity from sugarcane were commercialized in Brazil (UNICA, 2006).

Reviewing these numbers for previous harvests, it is possible to see that the sugar and alcohol industry is gaining more and more importance over the last years. This increase is a result of the new incentives for the alcohol market and high prices of sugar from cane in international markets.

Accompanying this growth, an effort is being made to improve the use of energy in the industrial production and in cogeneration facilities.

Back in 1970's and 1980's, cogeneration plants in sugarcane mills were primarily designed to consume all bagasse, and produce steam and electricity to the process. The plants used medium pressure steam boilers (21 bar and 300°C) and backpressure steam turbines. Some plants needed also an additional fuel, as the boilers were very inefficient. In those times, sugarcane bagasse did not have an economic value, and it was considered a problem by most mills.

Today, bagasse-fired boilers raise steam to 300°C and 21 bar that is used in backpressure turbines, responsible for the electromechanical demands of the mill. Backpressure steam (2.5 bar) is used to fulfill the thermal requirements of the process, and its condensate is returned to the boiler. Normally, the electromechanical energy produced is for internal use only. However, some mills already use steam with higher parameters (42 – 66 bar), generating an excess of electricity that is sold to the grid. Also, there is a tendency in the sector to replace old boilers by new ones with greater capacity (82 bar, for instance).

In the future, some authors suggest that biomass integrated gasification combined cycles (BIGCC) are the best alternative to cogeneration plants in sugarcane mills. These systems might attain 35-40% efficiency for the conversion of power (Ogden et al., 1990, Wlater, 1994, Souza-Santos, 1997, Arrieta et al., 2001, Larson et al., 2001, Hassuani et al., 2005, Pellegrini and Oliveira Jr., 2007a).

Supercritical steam cycles might also attain these efficiency values, what makes them an alternative to gasification-based systems (Béer, 2007). Different works discuss the use of supercritical power plants as an alternative to integrated gasification combined cycles (DOE, 1999).

This paper presents an exergetic comparative study of these systems for sugarcane mills. The configurations studied are based on real systems that could be adapted to biomass use. Different steam consumptions in the process are considered, and the possibility of producing power during the whole year is evaluated.

2. SUPERCRITICAL STEAM POWER PLANT TECHNOLOGY

Supercritical steam means steam at temperatures and pressures above the critical point, Tc =647 K = 374 °C and Pc = 22.1 MPa.

According to Beér (2007), Supercritical Plants have been in use since the 1930's, mainly in Europe. In the US, supercritical plants were first developed in the 1950's and 1960's. The first units, however, experienced problems related to reliability and operational flexibility and subcritical pressure units became the US norm. Despite that, development continued overseas and there is now little differences in reliability between subcritical versus supercritical units (Richardson et al., 2005).

Improvements in materials, and the increasing demand for high efficiency power generation units are making supercritical the choice of new coal-fired utility plant world wide (Beér, 2007). The US Department of Energy (DOE) developed a report on advanced power generation technologies from coal in order to provide economic data and supporting analyses in determining commercially mature costs for clean coal technologies through evaluation and correlation to the cost improvement trends of the state-of-the-art PC and gas turbine power plants (DOE, 1999). Also, the UK Department of Trade and Industry (DTI) developed a report on advanced power plant using high efficiency boilers and turbines, showing the most recent achievements of researches on supercritical power plants (DTI, 2006).

Most supercritical units commissioned during the 1960's and 1970's operated with steam parameters in the 250 bar range and steam temperature of 540°C to 560°C, with single and double re-heat. However, in 1957, a 310 bar and 621°C double reheat (565°C/538°C) was designed, and put into operation to demonstrate the feasibility of supercritical pressure cyles. The plant operated until 1979 (Smith, 1998).

In the early 1990's, the Japanese were the first to put a supercritical plant operating with temperatures near 600°C (Jin et al., 1997 and Bugge et al., 2006). By the late 1990's, the Ultrasupercritical (USC) concept was introduced, and steam parameters raised to 290 bar range and temperatures around 600°C. Bugge et al. (2006) present data for different ultrasupercritical steam plants in service or under construction, called by the authors '600°C' power plants. The efficiencies reported vary from 40% to almost 50% (LHV) for a single reheat (580°C/600°C) 300 bar plant, located in Denmark.

A '700°C' steam power plant will be constructed during the next 7 – 10 years constituting a benchmark for a 50% efficiency (LHV) coal-fired power plant (Beér, 2007). The technical realisation of a '700°C' steam power plant depends on a successful development and qualification of advanced ferritic, austenitic and Ni-based alloys (Bugge et al., 2006).

In what follows a brief discussion about the main aspects of the supercritical power plant technology will be presented.

2.1. Boiler Technology

Mark Benson made the first significant commercial applications of once-through boilers in the 1920's and 1930's, providing two units to operate at critical pressure. Mark Benson's concept was ultimately acquired by Simens, who further developed the concept, and now licenses this technology worldwide (Smith, 1998).

