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SECOND LAW APPLIED ON BOILERS FUELED BY SUGAR CANE BAGASSE

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Abstract. *In the sugar – alcohol industry, sugar cane bagasse is used to generate steam in the boilers, supplying the thermal energy needed in the processes, and besides that this steam is used to cogenerate electrical and mechanical energy to supply the industrial needs and also to sell the surplus to the grid. Boiler exergetic efficiency directly indicates the maximum system cogeneration efficiency theoretically achievable. Due to recent increase in practiced cogeneration levels, exit boiler steam pressure is being increased joined with the combustion gas exit temperature. Other aspect is that the bagasse presents about 50% of moisture. These facts request for improving the utilization of the gas exit energy that can be used for pre-heating the combustion air and boiler feeding water or for drying the bagasse. The aim of this study is to assess, through the first and second law analyses, two kinds of setups: the first is made up of a steam generator, an air heater and an economizer, and the second one is made up of a steam generator, an air heater and a bagasse dryer. Two proposals were used to asses the first law boiler efficiency: Beatón and Lora Proposal's and the ASME PTC 4.1 proposal. In this study, the spontaneous ignition temperature of sugar cane bagasse was considered in the assumed dryer temperature levels.*

Keywords*.* *bagasse, dryer, cogeneration, exergetic analyses, boiler*

Nomenclature

a= theoretical air flow, [kmol/s];
e = air flow [kmol/s];
f, g h, i = combustion products flow [kmol/s];
exe= specific exergy [kJ/kg];
h= specific enthalpy [kJ/kg];
nf= fuel flow [kmol/s];
n_C, n_H, n_O = dry mass of fuel flow, [kmol/s].
HHV= Higher heating vale [kJ/kg];
LHV= Lower heating value [kJ/kg];
BMC = bagasse moisture content (w.b);
$\dot{m}$ = mass flow rate [kg/s];
P_0= reference pressure [bar];
Q = Heat flow [kW];
s= specific entropy [kJ/kg K];
T_0= reference temperature [C];
T_{0K} = reference temperature [K];
w= bagasse water content [w.b.]
z= mass fraction of the components of fuel [%]
af= fuel ash fraction [%]
cf= fixed carbon content [%]
qa= available heat of bagasse (kJ/kg);
q_2^* = Heat loss due sensible heat of dry gas [%]
q_2 = exhaust gases heat losses [%];
q_3 = Incomplete chemical combustion heat losses [%];
q_4 = Heat loss by incomplete combustion due to mechanical causes [%];
q_5 = Heat losses due to surface radiation and convection [%];
q_6 = Heat losses by slag and ashes [%];
q_7 = heat loss by bleeding [%];
q_8^* = Heat loss due evaporation of water formed from hydrogen in the fuel [%];
q_9^* = Heat loss due evaporation of water from bagasse moisture content [%];
$q_{ph,b}$ = physical enthalpy of fuel [kJ/kg];
c_p= specific heat of bagasse [kJ/kg K]
T_{satu} = Temperature of saturation at boiler pressure [ºC]

Greek symbols
λ = enthalpy of water vaporization [kJ/kg];
ξ = exergetic efficiency [%];
β = ratio of standard chemical exergy [-];
ε = effectiveness [%];
η = efficiency by first law [%];
Ø = air excess coefficient [-];

Subscripts
a, b, db g, dg, w, vap, liq = air, bagasse, dry bagasse, gas, dry gas, water, vapor, liquid.
H, C, O, N, H2O, S = hydrogen, carbon, oxygen, nitrogen, water and sulphur (%)
l, SG, ECO, AH, gr, wh, un= lost, steam generator, economizer and air heater, grate, washing, unburned.
wh = Water vapour from fuel hydrogen
wBMC = Water vapour formed from BMC.
p = bleeding of boiler.
chem., phy = chemical, physical.
OECO = economizer outlet;
IECO = economizer inlet;
OAH = air heater outlet;
IAH = air heater inlet;
ID = dryer inlet;
OD = dryer outlet.

1. Introduction

The industry of sugar and alcohol is privileged, because it generates its own fuel, the sugar cane bagasse. This industry produces, by cogeneration, electrical energy for itself and for the market.

Industrialization and population growth have led to a sharp increase in power demand. Thus, the economic and social growth of many countries is jeopardizing. In fact, in sugar cane producing countries, the cogeneration of energy in sugar cane mills is becoming an excellent alternative solution to this problem (Therdyothin et al. 1992, Sharma and Sharma, 1999; and Ibarra and Medellin, 2004).

Currently, the boiler steam pressure and temperature increase is resulting very interesting to sugar cane mills, which presents your maximum values at 67 bar and 520ºC. Even though, other productive sectors, such as, paper industry are operating with 120 bar and 520ºC (Kawano, 2006).

Therefore, the *Sucroalcooleiro* sector needs studies on the parameters that affect the bagasse boiler efficiency aiming to optimize its performance. The objective of this paper is to analyze two arrangements through two proposals Beatón and Lora and ASME PTC 4.1. The exergetic analysis on bagasse boiler also was applied.

2. Systems analyzed

The arrangements analyzed in this work are commonly denominated *sequential*. The first arrangement is made up by a steam generator, an air heater and an economizer Fig. (1); whilst the second arrangement is made up by a steam generator, an air heater and a dryer Fig (2). They were chosen considering arrangements that are used at industry. Perhaps, in the first one, the position of air heater and economizer could be inverted.

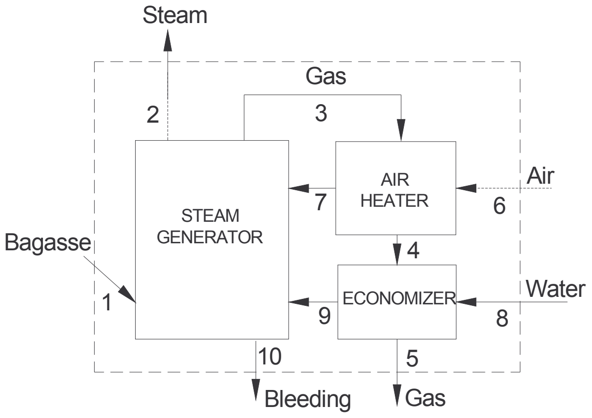

Figure 1. First arrangement made up a steam generator, an air heater and an economizer.

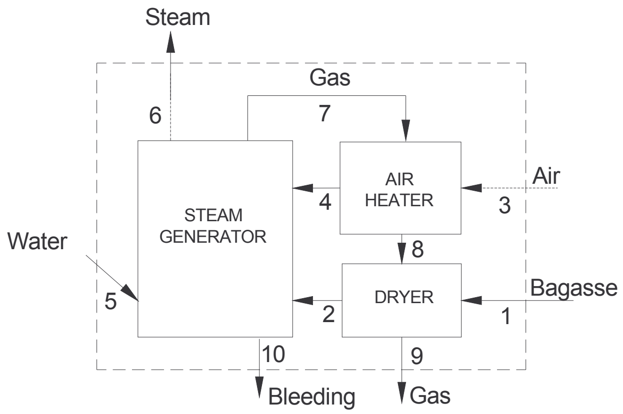

Figure 2. Second arrangement made up a steam generator, an air heater and a dryer.

