THE EVOLUTION THROUGH THE SINGLE-DRUM STEAM BOILER INSIDE THE EXPANSION OF COGENERATION IN THE BRAZILIAN SUGAR MILL CONTEXT

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Abstract. *Recent years' work experience in the Brazilian Sugar and Alcohol sector, still predominantly based on steam-powered plants, have stressed the benefits of cogeneration, in a context where necessary modifications aiming at adapting modern technology towards efficient strategies has brought improvements in fuel economy. In those plants, reaching electricity surplus for sale has been the result of increasing both; capacity and steam generation parameters. This paper presents an assessment on the evolution of bagasse-fired steam boilers in the current cogeneration context of Brazilian sugar mills. For such a purpose, a typical Brazilian bagasse-fired boiler design is depicted from earlier to current stages through its constructive and operational features. Most important thermodynamic performance indexes, including some related with constructive features are used to compare the performance of such boilers. The paper also discussed how the shift towards increased power generation in the Brazilian sugar mills has led to the development of the Single-Drum boiler for these applications. Finally, it compares the performance of a Single-Drum boiler against traditional Bi-Drum boilers in the context of modern cogeneration plants in the Brazilian sugar industry.*

Keywords. boiler, drum, energy, steam, bagasse

1. Introduction

A description of recent changes in the Brazilian Sugar Mill scenario featured by the ever growing trend of independent energy generation, stressed the importance of high quality technical management of cogeneration plants, in which, high pressure steam boilers must operate with high-efficiency multi-stage steam turbines to generate increasing surplus of electric energy. Based on this statement, the increase of thermodynamics steam generation parameters and the capacity of boilers have caused continuous evolution in the equipments offer range, as well as in the vision of both, power plant owners and equipment suppliers. In the mean time, strong evidences of the benefits of such modifications in different alternatives of sugar cane steam-based power plants have been recently published (Teixeira and Milanez 2000), and (Sánchez and Nebra, 2004).

The referred progress passes necessarily through a review of how the internal functioning, together with the transformation of its constructive features advantageously affected the typical 1970-1980 Brazilian Sugar Cane bagasse-fired steam boiler. It includes the evolution of several topics, such as; steam generation capacity, steam pressure and temperature, thermal efficiency, combustion technology, furnace dimensions, air excess coefficient, steam exergy, heat exchange surfaces, as well as other technical and operational performance indexes.

In recent sugar cane world history, perhaps, the most expressive bi-drum bagasse fired boiler is until now, the CSR Invicta Sugar Mill boiler, designed and built by John Thompson Engineering in Australia in the mid 1990´s. The Invicta boiler, at that time the largest bagasse fired boiler in the world, had according to Harris (2004), a steam output of 320 tons/hour, 4,3 MPa and 350 ^oC. Also in Australia, according to Stark (2006), new bagasse fired boiler projects have been built, all involving cogeneration plants. Steam generation parameters exit the boilers at nominally 7,2 MPa, 510 ^oC and 170 tons/hr.

According to McIntyre (2006), higher pressure/temperature units for cogeneration projects in Mauritius and Reunion reach 8,2 MPa and 520 ^oC. While in India, such level, as appointed by Natu (2005), reaches 8,7 MPa and 515 ^oC.

The Brazilian Sugar Industry has witnessed a fast development over the past 15 years. Recent regulations setting goals and rules for energy generation, therefore favoring efficiency in cogeneration have encouraged significant research work and progress in the evolution of power generation equipment in general. Boilers had an specifically distinct evolve, coming up from old multipass three-drums steam boilers designs to high efficiency single–pass bi-drum steam generators. The development of those bi-drums boilers accomplished excellent results at steam condition up to 6,3 MPa and 200 t/h, however there seems to be a consensus among Brazilian boilers suppliers that there are some technological limitations to exceed these parameters. Barata *et al.* (2005), has resumed some of those limitations in the following points:

- High-pressure steam boilers demand long start-up and shutdown curves.
- The control of steam temperature in the range of 480 – 520 °C is quite sensible to load variations, air excess, the primary and secondary air relation, bagasse moisture and uniformity in bagasse feeding.
- The Brazilian market had developed the concept that the limit for technical/economical feasibility of bagasse fired boiler capacity was 200 tons/hr. The solution to satisfy higher steam demands was to use two or more boilers.
- Several bi-drums boilers at 6,3 MPa had shown leakage problems at first crop, related to bank tubes expansions to the drums.

The following work has the aim of examining the most important constructive and operational backgrounds in the evolution of bagasse burning steam boiler inside the Brazilian Sugar Cane Industry frame and how it led to the development of technological solutions for higher steam capacities and pressures through the single-drum steam boilers and its novelty use in the industry. To illustrate our goal, some of the most important constructive features, as well as some of the most important thermodynamic performance indexes of boilers are reviewed in a scenario of a single backpressure-steam turbine-based cogeneration plant.

2. Description and Calculation Methodology

From the constructive and operational points of view, water tube boilers, consisting of two or more drums linked by a series of tubes, whose amount and arrangement depend on each manufacturer can be taken as a common starting point. Some of those old design Sugar Cane boilers were manufactured with dumping grates; some of them even without grate, and most had in common the air pre-heaters as the only heat recovery surface. Steam superheaters and mainly economizers were rarely used. The steam at the exit of the boiler averaged 2,1 MPa and 300 °C mostly rated under 100 ton/hr. The fuel feeding system was highly unstable, and the whole context led to low efficiency steam boilers Barata (2005).