The once-through boiler is the only type suited to supercritical-pressure operation, as liquid and vapour are one and the same, so no separation in a drum is possible or necessary. In contrast to drum type boilers, the feedwater goes through the economizer, furnace walls, and superheater sections, changing sequentially to saturated water, saturated steam and superheated steam in one continuous pass (see Fig. 1). Also known as Benson boiler or Universal-Pressure (UP) boiler, the main characteristics of this technology are: the evaporation endpoint shifts automatically within one or more heating surfaces depending on operating conditions, and another one is that the system can be operated at subcritical or supercritical pressures (El-Wakil, 1984).

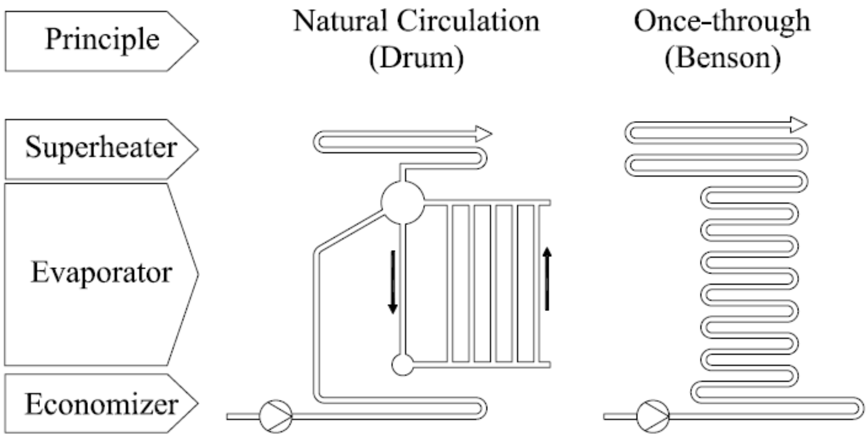

Figure 1 – Water/Steam Path in Drum Boilers and Once-through Boilers.

Figure 2 shows the two main configurations for supercritical boiler to date: single-pass and two-pass design. Both two-pass and tower (single-pass) boiler designs are widespread, with two-pass the market leader. All lignite-fired plant utilise a tower boiler principle. European bituminous coal-fired plant of both types are common, but Japanese and US plant are normally of the two-pass design (DTI, 1999).

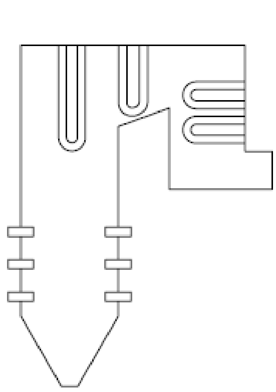

Figure 2. Two configurations for the supercritical boiler to date: a) two-pass design and b) tower design.

Another interesting aspect regarding the design of the boiler is tubing arrangement in the combustion zone. The most popular one is the spiral wound furnace, which uses a relatively high mass flux to provide adequate cooling of the furnace walls. New concepts are using vertical tube design, using vertical internal ribbing in the tubes to improve heat transfer. The main advantage of such design is the reduced pressure loss across the boiler, improving the overall efficiency (DTI, 1999 and 2006, Lundqvist, 2003).

Still, the most important point to be considered, regarding the supercritical boiler technology, is materials. The various components of the boiler are employed over a range of temperatures, and pressures and corrosive atmospheres, and oxidation conditions; thus, the development of improved materials for supercritical steam conditions is a task extremely important that researchers are working on. The range of alloys necessary to best meet the design demands covers the simple carbon manganese (CMn) steels, the 9-12Cr martensitic family and the austenitic range with chromium varying from 18 to in excess of 25% (DTI, 2006).

Paul (1999) states that steam conditions up to 30 MPa/600oC/620oC are achieved using steels with 12% chromium content. Up to 31,5 MPa/620oC/620oC is achieved using austenitic steels, which is a proven, but expensive material. In addition, Ni-based alloys would permit 35 MPa/700oC/720oC, yielding efficiencies up to 48%. Bugge et al. (2007) discusses the new developments that are taking place regarding new materials to attain temperatures of 700°C.

Circulating fluidized bed (CFB) boiler technology based on natural circulation has reached utility scale over the last decade. Plants sizes up to 300 MW_e are in operation. A natural development is to take the technology a step further with larger sizes and supercritical steam parameters. CFB boilers have features that make them advantageous to use in a once-through mode. One advantage of the CFB is its insensitiveness to fuel composition variations and its fuel flexibility. CFB boilers have the potential to extend the limits of the technology and also further reduce emission levels. The CFB process also has a number of merits when applying supercritical once-trough boilers technology. In particular, the nature of CFB combustion results in low and uniform heat flux, due to relatively low combustion temperature and uniformity of temperature resulting from the circulating solids in the furnace. Although it can seem self evident that circulating solids provide a thermal wheel, smoothening out any temperature spikes, it has to be proven under all types of conditions to ensure that overheating of the furnace tubes cannot take place (Lundqvist, 2003).

All in all, supercritical boiler technology has matured, through advancements in design and materials. However, the state-of-the-art steam generator technology still has considerable potential for further development to achieve pressures of 350 bar and temperatures in 700°C range.