3. Calculation Methodology

The temperature and pressure parameters of exit boiler steam, used in this work, were the following: P=21 bar, T=320ºC; P=62 bar, T= 480ºC and P=120 bar, T=560ºC. The first two parameters correspond to boilers commercially produced by Equipalcool Industry. The last pair of parameters was considered aiming to analyze the effect of steam temperature and pressure increasing.

3.1 Bagasse composition

Bagasse composition is function of the following factors: cane characteristics, soil type, season, harvest type and extraction method. Baloh and Wittwer (1995) compiled bagasse analysis of different authors. They assumed an average composition, which has 47% of carbon, 6.5 % of hydrogen, 44 % of oxygen and 2.5% of ashes (not considered in the formulation, because they do not react). The percentages are based on dry mass.

3.2 Bagasse combustion.

As is usual in this type of boilers, the combustion was supposed to be with air in excess, and since the purpose of this work is to perform only an energy balance, generation of CO and NO_x, as well as other products as result of incomplete combustion were not considered. The generated substances were determined by the combustion equation. Ideal gas conditions were considered. Air composition was 21 % of oxygen and 79 % of nitrogen (the entrance air humidity was not considered). One kilogram of dry mass of fuel was taken as a base. The balance equation for air in excess conditions is presented in Eq. (1). In stoichiometric combustion conditions, the "h" term is zero.

$$(n_C \cdot C + n_H \cdot H + n_O \cdot O) + e \cdot (O_2 + 3.76 \cdot N_2) = f \cdot CO_2 + g \cdot H_2O + h \cdot O_2 + i \cdot N_2 \tag{1}$$

The air excess is calculated following Eq. (2), proposed by Beaton and Lora (1991), which takes into account that less excess of air is necessary to burn bagasse less humid (*w* is the bagasse moisture content, wet base).

$$\phi = -2{,}5 + 75w \tag{2}$$

The excess air-fuel ratio ($AF_{molar,\ exc}$) is presented in Eq. (3):

$$AF_{molar,exc} = e\left(\frac{1+3.76}{nf}\right) \tag{3}$$

Where the dry fuel flow, n_f, in kmol/s is:

$$nf = n_c + n_H + n_O \tag{4}$$

The Eq. (5) permits to determine the air excess trough the coefficient of air excess ϕ.

$$1 + \frac{\phi}{100} = \frac{AF_{molar,excess}}{AF_{molar,teo}} = \frac{e}{a} \tag{5}$$

Where $AF_{molar,teo}$ represent the theoretical air-fuel ratio, in stoichiometric combustion conditions.

3.3 Boiler Efficiency

The code ASME PTC 4.1 (1975) describes two methods to determine the boiler efficiency: the *input-output* and the *heat loss* method.

The boiler efficiency determined by the heat loss method presents values more accurate than that obtained through the input-output method. Also, it permits identify the heat losses that happens in the boiler. Therefore, it is possible to solve problems, improving the boiler efficiency and performance (ASME PTC 4-1998)).

In boiler fuelled by sugar cane bagasse is very difficult to measure the cane bagasse mass flow, therefore, the boiler efficiency determination through the heat loss method is a common practice, and then, with this value in hands, the cane bagasse mass flow is calculated (Beatón and Lora 1991; Acosta 1995; Sanchez et al. 2001 and Sosa-Arnao et al. 2005a). In this paper are presented two proposals, both based on the heat loss method and applied to arrangements proposed, to determine the boiler efficiency: The Beatón and Lora's proposal (1991) and the code ASME PTC 4.1 proposal (1975).

3.3.1 Beatón and Lora proposal: (Proposal I)

In this proposal, to calculate the boiler efficiency, the bagasse lower heating value (LHV.) is considered as base, so the heat absorbed to evaporate the water contained in the bagasse and also that formed by oxidation of hydrogen content are discounted from the higher heating value (HHV).

The boiler efficiency is determined from the sum of all heat loss fractions, Eq. (6).

$$\eta_{boiler} = 100 - (q_2 + q_3 + q_4 + q_5 + q_6 + q_7)\ \% \tag{6}$$

The bagasse lower heating value LHV (kJ/kg) can be determined by the correlation below Eq.(7), proposed by Hugot (1964).

$$\mathrm{LHV} = 17790 - 50.23\,\mathrm{s} - 203\,\mathrm{w} \tag{7}$$

If the fuel is heated above the reference temperature (as in the case of the dryer use), the physical enthalpy of fuel ($q_{ph,b}$) can be determined by Eq. (8)

$$q_{ph,b} = c_p \cdot (T - T_0),\ \text{kJ/kg} \tag{8}$$

In the entire calculation, a temperature of 25°C was taken as reference.

Therefore, the available heat from fuel (q_a) is:

$$q_a = LHV + q_{ph,b},\ \text{kJ/kg} \tag{9}$$

These authors considered the following heat loss:

(i) Exhaust gases heat losses (q_2): Among all heat loss fractions, this is the most significant and it is function of exhaust gas mass flow and temperature (Beatón and Lora 1991). In the enthalpy calculation of exhaust gas is considered the sensible heat from T → T_0. The next equation (10) allows to calculate it:

$$q_2 = \frac{m_g\left(\cdot h_{g,OECO} - h_{g,0}\right)}{m_b q_{ph,b}} \cdot \left(100 - q_4\right), \% \tag{10}$$

(ii) Incomplete chemical combustion heat losses (q_3): These losses are related to CO, H_2 and CH_4 formation, as well as other products resulting of an incomplete combustion. Those elements were previously neglected, thus this loss was done equal to zero. Anyway it is very well know that this loss is small due to the fact the combustion happens with a good quantity of air excess. (Acosta, 1995)

iii) Heat loss by incomplete combustion due to mechanical causes (q_4): is a fraction referred to unburned fuel particles, that go out mixed with the ashes, or are carried by the exit gases. It is calculated by the following equation:

$$q_4 = \left(af_{gr} \cdot \frac{cf_{gr}}{100 - cf_{gr}} + af_{AH} \cdot \frac{cf_{AH}}{100 - cf_{AH}} + af_{wh} \cdot \frac{cf_{wh}}{100 - cf_{wh}} \right) \cdot \frac{327.9 \cdot m_{ashes}}{q_a}, \% \tag{11}$$

iv) Heat losses due to surface radiation and convection (q_5): The correct way to calculate these losses would be equating all the heat exchanged by convection and radiation from boiler walls to the environment, but, in practice terms, this work would take a lot of time and also a lot of measurements need to be done. Thus a solution for the q_5 calculation is to use the ABMA standard radiation loss chart (ASME PTC 4.1, 1975), which is based on an average boiler wall temperature, measured by the staff. To use this abacus, its calculation base, HHV, needs to be converted to LHV used by Beatón and Lora. These authors also presented a chart to determine the radiation and convection boiler heat loss, but in that chart, the heat loss is only function of steam mass flow and it does not offered difference when different pressure and temperature of steam are used. So, the ABMA chart was preferred (Sosa-Arnao et al. 2006).

