ON THE OPTIMIZATION OF BOILER EFFICIENCY USING BAGASSE AS FUEL

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Abstract

The present investigation has been carried out in order to increase the efficiency of the RETAL-type boiler, used in the Cuban sugar mills. Test methods generally used in the evaluation process and further adjustment of the boilers operation have been analyzed, pointing the attention on the importance of the stoichiometric ratio and steam power on the overall efficiency. Important general rules have been extracted from the complete regular tests following ASME and GOST methodologies, and, as a result, a *simplified test code* has been obtained. Boiler design optimization has also been achieved determining the optimum waste heat recovery scheme from both, thermal and economical viewpoints. As a result, the optimal stack gas temperature has been calculated as well as the range of the optimal value for the excess air fraction. Their influence on the efficiency has been analyzed and the total costs determined. Once the total costs are included in the analysis, the most efficient low-temperature heat recovery scheme results to be the combination of an economizer followed, in the direction of the exhaust gas flow, by an air heater.

Keywords: Biomass; Bagasse-boilers; Efficiency; Optimization

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Nomenclature

a	ash ratio respect to the total ash in the bagasse [$kg_{ash\ in\ refuse}/kg_{ash\ in\ fuel}$]
A	ash content in fuel or in refuse [%]
B	bagasse consumption [kg/s]
B_{ef}	equivalent fuel-oil consumption [kg/s]
C	carbon content in bagasse [%]
C_{uf}	unburned carbon in the fly ash [kg_c/kg_{fa}]
CO	carbon monoxide in stack gas [%]
CO_2	carbon dioxide in stack gas [%]
D	steam power [t/h]
ΔH_C	heat of combustion [kJ/kg]
F	heat transfer area [m^2]
G	refuse collected per time [kg_{refuse}/s]
H	hydrogen content in bagasse [%]
I	enthalpy [kJ/kg]
$m_{a/f}$	air-to-fuel mole number ratio [$mole_{air}/mole_{fuel}$]
O	oxygen content in bagasse [%]
O_2	oxygen percentage in stack gas [%]
q_2	exhaust gas loss [%]
q_3	chemical carbon loss [%]
q_4	fixed carbon loss [%]
q_5	conduction heat loss [%]
Q_l^P	bagasse heating value (as received) [kJ/kg]
Q_{ef}^P	commercial fuel oil heating value [kJ/kg]
P	annual cost per m^2 of surface area [$\$/(m^2\ year)$]
P_{ef}	equivalent fuel-oil cost [$\$\ s/(kg\ year)$]
$R_{CO/f}$	kg of CO produced per kg of fuel
S	sulfur content in bagasse [%]
T	temperature [^oC]
W	bagasse moisture [%]
Z	total cost [$\$/year$]

Greek symbols

α	stoichiometric ratio
γ	heat transfer coefficient [$kW/(m^2 K)$]
η	overall boiler efficiency [%]
μ	molecular weight
Ψ	thermal efficiency

Subscripts

ah	ash hopper
AH	air heater
b	boiler
ba	bottom ash
bd	bagasse dryer
ea	external air
ec	economizer
ef	equivalent to fuel oil
eg	exhaust gas (stack)
f	furnace
fa	fly ash
gt	generating tubes
H	chemical composition given by Hugot
i	different heat losses, heat transfer surfaces or refuse collected
L	laboratory analysis
sh	superheater
w	waterwalls

Superscripts

e	entrance
o	theoretical
p	ultimate bagasse analysis (as received)
nom	nominal

1.- Introduction

Bagasse is the matted cellulose fiber residue from sugar cane that has been processed in a sugar mill. Previously, bagasse was burned as a means of solid waste disposal. However, as the cost of fuel oil, natural gas, and electricity increased after the energy crisis in 1970, special attention was paid to alternative fuels in an efficient way. Consequently, conception of bagasse combustion changed and it has come to be regarded as a biomass fuel rather than refuse. Another important aspect is the increasing demand of bagasse as raw material for paper, furniture, and other industries. For all these reasons, the saving of this product has become one of the main objectives of the Cuban sugar-cane industry. The actual tendency is to use bagasse as fuel, especially for co-generation of electric power and steam, to increase its contribution to the country's energy supply.