2.2. Turbine Technology

Although the steam turbine remains unchanged in its basic principle of operation over nearly 150 years of industrial service, this device has experienced a continuous development through the years. Early steam turbines produced at the turn of the 20th Century were designed for inlet pressures and temperatures of approximately 13.7 bar and 260°C, respectively. Nowadays, such turbines are designed for inlet conditions of 300 bar and 600°C, with single or double reheat (Retzlaff and Ruegger, 1996, Bugge et al., 2006).

The design of a steam turbine set for supercritical applications depends on the number of reheats selected, unit rating and site backpressure characteristics. For a single reheat and a power output in the range of 600-1000 MW, a typical turboset design will consist of three separate turbine modules operating at different pressure and temperature levels. These modules are: the high pressure turbine (HP), the intermediate pressure turbine (IP) and up to three low pressure turbines (LP). Figure 3 shows a 600-1000MW-class turboset from Siemens (Rosenkranz and Wichtmann, 2005).

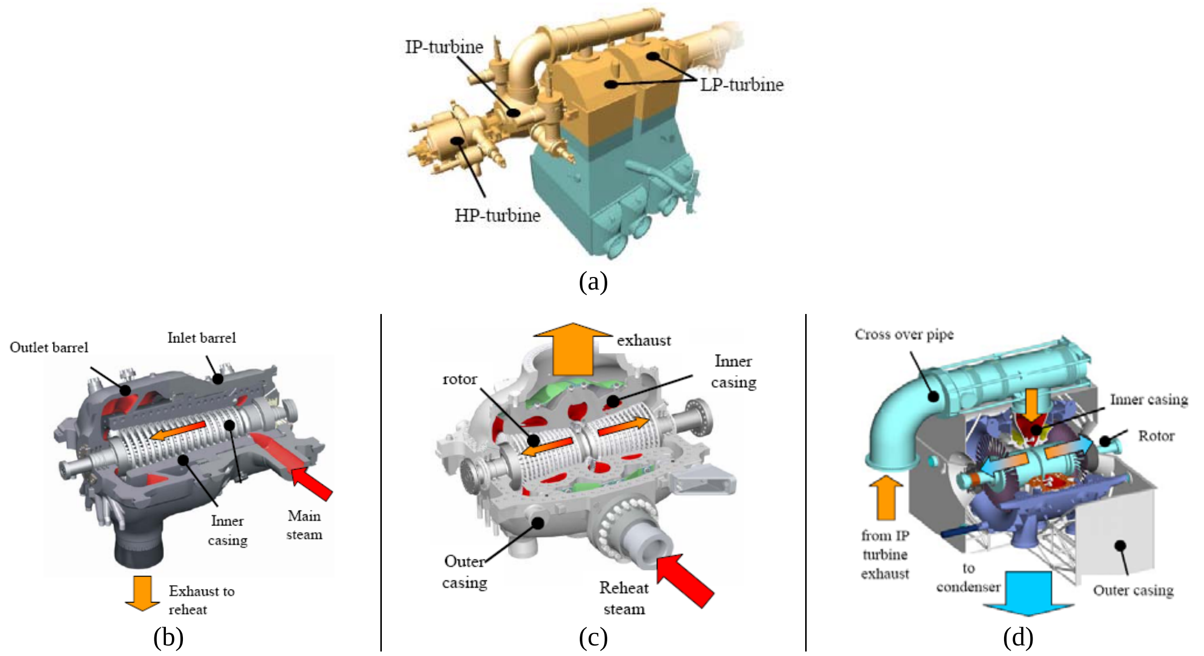

Figure 3. (a) 600-1000MW-class turboset. (b) Barrel-type high pressure turbine (HP). (c) Intermediate pressure turbine (IP). Low pressure turbine (LP) (Rosenkranz and Wichtmann, 2005).

The basic design principle for the HP turbine, capable to cope with supercritical main steam conditions, is the barrel type outer casing design. Today, this design can enable 300 bar and 600°C. The high temperature components such as the inlet barrel, rotor and inner casing are made out of 9-12 % CrMoV steel. The barrel type outer casing has a vertical casing split which can handle highest pressure loadings by adopting the wall thickness. The IP turbine is designed to take reheat steam conditions of 620°C. The rotor and inner casing are made of 9-12 % CrMoV-steel. The high steam temperature can be handled by reducing the rotor surface temperature by the principle of Vortex cooling. This cooling principle enables a temperature decrease due to the reduction of relative steam velocity at the rotor surface up to 20 Kelvin. In addition the first blade stages are made of Nickel-based-alloyed steel to withstand the centrifugal load in combination with high temperatures. On the other hand, the LP turbine consists of a double flow with a horizontal split casing. The typical steam conditions are up to 7 bar and 350°C. The steam will expand to the condenser at condenser pressures in the range of 30 - 100 mbar. Furthermore, special care has to be taken to the appropriate choice of LP turbine exhaust area and design because of the high volumetric flow rates. The development of optimal last stage blade families and long last stage blades is the key for reasonable exhaust areas, i.e. reduced exhaust losses (Rosenkranz and Wichtmann, 2005).

According to the report from UK DTI (2006), today's state-of-art steam turbines are based on the exploitation of advanced 9-12% Cr martensitic steels for rotors and casings, with nickel-based alloys or high-strength austenitic steels being required only for the early stages of blading.