(v) Heat losses by slag and ashes (q_6): The last lost fraction refers to sensible heat lost by slag and ashes. According Beatón and Lora (1991), this fraction is responsible for less than 0.1 % of the available heat, therefore it can be neglected.

3.3.2 The Code ASME PTC 4.1 proposal: (Proposal II)

This proposal is based on HHV of the fuel, and it also requires the determination of losses, heat credits, ultimate analysis. It considers the same heat losses than Beatón and Lora proposal (q_3, q_4, q_5, and q_6) but the calculation base is different. So, there are differences in the analysis of boiler exhaust gas heat loss (q_2), according ASME PTC 4.1, this heat loss is separated in dried gas heat loss (q_2*), heat loss due water vapour from burning hydrogen (q_8) and heat loss due BMC (q_9).
The boiler efficiency is determined from the sum of all heat loss fractions, Eq. (12).

$$\eta_{boiler} = 100 - (q_2^* + q_3 + q_4 + q_5 + q_6 + q_7 + q_8^* + q_9^*) \ \% \tag{12*}$$

$$q_a^* = HHV + q_{ph,b} \tag{13*}$$

(vi) Heat loss due sensible heat of dry gas (q_2*),

$$q_2{}^* = \frac{m_{dg} h_{g,OECO} \left(100 - q_4\right)}{m_b q_a^*} \% \tag{14*}$$

vii) Heat loss due evaporation of water formed from hydrogen in the fuel (q_8)

$$q_8^* = \frac{m_{wh,OECO}\left(h_{wh,OECO} - h_{wh,0}\right)}{m_b q_a^*} 100 \% \tag{15*}$$

vii) Heat loss due evaporation of water from bagasse moisture content (q_9)

$$q_9^* = \frac{m_{wBMC,OECO}\left(h_{w,BMC,OECO} - h_{wBMC,0}\right)}{m_b q_a} 100\ \% \tag{16*}$$

In this work was considered, for both proposals, besides the heat losses mentioned above, the heat loss by bleeding in boiler (q_7). This heat loss was considered corresponding at 2% of boiler heat loss, according Acosta (1995).

3.4 Air Heater (First and Second arrangement)

The steam generator exit gases temperature ($T_{g,OSG}$) was determined through the Eq. (17). From a series of boiler data (Dalmazo 2005), a relationship was obtained (Eq. 17), between the exit gas temperature and the steam saturation temperature (T_{satu}) at the exit steam pressure.

$$T_{g,OSG} = 42.493 T_{satu}{}^{0.3962} \tag{17}$$

The air heater inlet cold air temperature was adopted as the average environment temperature, T_0=25°C. It was considered also that 1.17% of the interchanged heat is lost ($Q_{L,AH}$), according (Sanchez 2003).

The air heater gases exit temperature ($T_{g,OAH}$) was varied between 200°C and 300°C, in the first arrangement; and between 160ºC and 210ºC, in the second one. This choice was done to avoid higher temperatures in the dryer, which can conduct to bagasse self-ignition.

The steam generator inlet air temperature ($T_{a,ISG}$) was determined through air heater energy balance Eq. (18), for both arrangements.

$$m_g\left(h_{g,IAH} - h_{g,OAH}\right) = m_a\left(h_{a,OAH} - h_{a,IAH}\right) + Q_{L,AH} \tag{18}$$

The exergetic efficiency was calculated according Eq. 19.

$$\xi_{AH} = \left(\frac{m_a\left(h_{a,OAH} - h_{a,IAH} - T_{0K}\left(s_{a,OAH} - s_{a,IAH}\right)\right)}{m_g\left(h_{g,IAH} - h_{g,OAH} - T_{0K}\left(s_{g,IAH} - s_{g,OAH}\right)\right)}\right)100 \tag{19}$$

The effectiveness of air heater (ε_{AH}) was calculated by Eq. (20).

$$\varepsilon_{AH} = \left(\frac{m_g\left(h_{g,IAH} - h_{g,OAH}\right)}{m_a\left(h_a(T_{g,IAH}) - h_{a,IAH}\right)}\right)100 \tag{20}$$

This equipment was modeled following Eq. 17, 18, 19 and 20 for both arrangements.

3.5 Economizer (First arrangement)

The economizer inlet water temperature ($T_{w,IECO}$) was adopted as 112°C (Sanchez 2003). The economizer exhaust gas temperature ($T_{g,OECO}$) was considered as 155ºC, which is a very common value in cane bagasse boilers. It was considered that 1% of interchanged heat is lost ($Q_{L,ECO}$). The steam generator inlet water temperature ($T_{w,ISG}$) is the unknown variable in the economizer energy balance Eq. (21):

$$m_g\left(h_{g,IECO} - h_{g,OECO}\right) = \left(m_w + m_p\right)\left(h_{w,OECO} - h_{w,IECO}\right) + Q_{L,ECO} \tag{21}$$

The economizer exergetic efficiency (ξ_{ECO}) was defined through two types of equations, Eq. (22) and (23). The differences between these equations are that the irreversibility due to the gas heat loss are not considered in Eq. (22) and are considered in Eq. (23), what means that in this last case, the economizer is penalized by an exergy loss that belongs in fact at the entire system.

$$\xi_{Eco,I} = \left(\frac{\left(m_w + m_p\right)\left(h_{w,OECO} - h_{w,IECO} - T_{0K}\left(s_{w,OECO} - s_{w,IECO}\right)\right)}{m_g\left(h_{g,IECO} - h_{g,OECO} - T_{0K}\left(s_{g,IECO} - s_{g,OECO}\right)\right)}\right)100 \tag{22}$$

$$\xi_{Eco,II} = \left(\frac{\left(m_w + m_p\right)\left(h_{w,OECO} - h_{w,IECO} - T_{0K}\left(s_{w,OECO} - s_{w,IECO}\right)\right)}{m_g\left(exe_{g,phy,3} + exe_{g,chem}\right)}\right)100 \tag{23}$$

The gases physical and chemical exergies, ($exe_{g,phy}$) and ($exe_{g,chem}$), are obtained through Eq. 24 and 25, respectively.

$$exe_{g,phy} = h_{g,IECO} - h_{g,0} - T_{0K}\left(s_{g,IECO} - s_{g,0}\right) \tag{24}$$

$$exe_{g,chem} = y_{CO_2} exe_{chem,CO_2} + y_{H_2O} exe_{chem,H_2O} + y_{N_2} exe_{chem,N_2} \tag{25}$$

The values of the chemical exergies of pure substances were taken from Szargut et al (1988).

