Thermodynamic considerations about the way from low to high pressure bagasse boilers

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Abstract:

The bagasse boilers of actual sugar cane industry are passing from low (20 bar) to high pressures (110 bar). Nowadays, there is not a satisfactorily explanation regarding to this technological change. Certain authors refer the need of export electricity to the grid, considering the use of steam boilers and high pressure condensation extraction steam turbines. Others explain that the cause obeys mainly to economic reasons. This work presents the thermodynamic considerations about this technological change from low to high pressure bagasse boilers. The dependence between boiler efficiency and initial pressure is presented and discussed, also the statistical analysis is showed. The considerations used permits to observe the change step – by – step of efficiency as a function of initial pressure. Though the major trend of the boiler efficiency increase occur from 3500 to 6000 kPa, where the efficiency of the boiler rise up in 4,5 %, while these does not occur from 7000 to 9500 kPa, where the efficiency only rise up 3 %.

Keywords:

Boiler, Efficiency, Pressure, Bagasse.

1. Introduction

The bagasse boilers of most of actual sugarcane mills were primarily designed and conceived until the 1980's to consume and eliminate all bagasse, due the sugarcane bagasse did not have an economic value, and it was considered a problem, an undesirable waste by most mills. The cogeneration plants in sugarcane mills according to [1] were primarily designed to consume all bagasse, and produce steam and electricity to the process passing through from low an medium (20 – 45 to 62 bar and 350 - 490°C) to high pressures and temperatures (82 - 110 bar, 520 - 600°C). Nowadays, it is continued investigating about the why this is in this manner. Certain authors [2,3] refer the need of export electricity to grid considering the use of steam boilers and high pressure condensation extraction steam turbines. Others [4,5] explain that the cause obeys to mainly economic reasons. The last authors [5] analyzed both the improvements to increase the parameters of steam and the boiler efficiency and the use of financial incentives such as the possible sale of carbon credits. One important topic to be considered here is the comparison between grates and fluidized bed boilers (higher efficiency but around 25% more expensive).

The Fluid Bed steam generator, especially the Bubbling Fluid Bed (BFB), have a history of reliable operation and have brought value due to their ability tu burn high moisture and high ash fuels, as it is the case of the bagasse. Today, this steam generators presents progressively advanced the state of BFB technology by incorporating design improvements like staged air mixing and gas recirculation systems. It is an interesting topic especially for current sugar mills in Brazil, where most of the installed operates at low efficiency and the change from low pressure to high pressure is already well established. While old and low efficient boilers are based on grate technology (high rate of unburned carbon), the favorite's ones today are based on fluidized bed technology, which can clearly achieve higher efficiencies (not only due to higher pressures). The major drawback of Fluid Bed boilers is the higher investment cost. This work presents the thermodynamic considerations about the way from low to high pressure bagasse boilers. The employment of the dependence between boiler efficiency and initial pressure is presented and discussed, also the statistic analysis is showed.

2. Overview of choice of steam boiler and turbines

Today, bagasse – fired boilers, are furnished with superheaters, thermal deareators, air preheaters [6], bagasse dryers, feed water treatment and better control on combustion. Anciently [7], and not only for bagasse boilers but, in general, is known the choice of pressure and temperature of steam generators. The economic pressure of steam boiler and the reheat temperature, often, belong to the following groups: *Group I*: Nominal pressure 125 bar, at the inlet of steam turbine 110 bar, temperature of outlet of steam reheater 500^{o}C, at the inlet of steam turbine 485^{o}C; feedwater temperature 190^{o}C to: installations with condenser and intermediate reheat, in steam power stations with units of great power and great steam consumption and installations with backpressure or placed before an another existent, with great steam consumption, from 80 to 100 t/h. *Group II*: Nominal pressure 80 bar, at the inlet of steam turbine 70 bar, temperature of outlet of steam reheater 500^{o}C, at the inlet of steam turbine 485^{o}C; feedwater temperature 190^{o}C to: installations with condenser without intermediate reheat, in enlargement of existent power stations or in new power stations, with steam turbines of less power and less steam consumption and installations with backpressure or placed before an another existent, with lesser steam consumption than the group I; *Group III*: Nominal pressure 40 bar, at the inlet of steam turbine 35 bar, temperature of outlet of steam reheater 450^{o}C, at the inlet of steam turbine 435^{o}C; feedwater temperature 150^{o}C to: new power stations or in enlargement of peak power stations, with steam turbines of less power and less efficiency when these work with high pressures.