Korobitsyn (1998) argues that modern supercritical Rankine plants with reheat and regeneration that operate at temperatures of 600 °C and pressures of 350 bar obtain an efficiency not higher than 48–49%. Rosenkranz and Wichtmann (2005) and Bugge et al. (2006) state that continuing development effort over the next decade will allow steam turbine operating at temperatures of some 700°C, giving a thermal efficiency of 56 per cent and net efficiency of 51 per cent. However, the thermodynamic benefit of increased main steam pressure at a given temperature is subject to diminishing returns in the efficiency, since the reduction on the volumetric flow at these conditions leads to shorter and wider turbine blading that is subject, on a relative basis, to higher passage boundary losses and increased steam path leakage. Such losses offset the thermodynamic benefits of elevated steam conditions with increased steam pressure (Avrutskii et al, 2005, DTI, 2006).

Rosenkranz and Wichtmann (2005) states that objective of power plants within today’s market boundaries is more than ever to ensure high efficiency (to reduce the environmental impact as much as possible) while at the same time to increase their economics in competition to existing alternatives. The development of an economical and efficient concept needs to look at all other main components of the plant, like boiler, flue gas cleaning equipment, steam turbines and the optimization of the water-steam-cycle.

Retzlaff and Ruegger (1996) evaluates feedwater heater selection and final feedwater temperature, warranting that in order to maximize the heat rate gain possible with supercritical steam conditions, the feedwater heater arrangement also needs to be optimized. Thus, the selection of higher steam conditions will result in additional feedwater heaters and an economically optimal higher final feedwater temperature. Design characteristics of feedwaters heater for supercritical steam power plant can be found in El-Wakil (1984) and Drbal and Boston (1996). Under consideration of a cost-effective heating surface design, feedwater temperatures should not exceed 300°C (Franke and Kral, 2003).

Avrustkii et al. (2005) analyzes the use of reheats in supercritical steam power plants. The authors indicate that, for a preliminary estimative, the reheat pressure can be set to 40 bar, from the standpoint of maximum efficiency. Considering the number o reheats, it has been long understood that improved plant performance is possible by employing a double, rather than a single, reheat cycle. However, from the use of double reheat, some problem arise, such as increased cost attributable to greater equipment complexity in the boiler, piping systems and steam turbine (Retzlaff and Ruegger, 1996). According to Avrustkii et al. (2005), as a rule double reheat should be used in units where very low temperature of cooling water is available and hence very low pressure in the condenser. The second reheat is necessary to avoid high final moisture content.

The potential improvement in the efficiency of a steam-based plant due to modifications in the thermodynamic parameters of the system is presented in Tab. 1 (Avrustkii et al., 2005).

Table 1. Relative growth in efficiency.

Increase in the temperature of live steam	0.02% / 1°C
Increase in the pressure of live steam	0.01% / 1 MPa
Increase in the reheat temperature	0.015% / 1°C
Use of second reheat	1.2%
Decrease in the pressure in condenser	1% / 1 MPa
Increase in the temperature of feed water	0.02% / 1°C

Compared to the development costs of advanced gas turbine technology, the levels of investment in research and development covering supercritical steam turbines are regarded as being relatively modest, but result in significant improvements in both fuel efficiency and stack emissions (Ashmore, 2006).

Paul (1999) shows how there is a misconception in that the components of supercritical power plants can only be designed and manufactured in developed countries due to the complexity of the technology. The work remarks that the differences in the technology between subcritical and supercritical power plants are limited to small number of components. The author mentions China and India, where there is already large manufacturing capacity in the components that are specific to supercritical.

2.3. Applicability to biomass-based plants

On the one hand, co-firing biomass with coal, in comparison with single coal firing, helps reduce the total emissions per unit energy produced. Coal and biomass fuels are quite different in composition. Cofiring biomass with coal has the capability to reduce both NOx and SOx levels from existing pulverized-coal fired power plants. Cofiring may also reduce fuel costs, minimize waste and reduce soil and water pollution depending upon the chemical composition of the biomass used (Demirbas, 2004).

On the other hand, biomass composition can differ considerably, especially with respect to its inorganic constituents (ash), and their concentration is of great importance regarding the critical problems of fouling and slagging. Alkali and alkaline earth metals, in combination with other fuel elements such as silica and sulfur, and facilitated by the presence of chlorine, are responsible for many undesirable reactions in combustion furnaces and power boilers. Reductions in the concentrations of alkali metals and chlorine, created by leaching the elements from the fuel with water, yield remarkable improvements in ash fusion temperatures (Jenkins et al., 1998). During combustion, the mineral matter transforms into ash, which may deposit on the heat transfer surfaces or other surfaces of the equipment. These phenomena are described as slagging (if the deposit is in a molten or highly viscous state) or fouling (if the deposit is built up by species that have vaporized and subsequently condensed) (Walter and Llagostera, 2007).

More over, biomass has a high moisture content and low density, leading to a high consumption in the furnace in order to provide all the heat required in supercritical plant. Hence, it is very important to seek for decreasing the moisture content in the biomass, using flue gases from the boiler, for instance.