In general terms, it can be sentenced that the boilers above described allow to illustrate a good steam generation unit designing conception of that early stage inside the Brazilian Sugar Cane scenario back in 1970-1980. In that period Brazilian Sugar Mills generated steam for sugar production based on many boilers linked in parallel. The milling process, main consumer of steam direct from boilers had constant load variations so the several boilers in parallel guaranteed the stability of steam demanded, which, despite of being inaccurate, was enough for the requirements. A better approach is offered through Tab. 1 where general data of one Brazilian bagasse-fired steam boiler of that period is illustrated in terms of capacity and steam generation parameters. Table 2 shows some of its constructive features and other general indexes.

Table 1. Summary of the performance indexes of the SZ-180[1] boiler designed in the 1970s.

Steam pressure (MPa)	2,1
Steam Temperature (°C)	300
Capacity (kg/hr)	45000
Water feed temperature (°C)	90
Gas leaving last heat exchanger (°C)	237
Fuel consumption (kg/hr)	20277

Table 2. Summary of the constructive features and indexes of the SZ-180[1] steam boiler

Steam super heater/Economizer/Air heater/Grate	Yes/No/Yes/No
Air excess coefficient (%)	50
Furnace volume (m^3)	196
Residence time (s)	1,83
Furnace width (m)	8,56
Evaporation surface (radiant + convective) (m^2)	1060
Air-preheating exit temperature (°C)	184
Thermal load furnace (kJ/m^3-hr)	776189
Specific surface evaporation rate (kg/hr-m^2)	42,45
Grate heat release rate (MJ/m^2-hr)	5740,87

1: Project Data supplied by CALDEMA Industrial Equipments LTDA; manufacturing year 1977.

As a past existing bagasse-fired boiler design trend in Brazilian Sugar Mills, the SZ-180 was a three-drum boiler designed without economizer. The airflow supplied for combustion was essentially primary air at temperature of 184 °C, and the bagasse was piled-up burned. The three-drums boiler was supported by metallic structures lined by refractory bricklaying and basically presented horseshoe furnace design –as the depicted SZ-180-, or a more efficient dumping grate system.

The constructive features are shortly detailed in the following equations:

- Thermal load of the furnace (T_L, kJ/m^3-hr):

$$T_L = \frac{m_b LHV_b}{V_f} \tag{1}$$

Where:
m_b: Fuel consumption (kg/hr)
V_f: Furnace volume (m^3)

- Specific surface evaporation rate (S_E, kg/hr-m^2):

$$S_E = \frac{m_s}{F_{RAD+CONV}} \tag{2}$$

Where:
m_s: Capacity of the boiler (kg/hr)
$F_{RAD+CONV}$: Evaporation surface (m^2)

- Grate heat release rate (f_G, kJ/m^2-hr)

$$f_G = \frac{m_b LHV}{F_G} \tag{3}$$

Where:
F_G: Grate surface (m^2)

Strongly influenced by both, the lack of investments and stimulating policies aiming at optimizing the profits of the products of the sugar cane industry, cogeneration also attended a similar level of development during a significant period of time. Lora (2003), remarks that low selling prices of electricity, combined with difficulties to guarantee the generation during the whole year were serious limitations. By the end of the 70´s and the early 1980´s the self-sufficiency of electric energy was the basic motivation of the plant owners, meanwhile very little was done in order to outstand the wide improvements possibilities of the sugar industry. Table 3 summarizes the cogeneration features associated to the steam-based sugar mill plants.

Table 3. General characteristics of cogeneration in the Sugar and Alcohol Brazilian sector during 1970-1980, referenced by Sánchez (2003)

Objectives of Cogeneration Plants	Self-Sufficiency
Bagasse selling market price	Very low prices
Surplus electricity selling prices	Very low prices
Installed Capacity of Cogeneration	150 MW (the whole country)
Transmission and Distribution systems	Low levels of suitability
Research, expansion and development	At low levels
Operational efficiencies (LHV based)	Bellow 75 - 80 %

It was obvious that the goal of increasing the capacity of steam boiler units would dictate new constructive references concerning the geometrical dimensions of heat exchange surfaces. Such goal became more evident at analyzing the fact that, in terms of cogeneration in sugar industries, it is necessary the use of a source of heat at low temperature levels, commonly under 150 ^{o}C, and for the production of this source of heat, the combustion of bagasse reports flame temperatures of about 1200 ^{o}C, (Lora and Nascimento 2004). So cogeneration as appointed by Nogueira (1996), by producing useful work and heat, reduces the energy losses and allows the achievements of both demands with almost the same fuel consumption.

On the other hand, it is well known that the sugar mill plant production process matches the cogeneration requirements since the plant meets local demands of heat and electric energy. In that way, the thermal efficiency of the process is not affected by long distance steam or hot water piping. Moreover, the consumed fuel, bagasse, is a rejection of the cane crushing.

However, based on a single backpressure steam turbine cogeneration plant described graphically in Fig. (1), worthless performance indexes are obtained working with the steam boiler SZ-180. The results are consequence of the low capacity and inefficiency of the previously depicted steam generation system, which in fact is a consequence of the context described in Tab. 3. Table 4 shows the results.