The former subdivision is founded in the following relations deduced from the observation: the curve of the Fig. 1 provide the heat gained, percent, between 4 to 15 MPa (40 to 150 bar); an increase of steam pressure from 4 to 6 MPa render so much as the increase from 6 to 15 MPa:

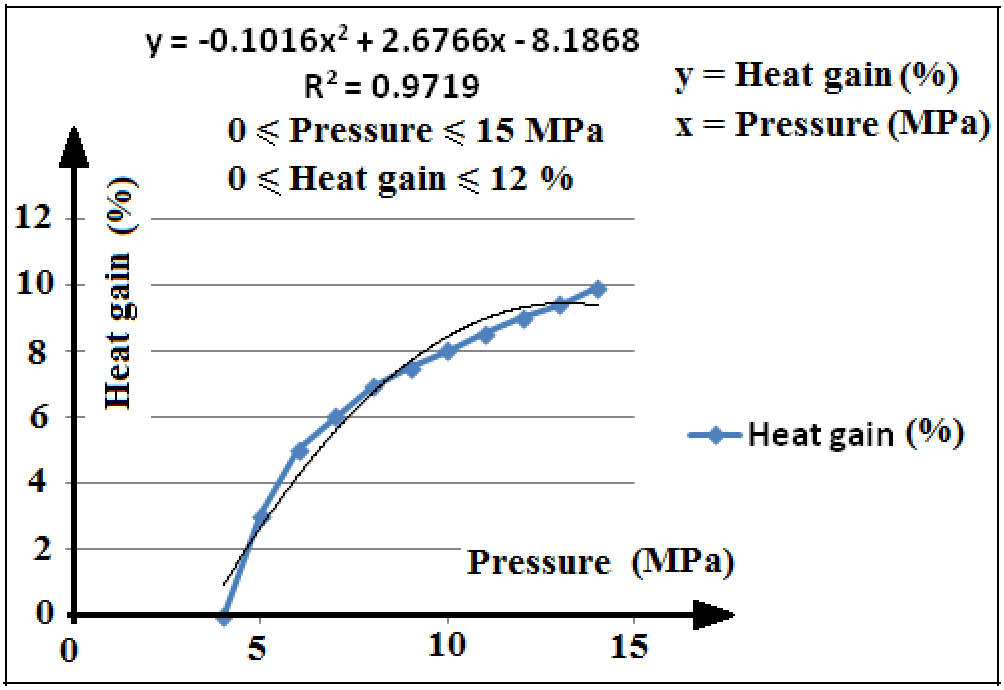

Fig. 1. Polynomial approach to heat gained % versus initial pressure.

The heat gained decrease excessively with the increase of pressure; the economic limit is founded between 10 to 12.5 MPa, even for backpressure installations. On the other hand, it is very important the improvement because of increase of reheat temperature, as shown in Fig. 2:

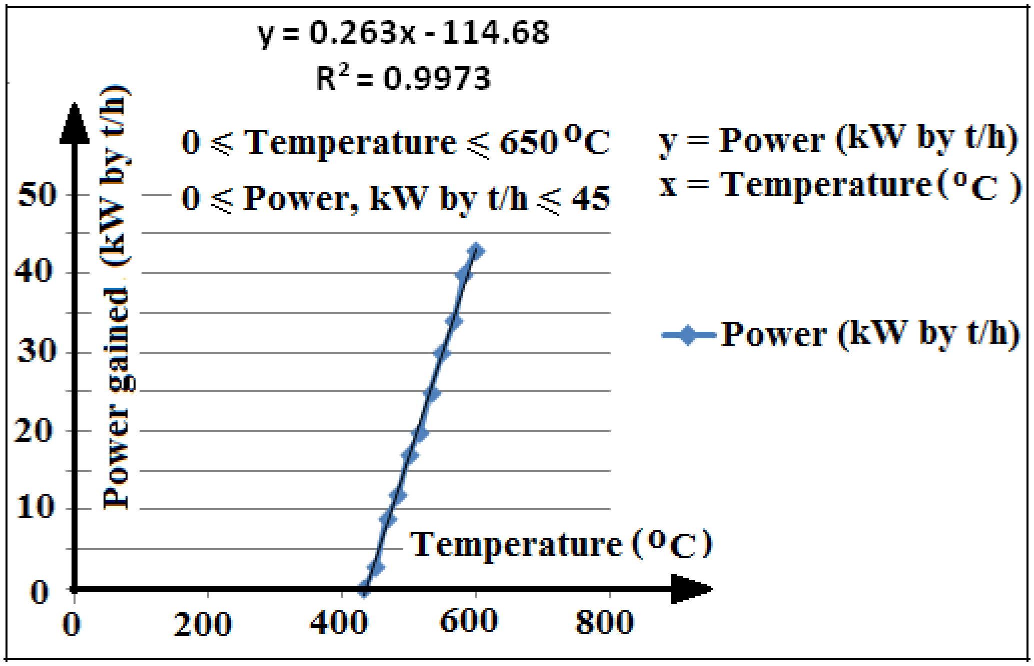

Fig. 2 Linear approach to power kW gained by t/h in the steam turbine.

Generating higher pressure and temperature steam, according to [4,14] requires special and more expensive alloys and thicker water tubes, so that boilers producing very high pressure steam can be more than twice as expensive as boilers generating low pressure steam. The pair pressure - temperature must follow ASME rules regarding material choice. Although it shows an important topic for sugar mills, the boiler efficiency depends on many parameters not only steam pressure and temperature.

2. Thermodynamic and statistical considerations

2.1. Dependence between boiler efficiency and initial pressure in bagasse boilers

The thermal calculations for steam boilers are carrying out, more commonly, through the net calorific value NCV [8] of the main, *m*, mass of fuel:

$$NCV = 338.C^m + 1025.H^m - 108.5(O^m - S^m_{vol}) - 25.W^m \qquad (1)$$

Where C^m, H^m, O^m, S^m_{vol}, W^m are the content of elements in the main mass of fuel, %

Neglecting the physical heat of the fuel and the heat introduced to the furnace by the air and steam blown, the NVC is approximately equal to available heat Q^m_{avlb} of the main mass of fuel, so that:

$$NCV = Q^m_{avlb} \qquad (2)$$

The useful heat, kJ/kg, of the steam boiler equipment is:

$$Q_u = \frac{\dot{m}_s}{\dot{m}_f}\left[h_1 - h_{fw} + (M/100)\left(h_{hw} - h_{fw}\right)\right] \qquad (3)$$

Where $\dot{m}_s, \dot{m}_f$, h_1, h_{fw}, M and h_{hw} are the flow rate of steam, the flow rate of fuel, the enthalpy of the superheated steam in the outlet of the boiler, approximately the same of the enthalpy of the inlet steam turbine. kJ/kg; the enthalpy of the feedwater, kJ/kg; the make – up water, in % and the enthalpy of the hot water in the drum, kJ/kg, respectively.

The enthalpies h_1, h_{fw} *and* h_{hw} are determined using any Engineering Software Package, namely, the Engineering Equation Solver, EES [9], en function of temperatures, pressures or qualities of the steam:

$$h_1 = h('Water', T = T_1, P = P_1) \qquad (4)$$

$$h_{fw} = h('Water', T = T_{fw}, X = 0) \qquad (5)$$

$$h_{hw} = h('Water', P = P_1, X = 0) \qquad (6)$$

Finally, using the direct method of determination of gross boiler equipment efficiency:

$$\eta_{gbe} = \frac{Q_u}{Q^m_{avlb}}.100 \qquad (7)$$

The previous expression this in agreement with the general definition of the efficiency of a boiler as the ratio of the heat made use of by the boiler to the heat available for its use.