In this sense, the applicability of supercritical power plants fired with biomass should be evaluated based on the availability of the biomass, its composition and combustion characteristics. Regarding the combustion of biomass, the use of CFB boilers seems to be the best possibility due to its flexibility regarding low grade fuels.

3. BIOMASS INTEGRATED GASIFICATION COMBINED CYCLE TECHNOLOGY

The biomass integrated-gasifier/gas turbine combined cycle (BIGCC) technology was first identified over a decade ago as an advanced technology with the potential to be cost-competitive with conventional condensing-extraction steam-turbine (CEST) technology using biomass by-products of sugarcane-processing as fuel, while dramatically increasing the electricity generated per unit of sugarcane processed (Larson et al., 2001).

Over the last 15 years, many different works arise that dealt with the different aspects regarding the applicability of BIGCC systems to sugarcane mills (Ogden et al., 1990, Wlater, 1994, Souza-Santos, 1997, Arrieta et al., 2001, Larson et al., 2001, Hassuani et al., 2005, Pellegrini and Oliveira Jr., 2007a).

Other works discussed the combined use of biomass derived gas and natural gas in cogeneration plants in order to overcome some difficulties related to BIGCC plants (Rodrigues et al., 2003, Zamboni et al., 2005, Zanetti et al., 2007, Walter and Llagostera, 2007).

The basic elements of a BIGCC power plant include a biomass dryer (ideally fueled by waste heat), a gasifier for converting the biomass into a combustible fuel gas, a gas cleanup system, a gas turbine-generator fueled by combustion of the biomass-derived gas, a heat recovery steam generator (HRSG) to raise steam from the hot exhaust of the gas turbine, and a steam turbine-generator to produce additional electricity (Larson et al., 2001).

In what follows a brief discussion about the main aspects of the BIGCC technology will be presented.

3.1. Gasification Technology

One possible definition for gasification is: a thermo-chemical process in which a solid/liquid fuel is converted, due to the addition of heat in a sub-oxidizing atmosphere, into a mixture of gases (produced gas) with low calorific value, composed mainly by H_2 and CO (Pellegrini and Oliveira Jr, 2007a).

Such process takes place in equipment called gasifier, which may be classified in different ways: atmospheric or pressurized, fixed bed or moving bed (fluidized bed), direct heated (air or oxygen blown) or indirect heated. Small scale system, with biomass as fuel, uses atmospheric direct-heated fixed-bed gasifiers coupled to an internal-combustion (IC) engine. As for large scale systems, using gas turbines, fluidized bed are preferred and different designs are available. Fluidized-bed gasifiers have higher throughput capabilities than fixed-beds, including the ability to handle low-density feedstocks like undensified crop residues Their ability to handle a wide range of biomass fuels with minimal preprocessing gas specifications may ultimately make fluidized-bed gasifiers the technology of choice for many biomass feedstocks (Larson and Williams, 1996).

Consonni and Larson (1996) described and analyzed the main designs available for gasifiers to be applied in BIGCC plants. Table 2 shows a comparison of these designs. Since the middle 1990's, some pilot plant have been commissioned and operated in order to show the technical feasibility of BIGCC systems. Among them, the Värnamo (Sweden) might be considered the most important one, being operated for several thousand hours from 1995 to 2000. Other pilot-plants are cited by Consonni and Larson (1996).

Hussuani et al. (2005) present a complete analysis of a cogeneration plant based on a near-atmospheric air-blown gasifier, applied to a sugarcane mill. This work has shown the results of the gasification of sugarcane bagasse and trash for different conditions of the biomass, as well as, results for the cleanup system.

In the literature, different approaches to model the gasification process are available based both on chemical equilibrium consideration and kinetic aspects. These models intend to predict the composition of the produced gas, its temperature, among other characteristics (Pellegrini and Oliveira Jr., 2007b).

Table 2. Relative advantages and disadvantages of BIGCC systems based on three different gasifier designs (Larson et al., 2001)

Gasifier design	Advantages	Disadvantages
Low-pressure, air blown	➢ Easier fuel feed to gasifier ➢ Conventional gas cleaning equipment ➢ Economically suited for modest size	➢ Waste water produced from gas cleaning system ➢ Fuel gas compressor adds cost, reduces efficiency ➢ Limited economically to modest size
Low-pressure, indirectly-heated	➢ Easier fuel feed to gasifier ➢ Conventional gas cleaning equipment ➢ Economically suited for modest size ➢ Higher energy content fuel gas	➢ Waste water produced from gas cleaning system ➢ Need fuel-gas compressor, but smaller than Variant 1 ➢ Limited economically to modest size ➢ Gasifier operation more challenging than air blown ones
High-pressure, air blown	➢ Higher efficiency due to lack of gas compressor ➢ Dry hot-gas cleanup system ➢ Economically suited to larger scale than others	➢ More difficult fuel feed to gasifier than others ➢ More challenging gas cleaning than others ➢ Higher NOx emissions than others ➢ Limited economically to larger scale

Aside from the choice of gasification technology, some of the key tradeoffs involved in designing and commercializing BIGCC systems relate to atmospheric versus pressurized gasification, hot versus cold atmospheric cleanup, the adaptability of commercial gas turbines, and the integration between the dryer, the gas production equipment, and the turbomachinery (Consonni and Larson, 1996).