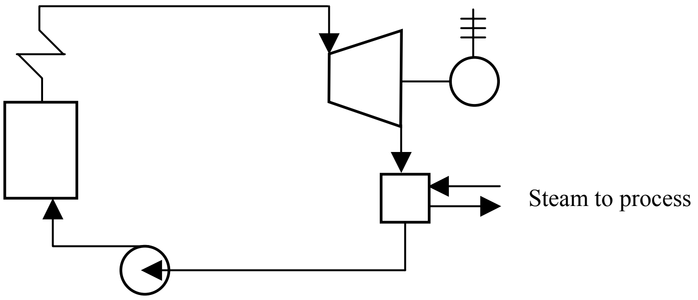

Figure 1. Diagram of a Cogeneration Plant

Table 4. Summary of the thermodynamic performance of the SZ-180 boiler itself, and associated to the cogeneration plant described in Fig (1)

Boiler's first law efficiency (%)[1]	78,2
Thermal specific energy rate (kJ/kg of fuel)[2]	5863
Steam/fuel consumption rate (kg of steam/kg of fuel)	2,219
Specific exergy of steam (kJ/kg)	1016,71
Boiler second law efficiency (%)	22,15
Total exergy rate (kW/m^3)	64,84
Specific exergy rate (kJ/kg of fuel)	2256,35
Electric Power (kW)	3500
Cogeneration Plant efficiency (%)	77,9
Power/Heat rate	0,119
Fuel specific consumption (kg of fuel/kWhr)	5,79

1: Based on Low Heating Value (LHV) of fuel (bagasse) = 7502,74 kJ/kg

2: Based on the relation between the flow of steam multiplied by the enthalpy difference (feeding water and steam) and the fuel consumption.

The thermodynamic performance indexes were calculated applying the following procedure:

- Exergy, as a true quality of the availability of an energetic carrier was calculated based on the Eq. (4) proposed by Szargut 1988, which states:

$$e_x = e_{xp} + e_{xc} \tag{4}$$

Where:
e_x: Specific exergy of an energy carrier (kJ/kg)
e_{xc}: Chemical component of the water steam exergy = 50 kJ/kg (Zsargut 1988)
e_{xp}: Physical component of the exergy (kJ/kg), calculated according to the following equation:

$$e_{xp} = (h - h_0) - T_0(s - s_0) \tag{5}$$

The terms h and s are the steam enthalpy (kJ/kg) and entropy (kJ/kg-°K) respectively, and the reference state was chosen at T_0 = 298 °K and P_0 = 101,325 kPa according to Zsargut (1988)

- The second law efficiency of the boiler is calculated by means of:

$$\eta_{II} = \frac{m_s(e_s - e_{wf})}{m_b e_b} \tag{6}$$

Where
e_s ; e_{wf} and e_b: Specific exergy of steam, feed water and fuel respectively (kJ/kg)
- The specific exergy of bagasse (e_b) was calculated from the equation proposed by Szargut (1988) for solid fuels:

$$e_b = \beta(LHV + LZ_w) + e_{xq}Z_w \tag{7}$$

L: Vaporization enthalpy of water at 298 ^oK (2442 kJ/kg)
Z_w: Water mass fraction in bagasse (0,5)
The coefficient β was determined by means of the following equation Gallo (1998):

$$\beta = \frac{1{,}0412 + 0{,}2160(\frac{Z_{H2}}{Z_C}) - 0{,}24909(\frac{Z_{O2}}{Z_C})[1 + 0{,}7884(\frac{Z_{H2}}{Z_C})] + 0{,}045\frac{Z_{N2}}{Z_C}}{1 - 0{,}3035(\frac{Z_{O2}}{Z_C})} \tag{8}$$

Where the term Z_i is the mass fraction of chemical elements from the ultimate analysis. See Appendix.

The electric power was calculated admitting similar conditions of the steam at the outlet of a turbine (at gauge pressure of 0,15 MPa). The result was the estimation of the MCE Steam Turbine Manufacturing Company.

- The Energy Utilization Factor or the cogeneration plant first thermodynamic law efficiency was calculated according to Huang (1996):

$$\eta = \frac{W_e + Q_p}{m_b LHV_b} \tag{9}$$

Where:
W_e: Electric power (kW)
Q_p : Process Heat (kW)
- The value of heat process (Q_p) was the result of:

$$Q_p = m_v(h_{et} - h_c) \tag{10}$$

Where:
h_{et}: Enthalpy of the steam at the outlet of the turbine (kJ/kg)
h_c: Enthalpy of the condensate from process (kJ/kg)
- The fuel specific consumption (b_f , kg of fuel/kWh), was calculated according to the following equation, where m_f is expressed in (kg/hr):

$$b_f = \frac{m_b}{W_e} \tag{11}$$

- The power/heat rate (R_{PH}) was calculated according to Horlock (1997), as:

$$R_{PH} = \frac{W_e}{Q_p} \tag{12}$$

- The total exergy rate (E_V, kW/m^3):

$$E_V = \frac{m_s e_s}{V_f} \tag{13}$$

- Specific exergy rate (E_{BR}, MJ/kg of fuel)

$$E_{BR} = \frac{m_s e_s}{m_b} \tag{14}$$

3. The evolution of bagasse-fired steam generator. Examples

The evolution of water tubes bagasse fired steam boilers in Brazil started a few years later, when the bi-drums succeeded the foregoing type of boiler. Aiming at cost reduction in terms of steam production, the partial elimination of refractory material, together with higher durability indexes of the combustion chamber lining were significant contributions. Also the decrease of the combustion temperature and faster water vaporization were important contributions towards more efficient and powerful bi-drums boilers, as appointed by Delgado and Azeredo (1977).