2.1.1 Case of Study

In the case of bagasse boiler, the data of bagasse commonly used to fired in these boilers appearing in the literature [10,11]

Data for determination of gross boiler equipment efficiency:

C^m = 23.5 %; $H^m = 3.25$ %; $O^m = 22$ %; $S^m_{vol} \approx 0$ %; $W^m = 50$ %

$N^m \approx 0$ %; $A^m = 1.25$ %; $M = 3$ %; t_{fw} = 110 °C; $\dot{m}_s = 12.5\ kg/s$; $\dot{m}_f = 5.73\ kg/s$

p_1 =2.85 MPa T_1 =400°C

Procedure:

Using, sequentially, the equations (1) to (7):

$NCV = Q^m_{avlb}$

$Q^m_{avlb} = 338.C^m + 1025.H^m - 108.5(O^m - S^m_{vol}) - 25.W^m$

$Q_u = \left(\frac{\dot{m}_s}{\dot{m}_f}\right)\left[h_1 - h_{fw} + (M/100)\left(h_{hw} - h_{fw}\right)\right]$

$h_1 = h('Water', T = T_1, P = P_1)$

$h_{fw} = h('Water', T = T_{fw}, X = 0)$

$h_{hw} = h('Water', P = P_1, X = 0)$

$\eta_{gbe} = \frac{Q_u}{Q^m_{avlb}}.100$

The principal results are:

$$\eta_{gbe} = 79.7\ \%$$
$$Q^m_{avlb} = 7637\ kJ/kg$$
$$Q_u = 6087\ kJ/kg$$

These are the results for only a point. Next, is shown a parametric study to investigate the variation of the gross boiler efficiency with respect to variation of pressure and temperature of outlet at the boiler or, approximately, the pressure and temperature at the inlet of the steam turbine, neglecting the drop pressure between the outlet of the boiler and the inlet of the steam turbine.

2.1.1 Parametric study

2.1.1.1 Assumptions

Considering an initial condition of entropy that guarantee, first, a little superheating of the steam extraction of the intermediate expansion of the turbine to sugarmill process, that is, a temperature corresponding to a pressure about of 2000 – 2500 kPa abs, an a humidity of steam at final of the expansion of the turbine, approximately, 8 to 12 % or a quality of steam between 88 to 92 %. This entropy could be about 6 – 8 kJ/(kg – K) and an initial temperature of approximately between 500 to 570°C.

2.1.1.2. Results

The Table 1 shown the values of pressure and temperature used in the analysis:

Table 1 Values of pressure p, kPa and temperature T, °C used in the analysis

P kPa	*T °C*
3685	396.3
3973	407.9
4279	419.5
4604	431.1

4948	442.6
5312	454.2
5698	465.8
6106	477.4
6537	488.9
6998	500.5
7473	512.1
7980	523.7
8514	535.3
9077	546.8
9670	558.4
10294	570

Table 2 Coefficients of polynomial dependence between temperature and pressure steam Coefficient of determination $R^2 = 0,999$

a	7.97E-035
b	-5.64E-030
c	1.77E-025
d	-3.25E-021
e	3.85E-017
f	-3.08E-013
g	1.69E-009
h	-6.22E-006
i	0.015
j	-20.44
k	12760.16

Next, are introduced the following data and equations in the above procedure:

2.1.1.3. Statistical results

The statistical results, according to [13] were the following:

$$T_1 = ap^{10} + bp^9 + cp^8 + dp^7 + ep^6 + fp^5 + gp^4 + hp^3 + ip^2 + j.p + k \qquad (8)$$