A pressurized gasifier will produce gas at a pressure suitable for direct turbine application and provide the highest overall process efficiency (avoids the need for a produced gas compressor). To take full advantage of operating pressure, however, a number of ancillary systems must be developed. Reliable, high pressure feed systems have not been commercially proven (Bain et al., 1998).

3.2. Gas Cleaning

Gas turbine will impose constraints on the level of particulates, alkali metals, and condensable tars in the produced gas delivered to the gas turbine combustor. Particulates can cause turbine blade erosion, as well as alkali metals. If tars condense on cool surfaces, severe operating problems can result, including constricted piping or clogged valves and filters. Furthermore, tars have relatively high heat contents and can be burned in combustors, thus removing them from the gas would result in a loss of efficiency. Two approaches have been considered for gas cleaning station: hot and cold.

In the hot cleanup, considered mainly for pressurized gasification, the system must remove those impurities from the hot product gas without lowering the temperature below the tar dew point, typically about 538°C. Thus, before the removal of alkali metals and particulates, the gas must pass through a tar cracker. After the tar cracker the produced gas will be partially cooled to minimize the amount of alkali vapors, typically to 538–649°C. The product will then pass through a ceramic filter to remove solids. Such processes avoid thermodynamic penalties related to lowering too much the gas temperature and additional power to compress the produced gas.

In the cold cleanup, a tar cracker will probably be used to minimize the amount of tars which must be handled during quenching. As these system are mainly used for near-atmospheric gasifiers, the waterand tar content must be low enough to ensure no condensation during compression, and the gas inlet temperature must be suitable for compressor materials of construction. Normally, the temperature should be held below about 93°C.. Usually, a combination of heat exchange, to reduce the gas from tar cracker exit temperature to residual tar dewpoint, and wet scrubbing will be used. The water vapor content will be at saturation at scrubber exit temperature and pressure (Consonni and Larson, 1996, Bain et al., 1998).

3.3. Gas Turbine

Three issues must be considered in assessing the suitability of produced gas for gas turbines: combustion stability, magnitude of pressure loss through the fuel injection system, and mass flow limits through the turbine. Due to the lower energy content of the produced gas, the gas turbine combustor must accommodate a larger volumetric flow of gas to achieve an equivalent same energy release (Consonni and Larson, 1996).

According to those authors, can-type combustors used in many industrial turbines generally provide adequate cross section and volume for complete and stable combustion with acceptable pressure drops. Moreover, commercial applications are available for the last three decades using blast furnace gases. However, there has been no commercial operating experience with aero-derivative gas turbines. Regarding the pressure loss associated with the injecting the large fuel volume, some turbines may need re-designed nozzles.

Gas turbines operate under choked flow conditions at the expander inlet, hence larger mass flows may only be accommodated by increasing the pressure ratio in the compressor or decreasing the turbine inlet temperature. The first option may move the compressor towards its stall limit. On the other hand, decreasing the inlet temperature (de-rating) implies in lower thermodynamic efficiencies.

Walter et al. (1998) and Rodrigues et al. (2003) evaluated the performance of gas turbine operating with produced gas, considering different control strategies (de-rating, close inlet guide vanes and blast-off). Pressurized gasification, blast-off operation is a good option, since the mass flow of air needed for gasification is approximately equal to the produced gas mass flow, hence the mass flow through the compressor will be almost equal to the mass flow to the turbine (Consonni and Larson , 1996).

3.4. Auxiliary Equipment

Several opportunities arise for integrating the gasification and power islands in BIGCC systems. Consonni and Larson (1996) provide different configurations, based on different gasifier designs, with thermal integration among the equipment in order to recovery heat.

4. EXERGY ANALYSIS OF ADVANCED COGENERATION PLANTS FOR SUGARCANE MILLS

In order to investigate the performance of the different energy conversion processes, a global model of the co-production of sugar, alcohol and electricity was developed (Pellegrini and Oliveira Jr., 2007b). The model allows the evaluation of different configurations of the co-generation system, as well as, of the heat exchanger network inside the mill. Besides that, the model allows the evaluation of the exergy-based production costs of each of the products.

Figures 4 and 5 show the schematic representation of the Supercritical Steam Power Plant (SuST) and of the BIGCC configurations used in the simulation.

The SuSt configuration presented in this paper is based on Jin et al., (1997) and Drbal and Boston (1996), with 6 regenerative heat exchangers and single reheat. The boiler efficiency is set to 88% (LHV basis), and the exhaust gases are used to dry the bagasse.

The BIGCC configuration is based on Zanetti et al. (2007), using the gasification model developed in (Pellegrini and Oliveira Jr., 2007a). The simulations are based on design parameters of the ALSTOM GT11 gas turbine, and the Heat Recovery Steam Generator design parameters are: pinch point of 10°C and approach point of 5°C. The exhaust gases from the HRSG are used to dry bagasse and trash before it is sent to the gasifier.

For the evaluation of both systems, modifications in the heat exchanger network were made in order to decrease the steam consumption (Avram et al., 2003 and Pellegrini and Oliveira Jr., 2006).