The effectiveness of the economizer can be calculated following Eq. (26).

$$\varepsilon_{ECO} = \left(\frac{m_g\left(h_{g,IECO} - h_{g,IECO}\right)}{m_w\left(h_w(T_{g,IECO}) - h_{w,IECO}\right)}\right)100 \tag{26}$$

3.6 Dryer (Second Arrangement)

It was assumed that the combustion gases withdraw moisture from the bagasse up to theoretical limit; therefore the exit gases will reach the adiabatic-saturation temperature of the combustion gases. In this arrangement, the dryer receives the gases from the air heater at $T_{g,OAH}$ and the bagasse with 50% moisture (wet basis) at T_0. It was also assumed that the humid bagasse reaches the adiabatic-saturation temperature. The adiabatic – saturation temperature calculation can be found in Sosa-Arnao (2005a). Moreover, it was considered that 1.0% of the interchanged heat is lost ($Q_{l,d}$). The dryer energy balance is shown bellow (Eq. 27):

$$\begin{aligned} &\mathrm{m_g} \cdot \left(\mathrm{h_{g,OAH}} - \mathrm{h_{g,OD}}\right) = \mathrm{m_{db}} \cdot \left(\mathrm{w_{db,ID}} - \mathrm{w_{db,OD}}\right) \cdot \left(\mathrm{h_{w,vap}} - \mathrm{h_{w,0}}\right) + \\ &\mathrm{m_{db}} \cdot \mathrm{c_{p,db}} \cdot \left(\mathrm{T_{sat}} - \mathrm{T_0}\right) + \mathrm{m_{db}} \cdot \mathrm{w_{db,OD}} \cdot \left(\mathrm{h_{w,liq}} - \mathrm{h_{w,0}}\right) + Q_{l,d} \end{aligned} \tag{27}$$

The calculation of dryer exergetic efficiency can be analyzed trough inlet/outlet efficiency method, because it is dissipative operation. Even though, since there are products from this operation, dryer efficiency was analyzed also trough of product/insumo efficiency method.

Dryer product/insumo exergetic efficiency ($\xi_{dryer,IP}$): It was considered two products in this analysis; i) evaporated water exergy (Eq. 28) and ii) cane bagasse exergy (Eq. 29).

$$\xi_{dryer,IP} = \frac{m_w\left(h_{w,vap} - h_{w,liq} - T_{0,K}\left(s_{w,vap} - s_{w,liq}\right)\right)}{m_{g,ID}\left(h_{g,ID} - h_{g,0} - T_{0,K}\left(s_{g,ID} - s_{g,0}\right)\right)} * 100 \tag{28}$$

The exergy of dryer evaporated water is lost, when it mixtures whit atmosphere gas. Therefore, it can be unconsidered.

When cane bagasse is dried its exergy increases. Therefore; the cane bagasse exergy increase was considered as product, Eq. 29.

In Eq. 28 and 29, the insumo was the gas flue exergy.

$$\xi_{dryer,IP} = \frac{m_{b,OD} exe_{b,OD} - m_{b,ID} exe_{b,ID}}{m_{g,ID}\left(h_{g,ID} - h_{g,0} - T_{0,K}\left(s_{g,ID} - s_{g,0}\right)\right)} * 100 \tag{29}$$

Dryer inlet/outlet exergetic efficiency ($\xi_{dryer,IO}$): It was determined trough Eq. 30; outlet bagasse exergy and outlet gas flue exergy represent the dryer outlet exergy whilst inlet bagasse exergy and inlet gas flue exergy represents the dryer inlet exergy.

$$\xi_{dryer,IO} = \frac{m_{b,OD} exe_{b,OD} + m_{g,OD}\left(h_{g,OD} - h_{g,0} - T_{0,K}\left(s_{g,OD} - s_{g,0}\right)\right)}{m_{b,ID} exe_{b,ID} + m_{g,ID}\left(h_{g,ID} - h_{g,0} - T_{0,K}\left(s_{g,ID} - s_{g,0}\right)\right)} * 100 \tag{30}$$

3.7 Steam Generator (First and Second Arrangement)

Since several conditions of exit boiler steam temperature and pressure were established; a balance equation as Eq.(31) can be written. The steam generator heat loss by radiation and convection ($Q_{L,SG}$), was determined from the heat loss in whole boiler, determined using the ABMA standard radiation loss chart (ASME PTC 4.1, 1975). The radiation and convection heat loss in the air heater and the economizer were discounted from the total value, obtaining the radiation and convection heat loss for steam generator Eq. (33). The bleed mass flow is determined from the heat loss due bleeding in the boiler (q_7). The heat loss by mechanical unburned in the steam generator ($Q_{L,un}$) is calculated from the heat loss due to this effect (q_4), Eq. (34). This relationship is obtained from Beatón and Lora's proposal and it was applied for both proposals.

$$m_w\left(h_{s,OSG}-h_{w,ISG}\right)+m_p\left(h_{w,OSG}-h_{w,ISG}\right)+Q_{L,SG}+m_g h_{g,OSG}+Q_{L,un}=m_b LHV+m_a h_{a,ISG} \tag{31}$$

$$q_5=\frac{Q_{L,boiler}}{m_b HHV}100 \tag{32}$$

Therefore: The boiler heat loss $Q_{l,boiler}$ was calculated through q_5.

The steam generator heat losses are obtained through the Eq. (33)

$$Q_{L,SG}=Q_{L,boiler}-Q_{L,ECO}-Q_{L,AH} \tag{33}$$

$$Q_{L,un}=\left(\frac{q_4}{100}\right)q_a \tag{34}$$

The steam generator exergetic efficiency (ξ_{SG}) is calculated through Eq. (35).

$$\xi_{SG}=\left(\frac{m_w\left(h_{s,OSG}-h_{w,ISG}-T_{0K}\left(s_{s,OSG}-s_{w,ISG}\right)\right)}{m_b exe_b+m_a\left(h_{a,ISG}-h_{a,OSG}-T_{0K}\left(s_{a,ISG}-s_{a,OSG}\right)\right)-m_g\left(exe_{g,phy}+exe_{g,chem}\right)}\right)100 \tag{35}$$

The exergetic efficiency of boiler (ξ_{Boiler}), which correspond to that of the entire system, is determined trough Eq. (36)

$$\xi_{boiler}=\left(\frac{m_{s,OSG}\left(h_{s,OSG}-h_{w,ISG}-T_{0K}\left(s_{s,OSG}-s_{w,ISG}\right)\right)}{m_b exe_b}\right)100 \tag{36}$$

The calculation procedure into steam generator is similar in both arrangements. But, in second arrangement, the bagasse mass flow and the bagasse heating lower value varied due to bagasse drying. In this last case the boiler outlet gas temperature varied slowly, about (74ºC), which is lower than that one in first arrangement (155ºC).