$$s_1 = 1.68\ kJ/(kg - K)$$

$$p_1 = PRESSURE(Water, T = T_1, s = s_1) \qquad (9)$$

Number of observations = 16
Number of missing observations = 0
Solver type: Nonlinear
Nonlinear iteration limit = 250
Diverging nonlinear iteration limit =10
Number of nonlinear iterations performed = 250
Residual tolerance = 0.0000000001
Sum of Residuals = -1.6E-09
Average Residual = -1.0E-10
Residual Sum of Squares (Absolute) = 8.88E-03
Residual Sum of Squares (Relative) = 8.88E-03
Standard Error of the Estimate = 0.042
Coefficient of Multiple Determination (R^2) = 0.99
Proportion of Variance Explained = 99.99 %
Adjusted coefficient of multiple determination (Ra^2) = 0.99
Durbin-Watson statistic = 3.39
The Durbin-Watson statistic is 3,39 (rounded) show good autocorrelation between the steam pressure and the steam temperature (the range must be from 0 to 4).

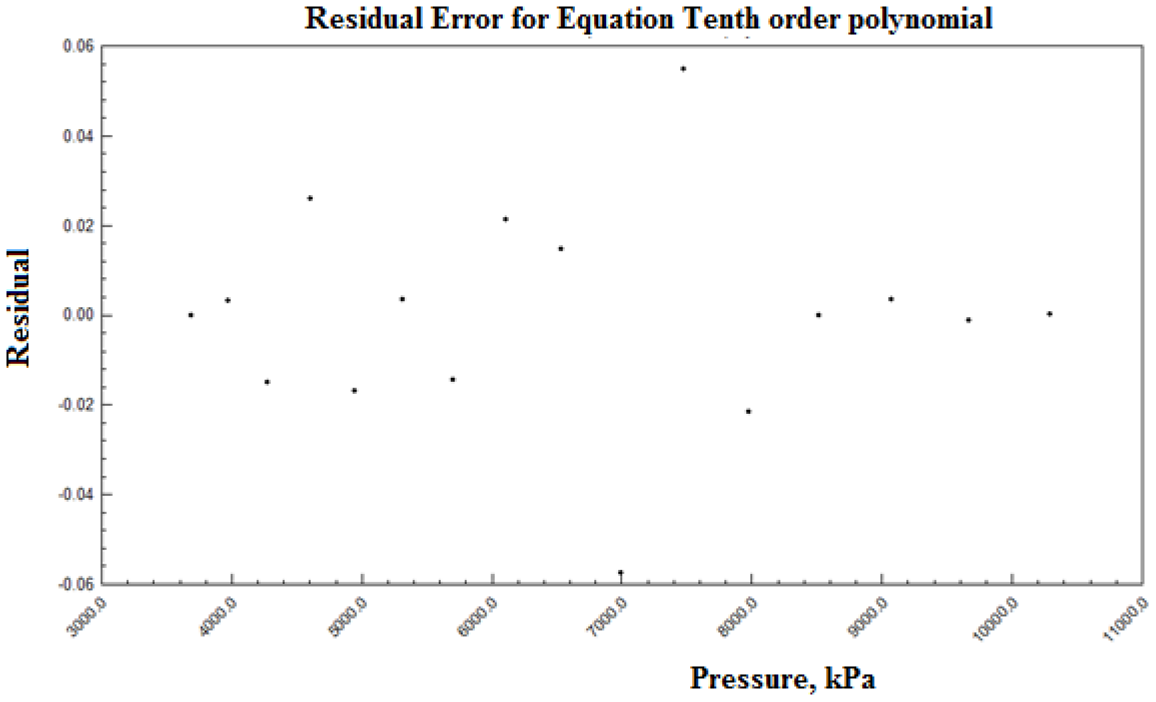

Fig. 3 Residual error for Equation Tenth order polynomial.

The observed residuals permit estimate the sampling distribution of the steam pressure and temperature. The residual error is aproximately 0, then the model fits the data almost perfectly and suggest the model has predictive ability.