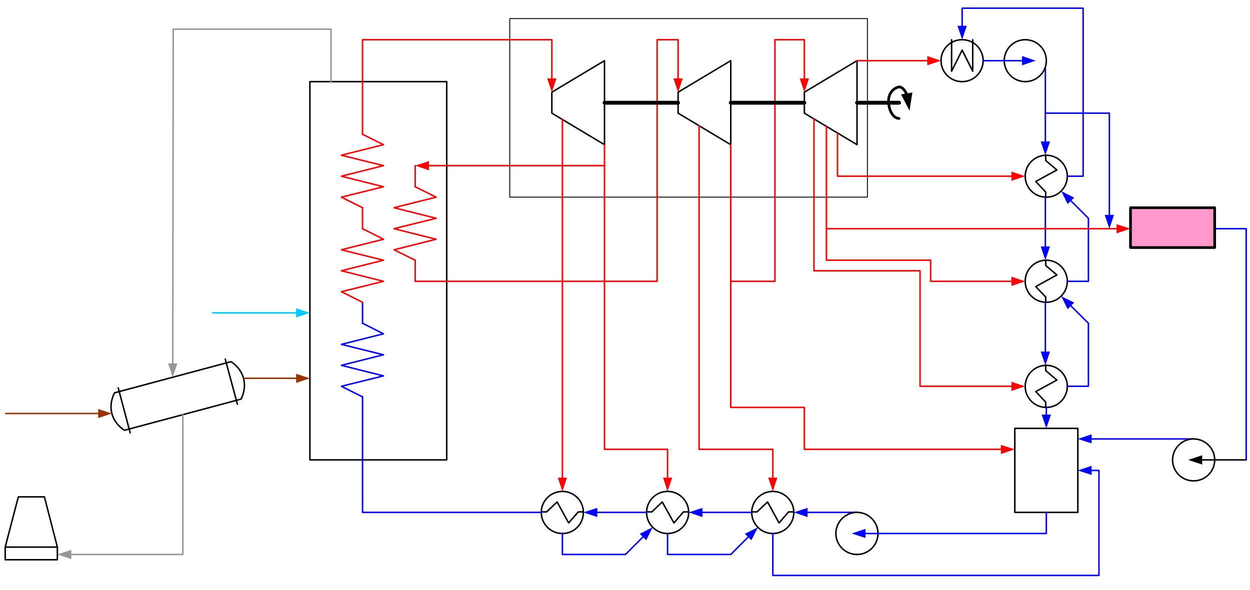

Figure 4 - Schematic representation of the SuST

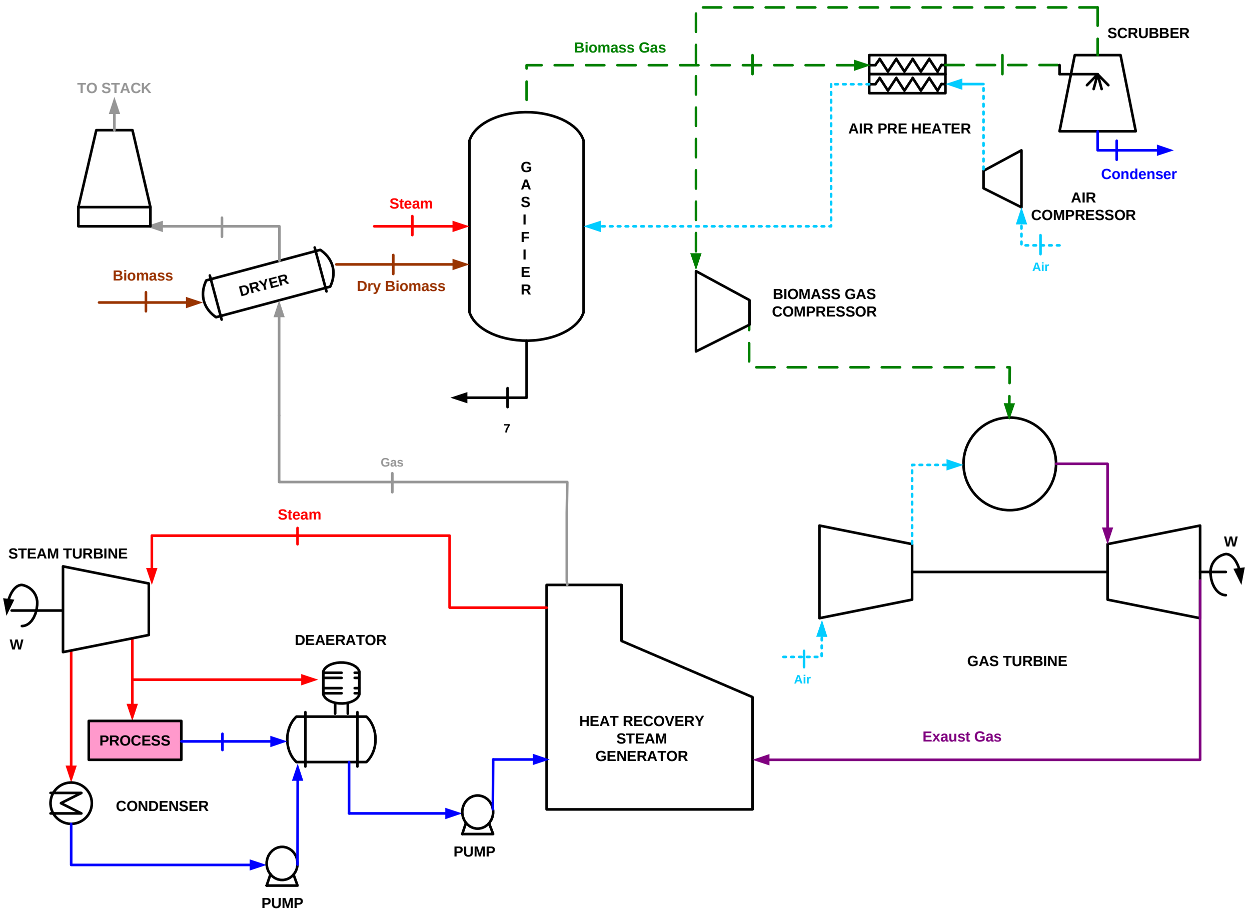

Figure 5 - Schematic representation of the BIGCC

Table 3 shows characteristic parameters of the analyzed systems, considering electricity generation only during the harvest (7 months for Centre-South), and no trash recovery.

Table 3 – Comparison of different cogeneration plants, during harvest season

Parameters	Typical Mill	SuST	BIGCC
Steam Temperature (°C)	300	590 / 590*	400
Steam Pressure (bar)	21	292	42
Specific Steam Consumption (kg/tc)	536	383	296
Specific Excess Electricity Generated (kWh/tc)	0	141	157
Specific Consumption of make-up water in the condenser (m³/tc)	-	0.18	0.03
Sugar Exergy-based Cost (kJ/kJ)	1.54	1.23	1.20
Ethanol Exergy-based Cost (kJ/kJ)	2.84	1.76	1.74
Electricity Exergy-based Cost (kJ/kJ)	-	3.17	2.66

*superheated / re-heated

It is possible to show a decrease in the exergy-based cost of all products with the use of more advanced systems. Regarding the exergy-based cost of sugar and ethanol, their values present a decrease of 20% for sugar and 38% for ethanol (related to a typical mill). Comparing the SuST system with the BIGCC system, there is a 10% difference (higher for the BIGCC) in the electricity generation, while the steam consumption is 22% lower for the BIGCC. Also, the water consumption of SuST is higher, however the water consumption for the cleanup gas station in BIGCC was not considered.

If electricity generation during the whole year is considered, then SuST and BIGCC configurations need a complementary fuel (sugarcane trash), as all bagasse would be consumed during the milling season. The amount of sugarcane trash available for electricity generation is set in 80 kg of dry matter/tc with 15% moisture (dry basis). These values are for baled trash with a recovery efficiency of 57% (Hassuani et al., 2005).

Table 4 shows the results for the CEST, SuST and BIGCC configurations, considering the generation of electricity during the whole year.

Table 4 – Comparison of different cogeneration plants, during whole year

Parameters	SuST	BIGCC
Steam Temperature (°C)	590 / 590*	400
Steam Pressure (bar)	292	42
Specific Steam Consumption (kg/tc)	383	294