3.8 Exergy of sugar cane bagasse

There are two methodologies to determine the exergy of sugar cane bagasse: The methodology of Szargut et al. (1988) and the methodology of Wittwer (1993). Even though the exergy of sugar cane bagasse is adapted from wood exergy calculation (methodology of Szargut et al. 1988), it is more robust than the methodology of Wittwer (Sosa-Arnao and Nebra, 2005b). Therefore, the exergy of bagasse was determined through Eq. (38).

$$\beta=\frac{1.0412+0.2160\left({}^{z_{H_2}}\!/_{z_C}\right)-0.2499\left({}^{z_{O_2}}\!/_{z_C}\right)\left[1+0.7884\left({}^{z_{H_2}}\!/_{z_C}\right)\right]+0.045\left({}^{z_{N_2}}\!/_{z_C}\right)}{1-0.3035\left({}^{z_{O_2}}\!/_{z_C}\right)} \tag{37}$$

$$Exe_b=\beta\left(LHV+\lambda z_w\right)+9683 z_S+b_{ch,ash}z_{ash}+b_{chem,w}z_w \tag{38}$$

4. Results

The distribution of boiler heat losses, for first and second arrangement, according proposals Beatón and Lora's and ASME PTC 4.1 are presented in the Fig. 3, 4; respectively.

To compare these results, a detail must be kept in mind: the total heat losses considered in both methods are not the same. The ASME PTC 4.1 considers the loss q_8 and q_9, that are the biggest in that method. Moreover, the total heat losses corresponding to each arrangement are also different between them.

According Beatón and Lora's proposal, in first arrangement, the biggest heat loss is represented by the exhaust gas heat loss (q_2=9.4%), which corresponds the 68.8 % of total heat loss. The other heat losses, such as, that due chemical unburned (q_3=0%), mechanical unburned (q_4=1.9%), radiation and convection (q_5=0.40%), slag (q_6=0%) and bleeding (q_7=2%) are lower. In second arrangement, the biggest heat loss is represented by the exhaust gas heat loss (q_2=3.33%), which correspond the 43.8% of total heat loss. Then, heat losses by bleeding (q_7=2%), by mechanical unburned (q_4=1.9%), by radiation and convection (q_5=0.43%), by chemical unburned (q_3=0%) and slag (q_6=0%) were determined.

According ASME PTC 4.1 proposal, in the first arrangement, the biggest heat losses is represented by the evaporation of BMC (q_9=14%), the second biggest is due to the evaporation of water vapour formed from hydrogen in the bagasse (q_8=8.2%), then comes the heat loss due dry exhaust gas (q_2 =5.5 %). The other heat losses, such as, q_3=0%; q_4= 0.7%; q_5= 0.33% and q_6= 0% are lower. In the second arrangement, the biggest heat loss is represented by the evaporation of bagasse moisture content (q_9=13.3%), which correspond to 49.78%, the second biggest is due to the evaporation of water formed from hydrogen in the bagasse (q_8=7.7%). The other heat losses, such as, (q_2 =1.9%), q_3= 0%; q_4= 1.5%; q_5= 0.4% and q_6= 0% are lower.

The heat loss decrease, in second arrangement, is produced basically by outlet gas temperature decrease. It observes the dry gas heat loss decrease (q_2), in second arrangement, when compared with first one (Fig. 3 and 4). These results correspond to the parameters following: exit steam pressure and temperature (62 bar, 480ºC) and bagasse moisture content of 35% (w.b) at steam generator inlet.

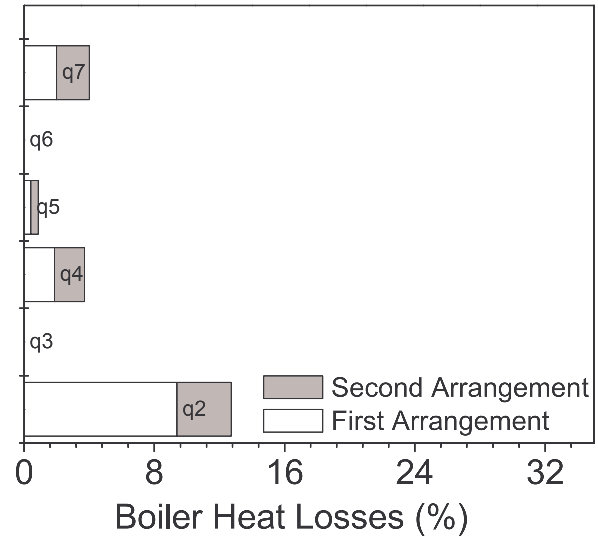

Figure 3 – Distribution boiler heat losses – First and Second Arrangement (Beatón and Lora's proposal)

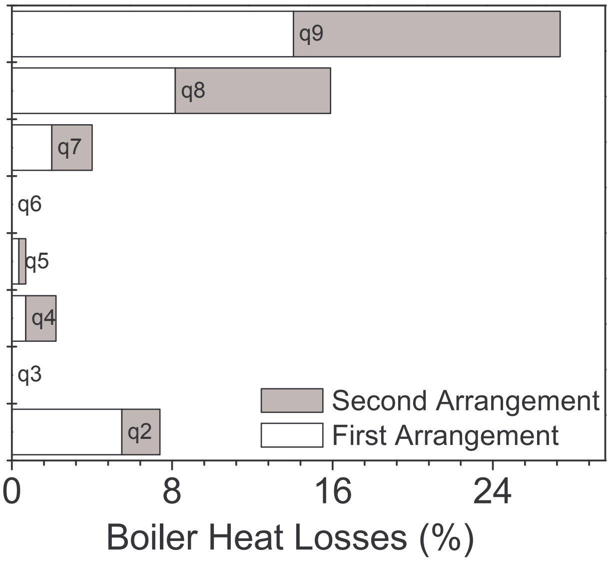

Figure 4 – Distribution boiler heat losses – First and Second Arrangement (PTC 4.1 proposal).

The boiler efficiency, for arrangements first and second, analyzed trough both proposals, is presented in the Fig. 5 and 6 respectively. The boiler efficiency obtained trough Beatón and Lora's proposal was higher than that ASME PTC 4.1 proposal, about 25% and 21% in the first and second arrangement, respectively. In the first arrangement, the boiler efficiency does not vary with the outlet gas temperature of air heater, but varies slowly when exit steam temperature and pressure increases, its maximum values were 69.2 % and 86.3 %, respectively. In the second arrangement, Fig. 6, the boiler efficiency slowly increases with the increase of air heater outlet gas temperature and exit steam temperature and pressure. This happens because that when the boiler output energy increases the proportional radiation and convection heat loss (q_5) decreases whilst the others proportional heat loss does not vary. The maximum boiler efficiency values obtained, through both proposals, were 73.23%, 92.39%, respectively.