Therefore, upon applying the growing capacity trend, similar conceptions of boiler construction were brought into question in terms of their dimensions and constructive characteristics, not only concerning the furnace, but also, the dimensions of the drums, the heat exchange surfaces, the type of grate, the number of fuel feeders, just to mention a few aspects.

The multipass bi-drums type of boiler presented membrane water wall furnace, and, constructively it was supported on a metallic beam structure installed under the mud drum, endowing the whole system with an unquestionable rigidity. Its multipass-convection bank assured high heat transfer coefficient, whose velocities were kept within suitable limits to allow reduction on the tubes erosion problems, which confirmedly, restrained its acceptance for capacities over 100 ton/h and pressures over 4,2 MPa, where the pressure loss at the gases flow side is more significant.

Thanks to the vision of continue progress, during the 90´s the energetic equipment for the sugar industry experimented the following steps: more efficient single pass bi-drum boilers with capacities over 100 tons/hr, steam pressure in the range of 4,0 – 6,3 MPa and temperatures on around 420 - 480 ^{o}C started to be more widely constructed and spread as representative bagasse fired steam boilers of the sector. The single pass bi-drums boiler was specifically developed to overcome the tube erosion problems prevailing in multi-pass boilers, and to eliminate structural refractory, a characteristic of many former boiler designs, which led to high maintenance costs (J Thompson, 2003). So it began to assured itself as the most efficient and promising boiler available in the Brazilian Sugar Cane market.

Bagasse, as most fibrous fuels requires a uniform distribution across the full width and depth of the combustion chamber. Feeding, in this type of boiler, is accomplished through pneumatic spreaders in order to continuously inject bagasse with part of the air into the combustion chamber, and therefore promote a better fuel distribution into the entire grate. In that way, the stability of the heat released in the combustion chamber meets the decreasing thermal load trend, the significant height of the furnace and the residence time to reduce the quantity of air excess coefficient to complete the combustion (J Thompson, 2003).

Moreover, the trend of Cogeneration plants required stable supply of steam where the high-pressure boilers are the only or a few at one plant featured by the variations of the bagasse firing process. In that way, the use of continuous firing systems became a must, and among them, two options were mostly used.

- Traveling grate
- Pinhole grate with continuous (or sequential) steam jets cleaning

Nowadays at the Brazilian and South African Sugar Mills the pinhole leads the commercial application due to almost no maintenance cost.

By the end of the 90´s and the early 2000´s in Brazil, the single-pass bi-drum bagasse fired steam boilers found their most significant constructive expression in the bottom supported and top supported single pass boilers, whose more efficient performance indexes imposed new practiced design criteria. In that sense, a few aspects can be summarized:

- The secondary air introduced at high temperature improved the combustion conditions provoking partial suspension burning with effective results
- The presence of the economizer in almost all the modern designs had a benefit influence in the gas exit temperature. Values bellow 160 ^{o}C, brought profitable consequences to the thermodynamic behavior of boilers.
- The dumping grate increased its effective surface in order to meet both, higher fuel consumption and higher furnace volume, necessary for an efficient combustion. Recently, the more economic pinhole grate has replaced it.
- The convective and radiant superheating surfaces were designed according to the increasing capacities. The same goes for the selected superheating materials whose surfaces are submitted to higher temperatures.

Tables 5 and 6 illustrate the operational data and constructive features of three different development stages of bagasse-fired steam boilers in Brazil. The choice of each boiler was based on the maximum capacity known according to each designing conception by the end of 2005.

Table 5. Summary of the thermodynamic indexes of three alternatives of bi-drum steam boilers

Thermodynamic parameters	A2C-43 6GB PSE[1]	AUP-58 6GI PSE[1]	APU-64 6GI PSE[1]
Steam pressure (MPa)	2,1	4,2	6,6
Steam Temperature (^{o}C)	306,7	420	490
Capacity (ton/hr)	130	175	191
Water feed temperature (^{o}C)	115	105	105
Gas temperature leaving last heat exchanger (^{o}C)	161,7	170	153
Fuel consumption (kg/h)	51449	76279	85438

1: Design data supplied by CALDEMA Industrial Equipments LTDA; manufacturing year 1994.

Table 6. Summary of the constructive features of the three alternatives of bi-drum steam boilers