Cuba has, in bagasse, a renewable energy source representing 30% of its total energy consumption. Traditionally, Cuban sugar mills were equipped with low efficiency boilers. The designs referred to as "fuel cell" and "horseshoe" boilers were those typically used for bagasse combustion. In these boilers, bagasse is gravity-fed through chutes and burned as a pile. Nowadays, bagasse is burned in spreader stoker boilers, replacing the combustors that use pile type approaches, and improving combustion efficiency. Furthermore, the use of additional heat transfer surfaces, as air heaters, economizers, etc, allows for a reduction of the stack temperature below 200°C. With these improvements, efficiency of the boilers can be increased up to 70%.

This experimental research, developed by the Center of Studies on Combustion and Energy (CECYEN) of the University of Matanzas, has been devoted to optimize both the operation and design parameters of RETAL boilers using bagasse as fuel in order to increase the efficiency of Cuban sugar mills. Special attention has been paid to the optimization of stoichimetric ratio as well as the stack gases temperature, for their influence on the principal heat losses and, consequently, on the overall efficiency of the boiler.

2.- Boiler and fuel characteristics

Sugar cane is a large grass with a stalk that grows 2-5 meters tall. Only the stalk contains sufficient sucrose to be processed into sugar. All other parts of the sugar cane including leaves, roots, etc. are termed "trash", which should be eliminated through the harvesting process. Once inside the mill, juice is extracted in the plant milling section by passing the chopped and crushed cane through a series of grooved rolls. The cane remaining after milling is the bagasse. Usually, it is a biomass-type fuel of varying composition, consistency and heating value. These characteristics depend on the climate, type of soil where the cane is grown, cane type, harvesting method, amount of cane washing, and efficiency of the milling plant.

The experiments were carried out in three RETAL boilers of two different Cuban sugar mills. Figure 1 shows a detailed sketch of the main thermal surfaces of these facilities. The total height and depth of the boiler are 10.6 *m* and 10.92 *m* respectively, and the width (not shown in the figure) is 8 *m*. Summarizing the main characteristics, a nominal steam power of 45 *t/h* is achieved for an approximate bagasse consumption of 22 *t/h*; with a pressure and temperature of the superheated steam of 1.9 *MPa* and 320 ℃, respectively. Bagasse fed to these boilers enters the furnace through five fuel chutes and is spread mechanically. The major part of the bagasse characterized by small and light pieces, burns in suspension. Simultaneously, large pieces of fuel are spread in a thin even bed on a stationary grate. An average ultimate (dry) analysis of the fuel used in the tests gave a 46.27% (in weight) of carbon, 6.4% of hydrogen, 43.33% of oxygen, 0% of nitrogen, 0% of sulfur, and 4% of ash. The moisture content of the bagasse ranged from 48% to 52% for all the analyzed samples.

3.- Operational test procedure

More than 60 tests were performed, attending the ASME [1] and GOST [2] recommendations for solid and liquid fuels. Each test comprised three stages, namely: preparation, measurements, and laboratory analysis. According to the standard procedures, one should wait at least 24 hours after start-up of the boiler and 2 hours after cleaning of the bottom ash, the ash hopper located in the U-turn of the flue gas duct (see number 13 in Fig. 1), and the heat transfer surfaces before starting a test. The boiler should reach, and maintain, a steady state for at least 8 hours before starting the test. The fuel chute and the stationary grate must also be cleaned one hour before starting, and the speed of rotation of the spreader stokers fixed. Some trays have to be placed in the proper locations for refuse collection, and the fly-ash wet scrubber has to be cleaned as well.