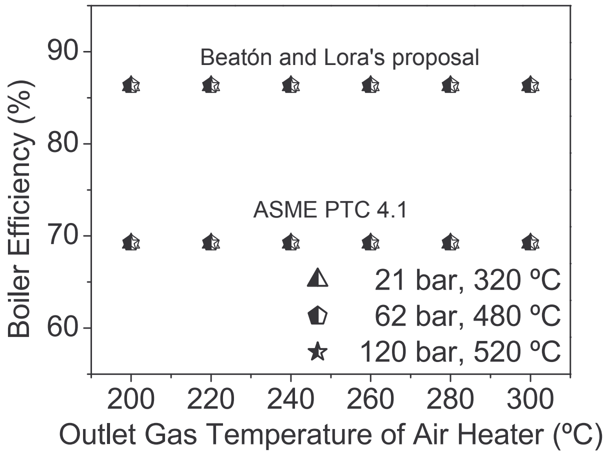

Figure 5: Boiler Efficiency with Outlet gas temperature of air heater for different levels of boiler pressure and temperature – First arrangement.

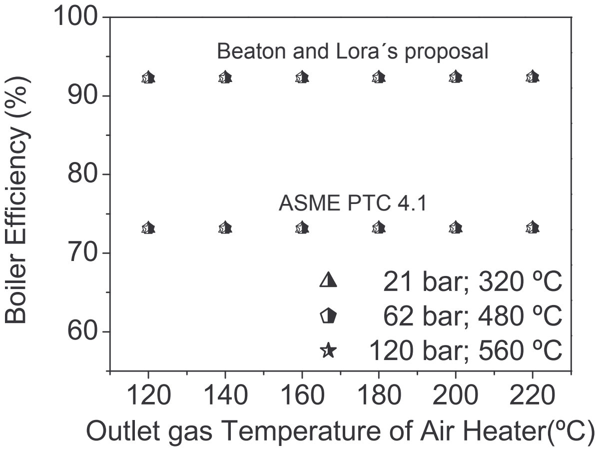

Figure 6: Boiler Efficiency with Outlet gas temperature of air heater for different levels of boiler pressure and temperature – Second arrangement.

The second arrangement presents better boiler efficiency than first one. This fact happens due to that the outlet gas temperature of boiler in the second arrangement (74ºC) is lower than first one (155ºC).

The Fig. 7 and 8 shows the air heater effectiveness with the outlet gas temperature of air heater, for the arrangement first and second, respectively. Also, the Fig. 9 and 10 presents the air heater exergetic efficiency with the outlet gas temperature of air heater for arrangements first and second, respectively.

In both arrangements, the air heater effectiveness and exergetic efficiency increases when the outlet gas temperature of air heater decrease. Since, second arrangement permits the drying operation process with lower gas temperature than first arrangement; it is possible to obtain better air heater exergetic efficiency and effectiveness of air heater. With a good dryer design, it is possible to dry the cane bagasse from 50% until 35% of BMC (w.b.) using gas heat at about 210ºC until 74ºC. It is an important advantage of second arrangement.

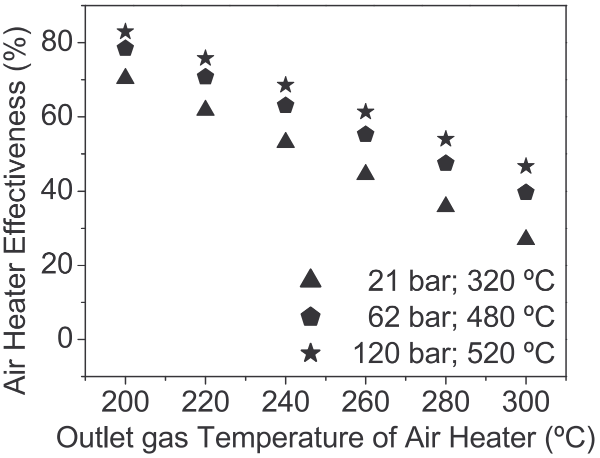

Figure 7: Air heater effectiveness with Outlet gas temperature of air heater for different levels of boiler pressure and temperature – First Arrangement.

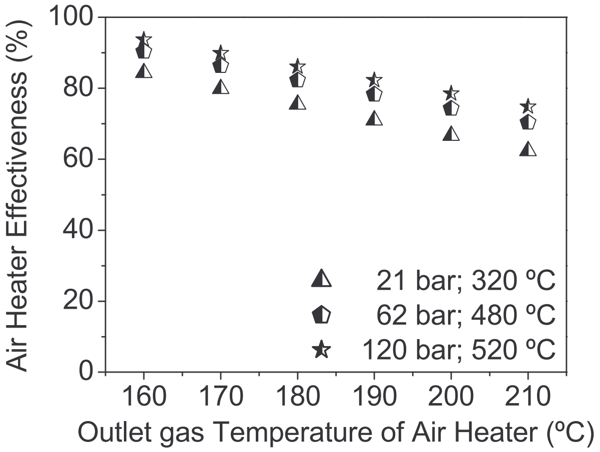

Figure 8: Air heater effectiveness with Outlet gas temperature of air heater for different levels of boiler pressure and temperature – Second Arrangement.

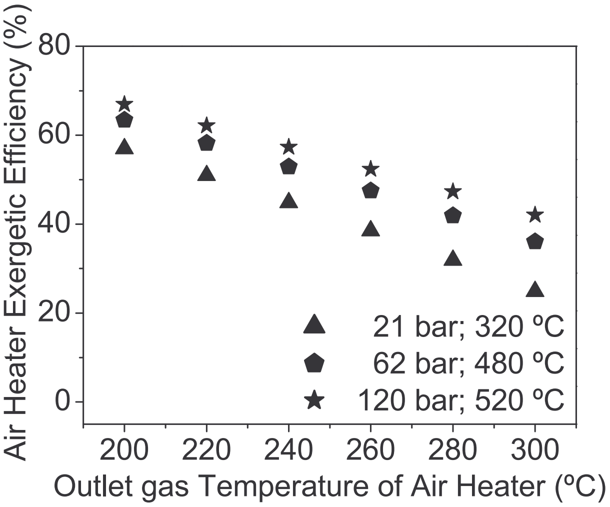

Figure 9: Air heater exergetic efficiency with Outlet gas temperature of air heater for different levels of boiler pressure and temperature – First arrangement.