Constructive Features	A2C-43 6GB PSE	AUP-58 6GI PSE	APU-64 6GI PSE
Type of Grate	Dumping	Pinhole[1]	Pinhole[1]
Boiler bank tubes	Multi-pass	Single-pass	Single-pass
Support	Bottom Supported (downcomers)	Bottom Supported (downcomers)	Top supported (by steel structure)
Width (furnace) (m)	9,900	10,200	9,078
Depth (furnace) (m)	5,200	6,783	8,012
Height (furnace) (m)	12,626	13,73	17,8
Effective volume (furnace) (m^3)	690	950	1295
Suspension firing (%)	55	55	56
Residence time (s)	2,57	2,64	2,74
Combustion air temperature (^{o}C)	245	212/327[2]	214/333[2]
Grate surface (m^2)	39,3	66,8	69,5
Steam super heater/Economizer/Air heater	Yes/Yes/Yes	Yes/Yes/Yes	Yes/Yes/Yes
Heating surface (radiant +convective) (m^2)	2779	3509	4070
Steam generated/furnace width (ton/h-m)	13,13	17,157	21,04
Steam drum tube holes (#/∅ mm)	1352/ 50,8; 170/ 76,2	2396/51,2; 152/ 77	2150/51,2; 218/77
Steam drum thickness (mm)	45	50/75[3]	50/89[3]
Specific surface evaporation rate (kg/m^2-hr)	46,78	49,87	46,93
Grate heat release rate (MJ/m^2-hr)	9822,1	8567,4	9223,3
Thermal load (furnace) (MJ/m^3h)	559,432	602,422	494,995

1-Referred to water-cooled pinhole grates; 2-Referred to the relation of air grate temperature/over fired air temperature
3-Referred to relation of steam drum thickness/steam drum drilled thickness

The most interesting constructive features are illustrated in Fig. 2.

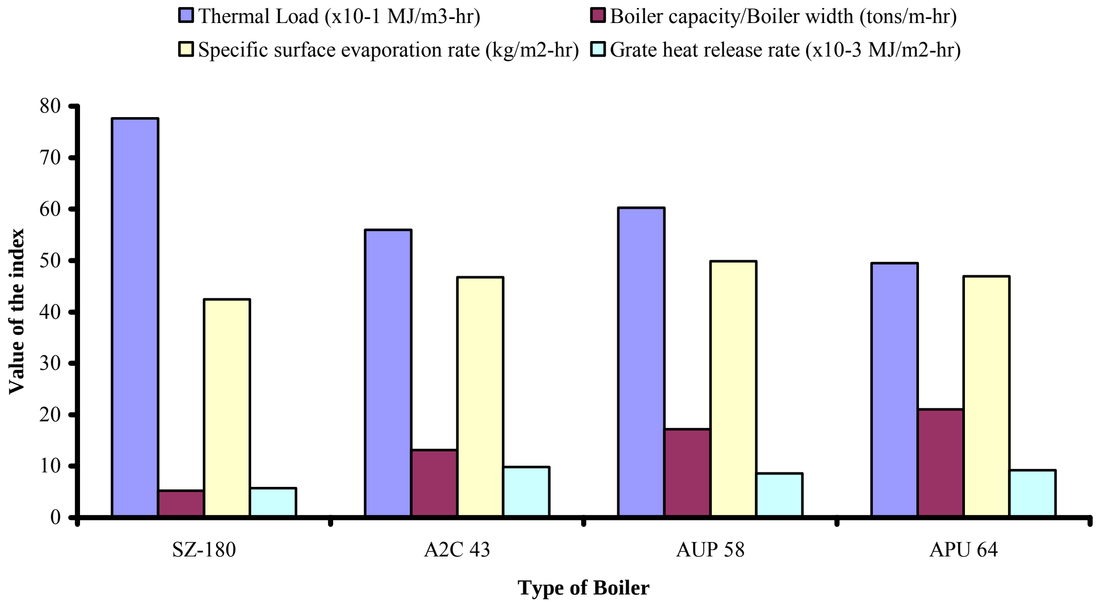

Figure 2. Constructive features of the boilers

The previous results evidence that the growth of the boilers in terms of capacity is strongly involved, among various aspects, with fuel consumption and the volume of the furnace, whose enlargement, according to the Thermal Load is more expressive than the one of the fuel consumption. This result sustains that the Thermal Load decreasing tendency promote better gains of the heat released. In terms of furnace volume, the height amounts too much, however, the width has no appreciable changes and that explains the steam specific generation tendency related to that dimension.

The grate heat release rate attempts a significant change between the SZ-180 and the A2C boilers, basically due to the significant difference in the heat released through combustion. The results denote that for higher capacities the grate surface does not have a noticeable increase, which means that suspension firing is imposed as another important aspect in modern bagasse fired boilers. Finally, the specific surface evaporation rate also shows a crescent tendency with the exception of the examined top supported APU boiler, whose relation between capacity and evaporation surface evidences a slight lessening. Table 7 shows some of the principal thermodynamic performance indexes.

Table 7. Summary of the thermodynamic features of the three steam boilers associated to Fig (1)

Thermodynamic indexes	A2C-43 6GB PSE	AUP-58 6GI PSE	APU-64 6GI PSE
First law Efficiency (boiler unit) (%)[1]	86,0	86,2	88
Steam/fuel rate (kg of steam/kg of fuel)[1]	2,5267	2,2942	2,2355
Thermal specific energy rate (kJ/kg of fuel)	6450	6464,5	6600
Specific exergy of steam (kJ/kg)	1024,256	1232,2	1370,036
Second law efficiency (boiler unit) (%)	24,85	27,6	30
Total exergy rate (kW/m^3)	53,60	63,05	56,13
Specific exergy rate (kJ/kg of fuel)	2588,06	2826,92	3062,78
Electric Power (kW)	13.800	27.760	37.173
Cogeneration plant efficiency (%)	88,6	87,6	89,2
Power/Heat rate (kW/kW)	0,169	0,249	0,305
Specific fuel consumption (kg of fuel/kWh)	3,7282	2,60	2,2984
Furnace heat total exchange (GJ/hr)[1]	114585,18	146107,7	195766,5
Superheater heat total exchange (GJ/hr)[1]	30285,17	80449,4	118011,4
Main bank heat total exchange (GJ/hr)[1]	168931,6	203558,3	191312,7
Economizer heat total exchange (GJ/hr)[1]	14143,8	44686,9	58638,6
Air pre-heater heat total exchange (GJ/hr)[1]	39759,1	65663,3	74187,6