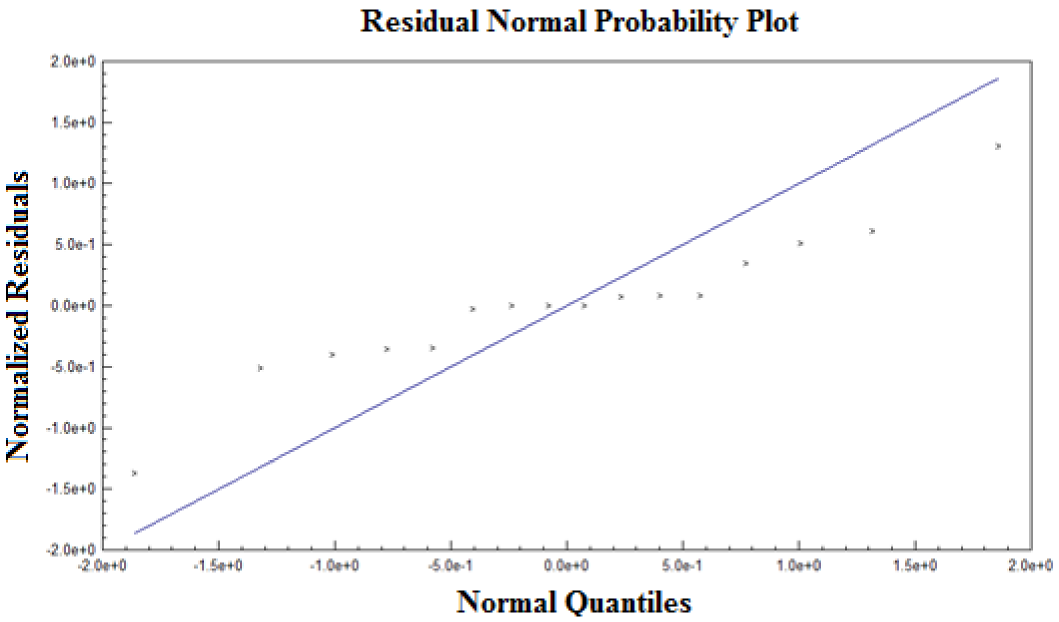

Fig. 4 Residual Normal Probability Plot.

Note that the relationship between the normalized residuals and the normal quantiles is approximately linear. Therefore, the normal probability plot of the residuals suggests that the error terms are indeed normally distributed.

Now, the polynomial above is introduced again in the EES. The Table 3 shown the values of parametric table generated by the EES for 20 observations:

Table 3. Parametric table η_{gbe}*, % vs* P, kPa

Run 1..20	η_{gbe}, %	*P, kPa*
1	77.7	*3000*
2	78.3	*3400*
3	79.3	*3800*
4	80.1	*4200*
5	80.9	*4600*
6	81.7	*5000*
7	82.4	*5400*
8	83.1	*5800*
9	83.7	*6200*
10	84.3	*6600*
11	84.9	*7000*
12	85.5	*7400*
13	86.0	*7800*
14	86.5	*8200*

15	87.0	*8600*
16	87.6	*9000*
17	88.0	*9400*
18	88.4	*9800*
19	88.8	*10200*
20	89.4	*10600*

The Fig. 5 shown the plot of the parametric table generated by the EES for 20 observations:

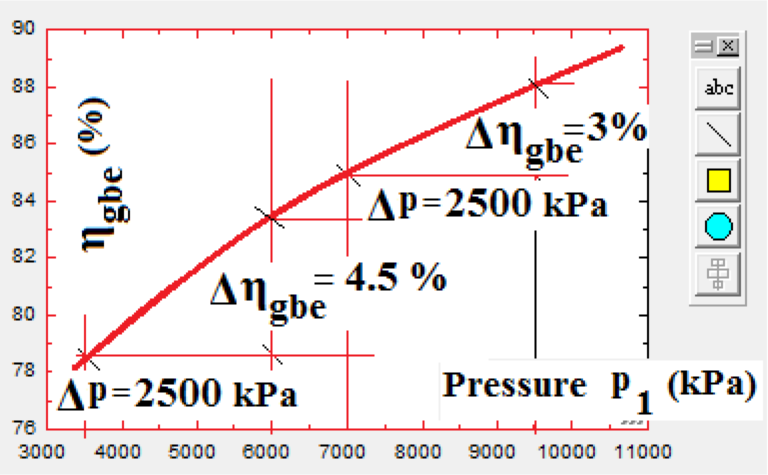

Fig. 5. Polynomial approach η_{gbe} versus pressure p_1

Model Definition:

$$\eta_{gbe} = a'p^{10} + b'p^9 + c'p^8 + d'p^7 + e'p^6 + f'p^5 + g'p^4 + h''p^3 + i'p^2 + j'.p + k'$$
(10)