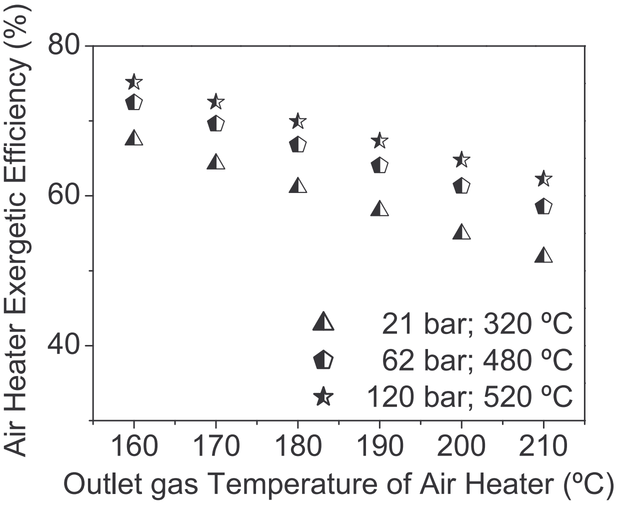

Figure 10: Air heater exergetic efficiency with Outlet gas temperature of air heater for different levels of boiler pressure and temperature – Second arrangement.

The economizer exergetic efficiency was analyzed through two view points. In Fig. (11), the irreversibility due to the gas heat loss is not considered; in Fig (12), it is considered. In other words, in this last case, the economizer is penalized by an exergy loss that belongs in fact at the entire system.

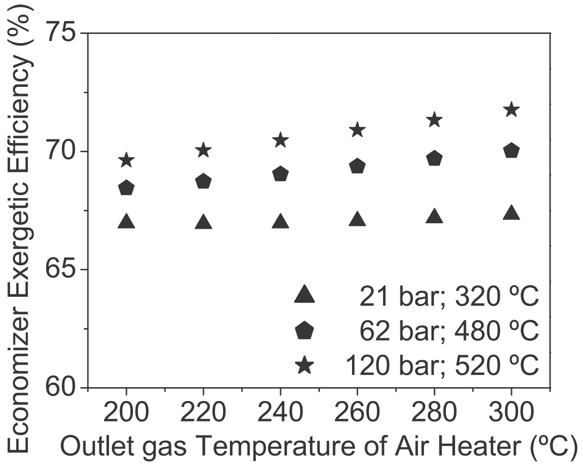

Figure 11: Economizer exergetic efficiency with Outlet gas temperature of air heater for different levels of boiler pressure and temperature - The economizer is not penalized – First Arrangement.

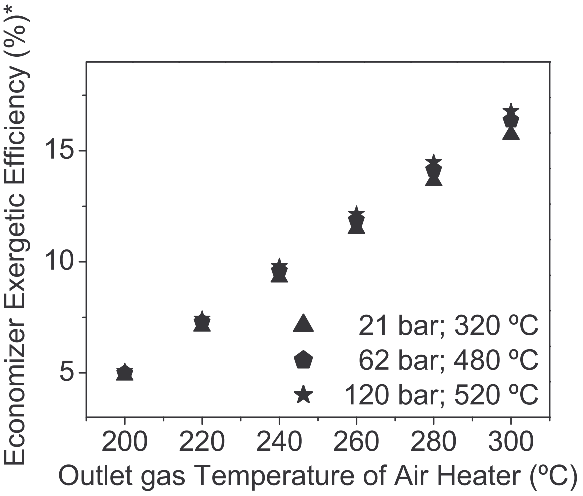

Figure 12: Economizer exergetic efficiency with Outlet gas temperature of air heater for different levels of boiler pressure and temperature - The economizer is penalized – First Arrangement.

In Fig. 13 and 14 are presented the dryer exergetic efficiency obtained through methods insumo/product and inlet /outlet, respectively. In Fig. 13, it can be observed that the dryer exergetic efficiency, obtained through insumo/product method, varied slowly with air heater outlet gas temperature increase. Two products were considered: evaporated water exergy and bagasse cane exergy. In this operation, the exergy of cane bagasse increases even though its flow mass decreases. In Fig14, it observed that the dryer exergetic efficiency, obtained through inlet/outlet method, decreases slowly when the outlet gas temperature of air heater increase. To determine the dryer exergetic efficiency is not easy. Between the analyzed methods the insumo/product one, when product is bagasse cane exergy, showed an interesting criterion, since, this fact directly affects the boiler performance and efficiency.

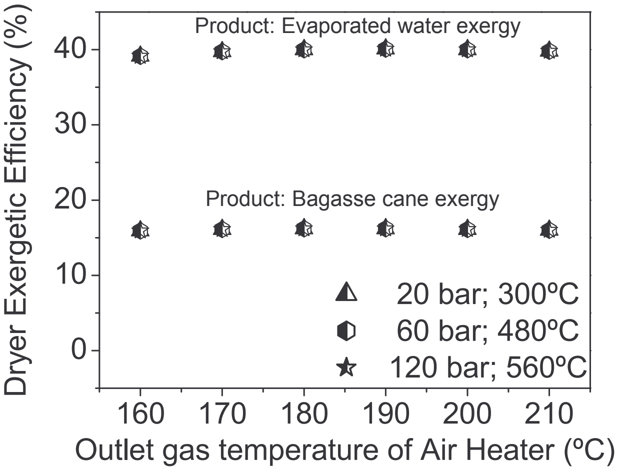

Figure 13: Dryer exergetic efficiency with Outlet gas temperature of air heater for different levels of boiler pressure and temperature – Insumo/product method. – Second Arrangement.

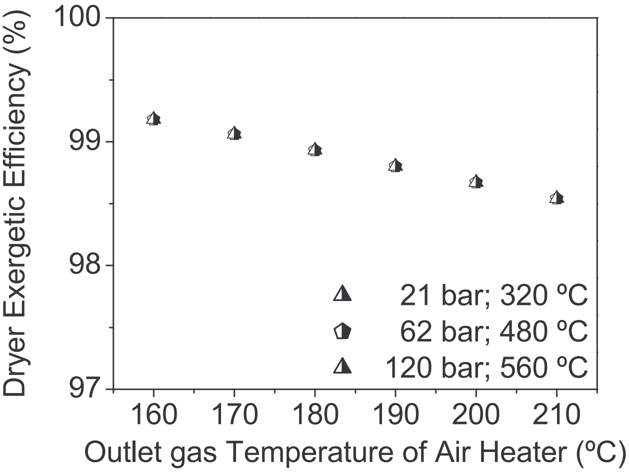

Figure 14: Dryer exergetic efficiency with Outlet gas temperature of air heater for different levels of boiler pressure and temperature – Inlet/Outlet method. – Second Arrangement.

In the first arrangement, Fig 15, the steam generator exergetic efficiency decreases slowly with the air heater outlet gas temperature increase. In the second one, Fig. 16, the steam generator exergetic efficiency increases with the air heater outlet gas temperature increase. The BMC decrease produces high furnace temperature and the reduction of flue gas volume improving the boiler efficiency (Upadhiaya, 1991). This fact is highlight in the second arrangement, which presents higher steam generator exergetic efficiency values than that first one. Also, the increase of exit steam temperature and pressure produces the increase of steam generator exergetic efficiency.