1- Results reported by Caldema Industrial equipments Ltda (2006)

Results from Table 7 show that growing tendency in terms of capacity involves, as observed earlier, the relation between the fuel consumption and the volume of the furnace as a main issue to explain the tendency of some of the performance indexes. The thermal specific energy rate (kJ/kg of fuel), the total exergy rate (kW/m^3) and the specific exergy rate (kJ/kg of fuel) support that the increasing furnace volume exercises more influence than the increased fuel consumption. As a consequence, the specific exergy rate as well as the thermal specific energy rate keeps a growing trend, which is not sustained by the total exergy rate (kW/m^3), caused by the significant increasing furnace volume of the supported boiler.

The increase of the furnace volume, as well as the heat exchange surfaces are closely related with the quality of the combustion process in higher capacity boilers. Therefore, the increase of the thermodynamic value of an energy carrier has definite cost implications whose analysis is out of the scope of this paper.

However, the enlargement of the thermodynamic parameters observed in each alternative does confirms that indexes such as the electric power, the steam exergy, the specific fuel consumption, the second law efficiency and the power heat rate are clear symptoms of how the same energy resource can be more profitably used. The total heat exchanged in the different surfaces in general follow the tendency imposed by the growing capacity.

3.1 The single-drum boiler

Extensively applied in the petrochemical, thermoelectric and other industries of Europe and the United States at medium and high-level steam pressure, the Single-Drum Boiler has recently begun to be a very suitable proposal for Sugar Cane Plants according to the significant profits of cogeneration and its optimization, as an answer to the necessity of increasing pressure, temperature and the capacity levels in the steam boiler/turbine units.

Its constructive characteristics lead the Single-Drum Boilers to a huge application. Several of these constructive topics are to be remarked:

1- The steam drum is disposed externally, i.e. out of the flow gases circuit and without bracing tubes. The result is a lower wall thickness drum with higher operational reliability, which is more easily adapted to higher capacities. Because of its many drum connections, the steam drum wall thickness of the bi-drum boiler is larger.

2- The previous endows the boiler with the capability of a faster start-up when compared with bi-drum boilers, which, as a rule consume about two times the start-up period of the single drum boiler (Barata 2005). Bi-drum boilers are not designed for a quick start-up, because the cold water remaining in the lower drum may lead to its bending, as reported by Schatz, (2000).

3- In the single drum boilers, the drum has no direct connections with the main bank tubes as in the bi-drum boilers so, a more flexible and modern components arrangement is possible with the furnace, superheater, main bank tubes, economizer, etc.

4- The furnace special characteristics, its height and large volume enable the suspension burning of a significant amount of fuel, decreasing the emission of solid particles to the ambient and therefore accomplishing a more efficient combustion.

5- The two main convection heat exchange elements, i.e. steam superheater and evaporator are assembled out of the furnace, in the descendent vertical gas flow. The effect of this constructive arrangement decreases the possibility of accumulation of ashes while enabling its retention at lower temperatures when compared to bi-drum boilers.

6- The steam superheater is totally drainable and convective, which allows a longer life period. In case of higher steam temperatures, the steam superheater can be designed as a two or even three-passes with intermediate temperature control.

7- The use of furnaces with high degree of radiation heat absorption and significant residence time of the combustion gases is another contribution to the increase in combustion efficiency.

All those elements are more clearly depicted in the following tables by showing the principal aspects of the performance of the AMD 100-9GI-PSE-steam boiler. As in the previous boiler performances, the option of this Single-Drum steam boiler was based on the maximum known capacity of this designing conception of bagasse-fired boiler referenced back in December 2005.

Table 8. Summary of the thermodynamic parameters of the AMD 100-9GI-PSE boiler

Steam pressure (MPa)	65
Steam Temperature (^{o}C)	480
Capacity (ton/hr)	300
Water feed temperature (^{o}C)	110
Gas temperature leaving last heat exchanger (^{o}C)	153
Fuel consumption (kg/h)	140219

Table 9. Summary of the constructive features of the AMD 100-9GI-PSE boiler

Type of Grate	Pinhole[1]
Boiler bank tubes	Single-pass
Support	Top Supported (hanged by steel structure)
Width (furnace) (m)	10,302
Depth (furnace) (m)	9,792
Height (furnace) (m)	22,294
Effective volume (furnace) (m^3)	2249
Grate surface (m^2)	73,4
Suspension firing (%)	56
Residence time (s)	3,55
Combustion air temperature (^{o}C)	384/274[2]
Heating surface (radiant +convective) (m^2)	3359
Steam super heater/Economizer/Air heater	Yes/Yes/Yes
Grate heat release rate (MJ/m^2-hr)	14332,8
Steam generated/furnace width (ton/hr-m)	29,1206
Steam drum tube holes (#/∅ mm)	31/139; 5/50; 2/276; 1/290; 2/36; 18/92; 4/328; 1/95; 1/116; 3/76,9
Steam drum thickness (mm)	63
Specific surface evaporation rate (kg/m^2-hr)	89,31
Thermal load (furnace) (MJ/m^3hr)	467,775