Specific Excess Electricity Generated (kWh/tc)	145 / 195**	153 / 198**
Specific Consumption of make-up water in the condenser (m³/tc)	0.21 / 1.38**	0.02 / 1.00**
Sugar Exergy-based Cost (kJ/kJ)	1.22	1.19
Ethanol Exergy-based Cost (kJ/kJ)	1.75	1.73
Electricity Exergy-based Cost (kJ/kJ)	3.02 / 3.26**	2.64 / 3.22**

*superheated / re-heated
**harvest season / offseason

It is interesting to see that during offseason, the SuST and BIGCC systems generates almost the same quantity of electricity with very similar efficiencies (~ 31%). This value could be further increased for both systems. For the SuST system an optimization procedure may find a better arrangement for the regenerative heat exchanger network. As for the BIGCC system, the use of pressurized gasification, using air extracted from the gas turbine compressor, will avoid the use of a produced gas compressor.

Regarding the increase in water consumption, during harvest season the increases are almost equal. During offseason, the water consumption in the condenser increases for the SuST and BIGCC systems; however such increases are still lower than the water consumption of the mill during harvest. Thus, it is possible to operate these systems during offseason.

5. CONCLUSIONS

After reviewing the main technological aspects of two advanced cogeneration plants, an exergetic comparative study of these systems for sugarcane mills was performed.

Both require additional development in order to overcome some technological issues that still prevent them from being commercial available.

Comparing the SuST system with the BIGCC system, both are able to produce 3 times more electricity when compared to current available options (Condensing-Extraction Turbines). Also, these systems decrease the exergy-based cost of sugar and ethanol by 20% and 38%, respectively. Furthermore, both of them have very similar conversion efficiencies, in the analyzed scenario, for electricity during offseason. Thus, supercritical steam-based cogeneration plants can be considered as an alternative to gasification-based plants.

Still, both systems could be further optimized through a better thermal integration of the auxiliary systems.

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