Number of observations = 20
Number of missing observations = 0
Solver type: Nonlinear
Nonlinear iteration limit = 250
Diverging nonlinear iteration limit =10
Number of nonlinear iterations performed = 250
Residual tolerance = 0.0000000001
Sum of Residuals = -2.84E-10
Average Residual = -1.42E-11
Residual Sum of Squares (Absolute) = 7.53E-05
Residual Sum of Squares (Relative) = 7.53E-05
Standard Error of the Estimate = 2.89E-03
Coefficient of Multiple Determination (R^2) = 0.99
Proportion of Variance Explained = 99.99%
Adjusted coefficient of multiple determination (Ra^2) = 0.99
Durbin-Watson statistic = 2.66

The Durbin-Watson statistic is 2,66 (rounded) show, as the foregoing case, a good autocorrelation between the efficiency of steam boiler and the steam pressure.
The residual scatter and the residual probability are similars to the foregoing adjust between the steam pressure and the steam temperature.

Table 4 Coefficients of polynomial dependence between steam boiler efficiency and pressure steam
Coefficient of determination $R^2 = 0,999$

a’	6.06E-036
b’	-4.28E-031
c’	1.34E-026
d’	-2.45E-022
e’	2.90E-018
f’	-2.31E-014
g’	1.26E-010
h’	-4.63E-007
i’	0.0011
j’	-1.51
k’	988.19

2.1.1.4. Discussion of the results

As it is observed in the figure 5, 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 thermodynamis benefits of elevated steam conditions with increased steam pressure.

Although it is a fact that bagasse boilers have been increasing the pressure of the steam, the main cause of diminishing returns in Figure 3 is that the heat of vaporization is reduced as the pressure increases, as seen in any Ts diagram (See Fig. 6). Moreover, increasing the steam pressure in these boilers leads to an increase in the steam temperature. So, the increased steam pressure leads to an increase of the steam temperature in the boiler. As the temperature goes up, the temperature difference between the combustion gases (T_{source}) and steam decreases (See Fig. 7) and less heat is transferred. This leads to a major loss for flue gas, making it less efficient boiler.

The considerations used permits to observe the change step – by – step of efficiency as a function of initial pressure. Though the major trend of growing up the boiler efficiency occur from 3500 to 6000 kPa, where the efficiency boiler grows $\Delta\eta_{gbe}$ = 4,5 %, does not occur these from 7000 to 9500 kPa, where the efficiency only grows $\Delta\eta_{gbe}$ = 3 %, confirming the law of diminishing returns. However, the little difference of 1.5% for different pressure ranges might not be conclusive.

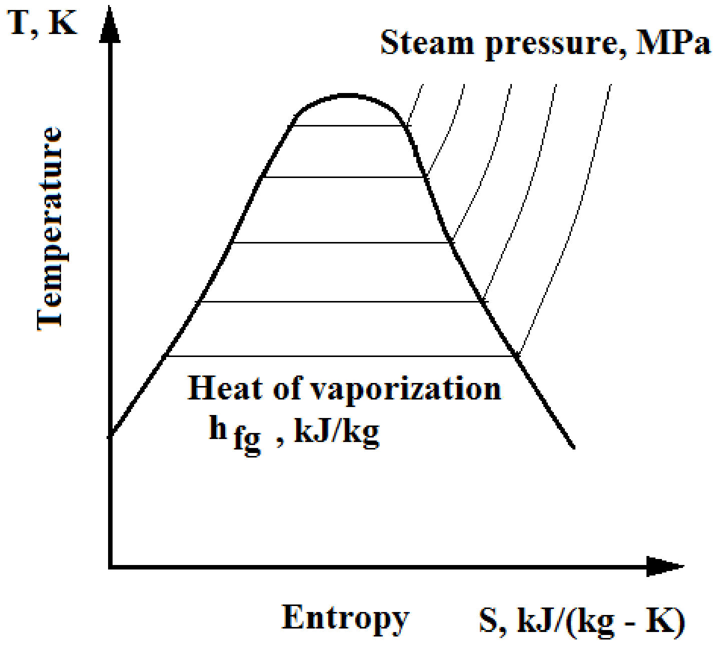

Fig. 6 As the steam pressure increases, it decreases the heat of vaporization hfg, kJ.kg.