1 and 2. The same reference of table 6

Table 10. Summary of the thermodynamic indexes of the AMD-9GI-PSE boiler

First law Efficiency (boiler unit) (%)	87,8
(kg of steam/kg of fuel)	2,14
Thermal specific energy (kJ/kg of fuel)	6221,6
Specific exergy (kJ/kg)	1354,1
Second law efficiency (%)	28,26
Electric energy (kW)	51400
Total exergy rate (kW/m^3)	50,17
Specific exergy rate (kJ/kg of fuel)	2897,1
Cogeneration plant efficiency (%)	82,8
Power/Heat rate (kW/kW)	0,272
Fuel specific consumption (kg of fuel/kWh)	2,728
Furnace heat total exchange $(GJ/hr)^2$	351765,7
Superheater heat total exchange $(GJ/hr)^2$	203016,62
Main bank heat total exchange $(GJ/hr)^2$	186601,3
Economizer heat total exchange $(GJ/hr)^2$	150565,7
Air pre-heater heat total exchange $(GJ/hr)^2$	-

From the constructive point of view the dimensions of the furnace directly contributes to keeping the tendency of the thermal load in order to promotes more efficient combustion by reaching a higher suspension burning degree. This influence meets the tendency of the Grate heat release and the Specific surface evaporation rates, whose significant increase is a symptom of the slight variation of the grate surface.

A better approach to analyze the thermodynamic indexes is given in Fig (3).

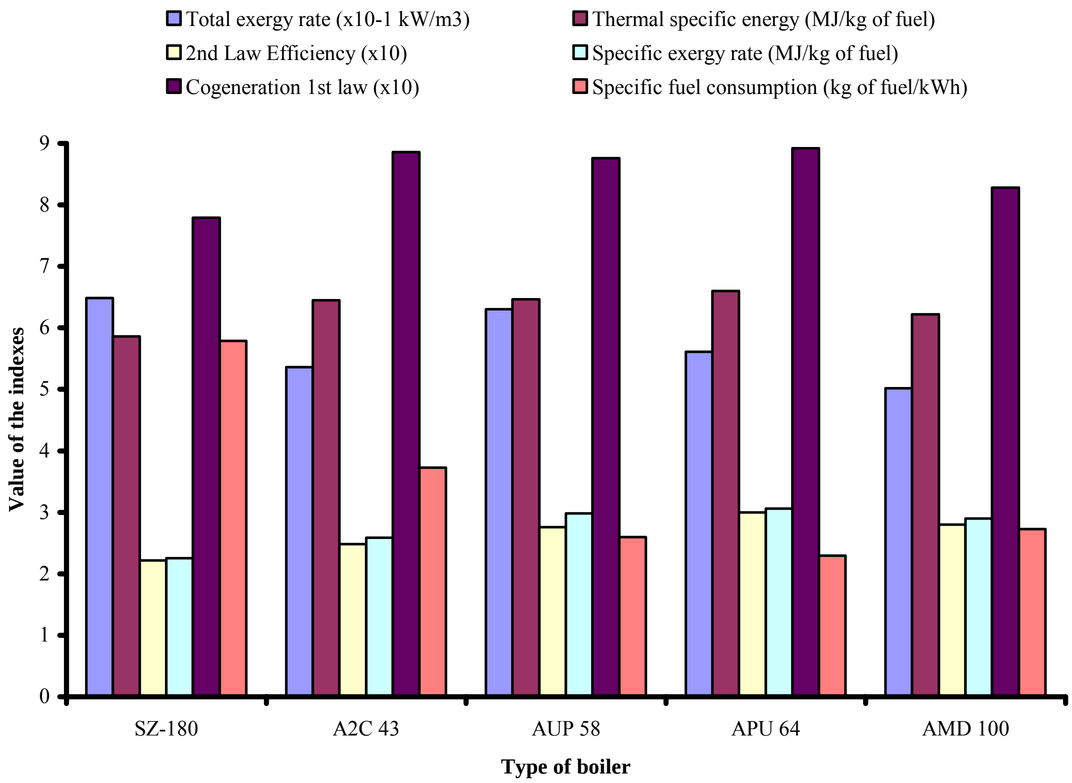

Figure 3. Thermodynamic indexes of the boilers

Comparing the results of the different alternatives, it is easy to distinguish the capacity of each boiler, its fuel consumption, as well as the thermodynamic steam parameters, as the issues to be discussed. Since the relation between the furnace volume and the fuel consumption has been exposed, it can be observed the decreasing tendency of the total exergy rate, only interrupted in the examined bottom supported AUP boiler, where the relation between the steam exergy and the furnace volume reach its highest value. The rest of the indexes based on the concept of exergy follow the tendency of the efficiency of the second law of thermodynamics for each boiler, and this behavior reflects the influence of the thermodynamic parameters and the relation between boiler capacity and fuel consumption. The previous idea explains the slight reduction tendency of the index associated to the Single-drum boiler. The performance indexes based on the first law for cogeneration plants practically showed the expected tendencies. However, it is remarkable that, among the evaluated boilers, the one with the best thermodynamic performance indexes (the top supported APU boiler), is not the boiler with the highest value of steam total exergy rate, (kW/m^3), (the bottom supported AUP boiler).