Boiler measurements and laboratory analyses are performed along the following nine hours. The first four hours are dedicated to measure all the boiler parameters every 15 minutes. Every half hour, stack gas composition (O_2, CO, and CO_2) is determined and bagasse

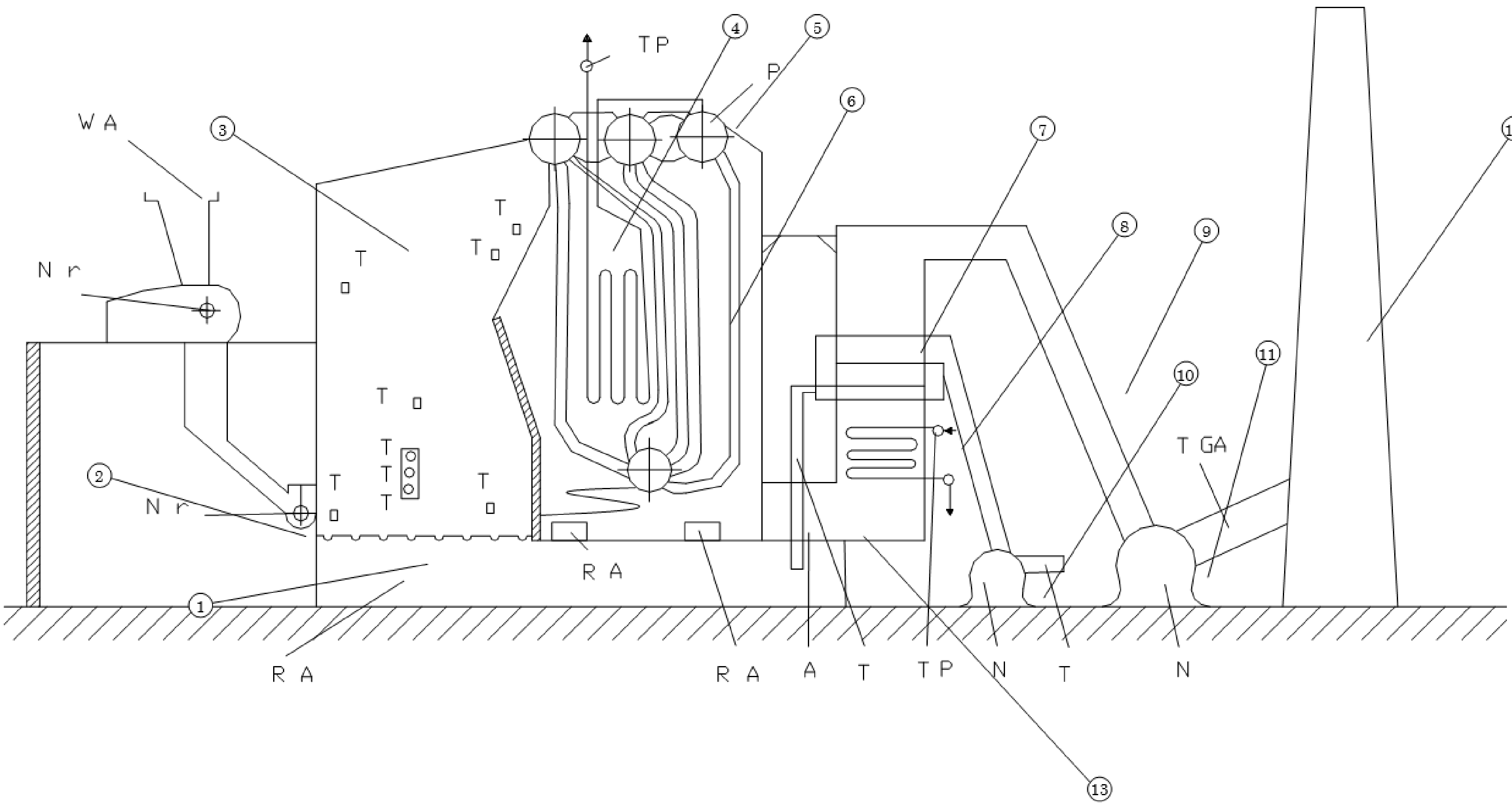

Fig. 1. Sketch of a RETAL bagasse-boiler showing the principal thermal surfaces (numbers) and location of measuring points: (1) furnace grill, (2) spreader stoker, (3) furnace, (4) superheater, (5) drums, (6) generating tubes, (7) air heater, (8) economizer, (9) exhaust gases duct, (10) air supply fan, (11) air extraction fan, (12) smokestack and (13) the ash hopper in the U-turn of the exhaust gas duct. Letters refer to the measured parameters; A; ash concentration; GA, exhaust gas composition analysis; N; motor power; P; pressure; r; revolutions per minute; R; residual weight; T; temperature, and W; bagasse moisture percentage.

samples collected for the determination of their moisture and ash contents. The furnace temperature is also measured every 15 minutes using water-cooled suction pyrometers. The sampling and measurement locations are shown in Fig. 1.