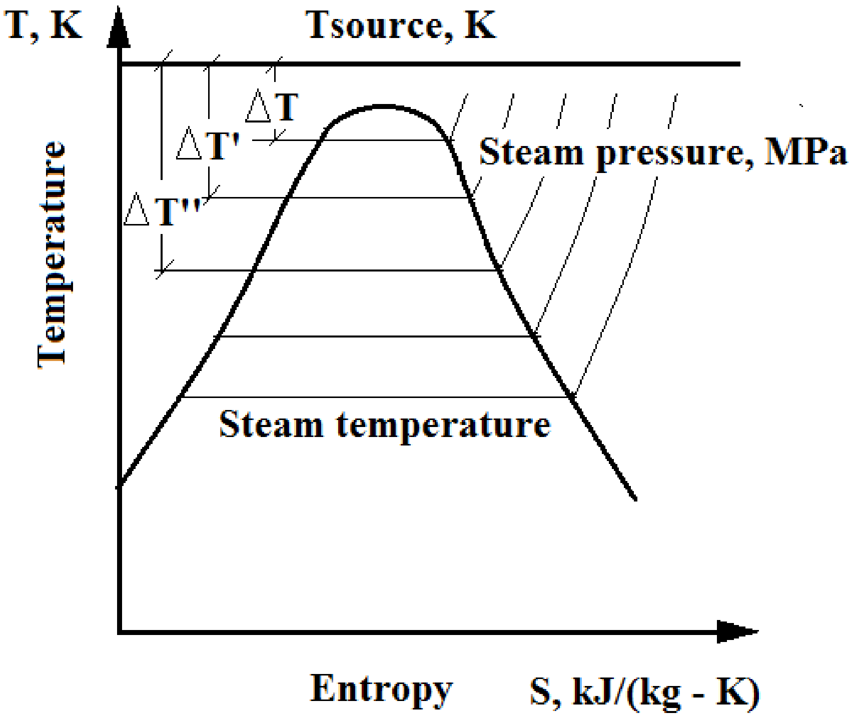

Fig. 7 As the steam pressure increases, the steam temperature increases and decreases the temperature difference with respect to a heat source , Tsource , K.

3.2. Conclusions

The thermodynamic analysis presented in this paper showed to be very useful in the explanation about how the bagasse boilers of actual sugar cane industry are passing through from low to high pressures.

In Fig. 5 is observed the asymmetric nature of the adjustment, that is, the modeled variable η_{gbe} reaction of different modes with increments or decrements of p_1, the transition variable.

The considerations used permits to observe a little change of efficiency as a function of initial pressure, confirming the law of diminishing returns.

More attention must be paid to the improvement because of increase of reheat temperature, as shown in Fig. 2. This shows a linear tendency instead the polynomial tendency of the pressure of the steam boiler.

Nomenclature

BFB	Bubbling Fluid Bed
EES	Engineering Equation Solver software
h	enthalpy, kJ/kg
Q	heat, kJ/kg
M	make – up water, %
$\dot{m}$	mass flow rate, kg/s
NCV	net calorific value, kJ/kg
P	pressure, kPa
R^2	coefficient of determination
T	temperature, ºC
X	quality, fraction

Greek symbols

η	efficiency

Subscripts and superscripts

avlb	Available
f	Fuel
fw	Feedwater
gbe	Gross boiler equipment
hw	Hot water in the drum
m	Main
s	Steam
u	Useful
vol	Volatile matter

1 Inlet of steam turbine

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