Finally, the calculations of the heat exchanged at different surfaces signalize the expected results.

4. Concluding remarks

Based on the evolution of steam boilers uses and applications in the Brazilian Sugar Mill scenario in the last 30 years, makes it evident how necessary constructive modifications towards more efficient steam generators were able to overcome cost implications regarding the increase of the capacities and the steam thermodynamic parameters.

The development process in boilers involves not only the well known increase of the thermodynamic generation level, but also the relation between higher capacities and the implications on the heat exchange equipment dimensions. The concept of exergy associated to the useful outcome of the boiler reported important results not only through the second law efficiency, but also at evidencing its relation with both, the furnace volume and the fuel consumption.

The single-drum boiler itself does not mean an improvement in thermodynamic performance when compared to the previous single-pass bi-drum boilers, even in the case of having both operating at identical steam parameter levels and with the same capacity. However its advantages and constructive features remarks its capability of being perhaps the only type of boiler in the Brazilian Sugar Cane scenario able to compensate for capacities higher than 200 tons/hr and working over 7,0 MPa and 520 ^oC.

5. References

ALSTOM JOHN THOMPSON, "Cogeneration in the sugar Cane Industry", Caldema Equips. Inds.Ltda., Internal Documents, 2005

Barata J.C.F. Lopes A.L.R. & Gómez, J.E. "A evolução da caldeira de bagaço: Da Fornalha Ferradura à Monodrum", SINATUB, Ribeirão Preto, São Paulo, Brasil, Dec. 2005. (In Portuguese)

Delgado A. A., César M. A. A. "Elementos de Tecnologia e Engenharia do Açúcar de Cana" Departamento de Tecnologia Rural Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo, 1977. (In Portuguese)

Gallo W.L.R., "Avaliação de Processos pelos Métodos da Segunda Lei da Termodinâmica", Curso de Pós-graduação, Universidade Estadual de Campinas, UNICAMP, 1998. (In Portuguese).

Harris S., General Manager, John Thompson Engineering, Division of Burns and Roe Worley, Personal Communication, June 2004.

Horlock J. H., "Cogeneration: Combined Heat and Power (CHP)", Rieger Publishing Company, Malabar, 226 p., 1997

Huang F. F., "Performance Assessment Parameters of a Cogeneration System", Proceedings: Efficiency, Cost, Optimization, Simulation and Environmental Aspects of Energy Systems. ECOS´96, June 25 – 27, Stockholm, pp 225-229

Lora E.E.S., Nascimento M.A.R., "Geração Termelétrica, Planejamento, Projeto e Operação", Editorial Interciência Ltda, Rio de Janeiro, 2004, Vol I, 631 p. (In Portuguese)

Lora E.E.S., "Calderas de Vapor y Cogeneración en la Industria Azucarera", Post-Graduation Course, CECICAÑA, Cali, Colombia, November 10-14, 2003, 225 p. (In Spanish)

McIntyre P., Director of Sales & Marketing, ALSTOM JOHN THOMPSON (Pty) Ltd, Personal Communication, April 2006.

Natu S.C., "Bagasse based cogeneration, India marching ahead", International Sugar Journal, Vol. 107, No 1279, pp 416-424, 2005.

Nogueira, L.A.H. & Alkmin, J.T. "Uma generalização do estudo de potencial de sistemas de cogeração", Eletricidade Moderna, Vol. 24, nº 265, Setembro de 1996, MG, Brazil, (In Portuguese)

Sánchez P.M.G., Nebra S.A. "Thermodynamic and exergetic cost analysis two steam-based cogeneration schemes proposed for a Brazilian Sugar Mill", Energy-Efficient, Cost-Effective and Environmentally-Sustainable Systems and Processes, ISNB 968-489-027-3. R. Rivero, L Monroy, R. Pulido & G. Tsatsaronis, Editors. Instituto Mexicano del Petróleo, México, 2004.

Sánchez P.M.G. "Alternativas de Cogeração na Industria Sucroalcooleira Brasileira. Estudo de Caso", Faculty of Mechanical Engineering, State University of Campinas, PHd Thesis, 2003, 280 p. (In Portuguese)

Schatz U., "Design of a 270 Tons/hr Bagasse-Fired Eckrohr-Boiler in Comparison with a Bi-Drum Boiler", Internal Documents, Caldema Equips. Inds.Ltda., 2006

Stark P., General Manager, John Thompson Engineering, Division of Burns and Roe Worley, Personal Communication, February 2006

Teixeira M. A., & Milanez L. F., "Cogeneration in the Brazilian Sugar Cane sector, future scenarios and the new legislation". Efficiency, Cost, Optimization, Simulation and Environmental Aspects of Energy Systems, Proceedings of ECOS 2000, University of Twente, Nederland, July 5-7, pp. 1621-1629

Szargut J., Morris D. R. & Steward F. R., "Exergy Analysis of Thermal, Chemical and Metallurgical Processes", 1988, Hemisphere Publishing Corporation, New York, 1988

APENDIX

Table A.1 Composition of 1 kg of bagasse at 50% moisture (ultimate analysis)

Element	Composition
Moisture	0,5
Carbon	0,235
Hydrogen	0,0325
Oxygen	0,22
Ash	0,0125