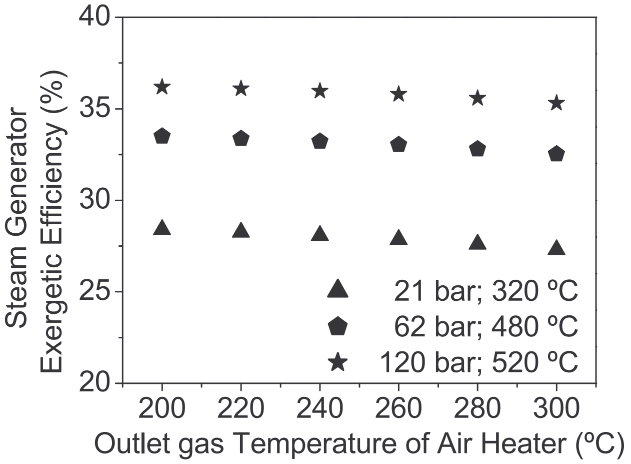

Figure 15: Steam generator exergetic efficiency with Outlet gas temperature of air heater for different levels of boiler pressure and temperature – First arrangement.

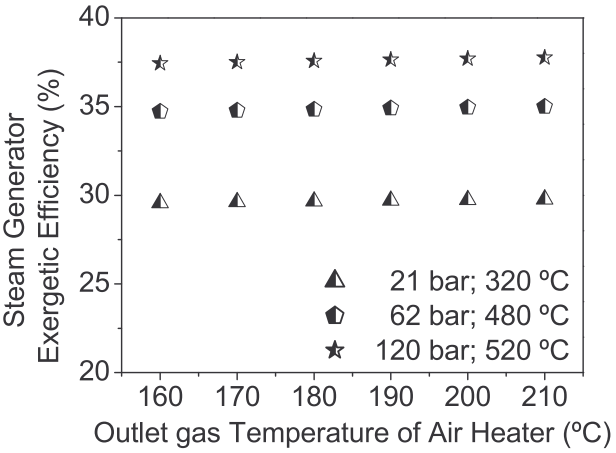

Figure 16: Steam generator exergetic efficiency with Outlet gas temperature of air heater for different levels of boiler pressure and temperature – Second arrangement.

In the first arrangement, the boiler exergetic efficiency does not vary with the outlet gas temperature of air heater whilst, in the second one this parameter increase with air heater outlet gas temperature increase. In both arrangements the boiler exergetic efficiency increases when the steam exit temperature and pressure increase (Fig. 17 and 18).

The higher boiler exergetic efficiency values were observed in the second arrangement, 33.51% whilst the maximum value in the first one was 31.70%. These values were obtained at maximum value of steam temperature and pressure and the minimum BMC.

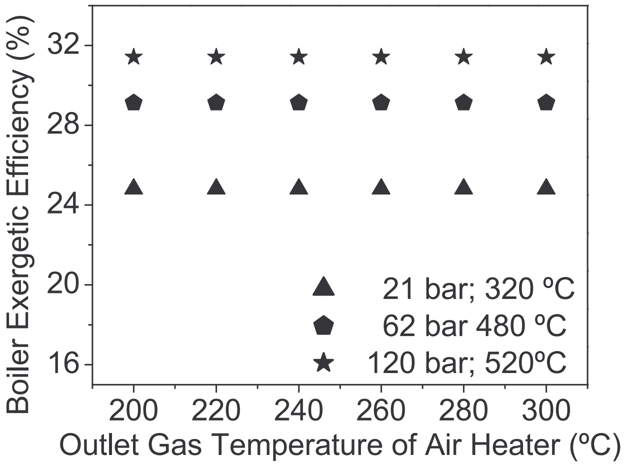

Figure 17: Boiler Efficiency with outlet gas temperature of air heater for different levels of boiler pressure and temperature – First arrangement.

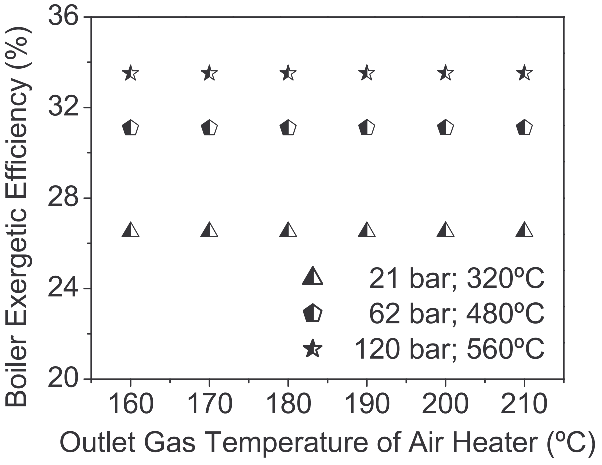

Figure 18: Boiler Efficiency with outlet gas temperature of air heater for different levels of boiler pressure and temperature – Second arrangement.

5. Conclusions

- ✓ The distribution of heat losses according the Beatón and Lora's proposal and the ASME PTC 4.1 proposal are different due to calculation base differences. The Beatón and Lora's proposal discounted in LHV calculation the heat absorbed to evaporate the water formed in the combustion reaction from bagasse hydrogen and also BMC, therefore it is not observed the heat losses by bagasse hydrogen and BMC (q_8 and q_9) in this proposal. The ASME PTC 4.1 proposal highlights these heat losses, which are the bigger in the proportional distribution. The authors recommend the use of the ASME PTC 4.1 proposal on the analysis of bagasse boilers since that through this it is easier to decide the improvements aiming the bagasse boilers optimization
- ✓ The second arrangement, made up steam generator, air heater and dryer, permits to obtain better boiler efficiency and performance than that the first one, first and second law analysis verified that. This fact can be explained because lower dryer outlet gas temperature about 74ºC whislt in first arrangement the outlet gas temperature was 155ºC. Currently, there are bagasse dryers operating at this final temperature; Ñuñorco Factory, Leales Factory (Argentina) and Cruz Alta Planta (Brasil) are examples

- ✓ The effect of bagasse drying into steam generator controle volume is very important because this permits to operate with higher temperatures in furnace and to reduce the vapor mass flow from bagasse moisture content. Therefore, the use of dryer in bagasse boilers became an interesting option for improve the boiler efficiency and performance. In brasil, this equipment has not succeeded but in other countries, such as Cuba, Argentina, Hawaii, they were very well succeeded.
- ✓ The effect of increase of exit steam temperature and pressure permitted to improve the boiler and its components performance and efficiency.
- ✓ Since, when bagasse dryer are used the outlet gas temperature of air heater can decrease, it is possible to considerate new arrangements made up steam generator, economizer, air heater and bagasse dryer. Exergoeconomics analysis applied to this system can help to improve boiler efficiency and performance.

6. Acknowledgement

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