Laboratory work begins with refuse collection from all the different locations (ash bottom, ash hopper and web scrubber). In the following five hours, moisture and ash contents of the bagasse and solid samples from the fly ash hoppers, wet scrubber, and bottom ash hopper are analyzed. When all the data are assembled, a statistical analysis determines the mean and standard deviation for each parameter. If a steady state has not been achieved in the boiler, the test must be rejected.

As it is well known, the overall efficiency of a boiler can be calculated using both direct and indirect methodologies. The direct measurement of the bagasse consumption, *B*, is always subjected to many error sources. For this reason, in the present study, efficiency has been calculated using the indirect methodology. In general, this method relates the efficiency (η) of the boiler with the different heat losses through the equation

$$\eta\ (\%) = 100 - \sum q_i \tag{1}$$

where $\sum q_i = q_2 + q_3 + q_4 + q_5$. In this equation, q_2 represents the exhaust gases heat loss, q_3 and q_4 are the chemical and fixed carbon loss, respectively, and q_5 the conduction heat loss from the external walls of the boiler. To quantify the heat losses, the following equations are used [2]:

$$q_2\ (\%) = \left(I_{eg} - \alpha_b I_{ea}\right)\left(\frac{100 - q_4}{Q_l^P}\right) \tag{2}$$

$$q_3\ (\%) = \frac{\Delta H_C^{CO}}{Q_l^P} \cdot R_{CO/f} \cdot 100 \tag{3}$$

$$q_4\ (\%) = \frac{\Delta H_C^C\ A^P}{Q_l^P}\left[\sum a_i \frac{\left(100 - A_i\right)}{A_i}\right] \tag{4}$$

$$q_5\ (\%) = \frac{\sum \gamma_T\ F_i\left(t_i - t_{ea}\right)}{B Q_l^P} \tag{5}$$

Here, I_{eg} and I_{ea} are the exhaust gases and external air enthalpy respectively, α_b the stoichiometric ratio at the exit of the boiler, Q_l^P the bagasse heating value (as received), ΔH_C^C the carbon heat of combustion, ΔH_C^{CO} the *CO* heat of combustion, A^p the ash contents of bagasse from ultimate analysis (as received) and $R_{CO/f}$ is the rate of kilograms of *CO* produced during the combustion of one kilogram of fuel.

The stoichiometric ratio, $\alpha = m_{a/f} / m_{a/f}^o$, is defined as the ratio of the actual air-to-fuel mole number ratio ($m_{a/f}$) to the theoretical one ($m^o_{a/f}$) for the same experimental conditions. In turn, the actual air-to-fuel mole number ratio ($m_{a/f}$) is defined as the theoretical number of moles of air plus the extra moles due to excess air needed to achieve the complete combustion of one mole of bagasse (in $mole_{air}/mole_{fuel}$). As it will be thoroughly discussed in Section V.2, in order to more accurately reproduce the physical influence of the different parameters and heat losses in the statistical models, two stoichiometric ratios have been defined, namely: stoichiometric ratio at the furnace, α_f, and stoichiometric ratio at the exit of the boiler, α_b. It should be pointed out that in the case of α_b, the amount of surrounding air in-leakage into the boiler due to non air-tightness, $\Delta\alpha$, is also included in the total air mole number.

A_i refers to A_{fa}, A_{ah} and A_{ba}, which correspond to ash percentages in the fly ash, ash hopper and bottom ash, respectively obtained through laboratory analysis combusting and weighting the different samples of refuse collected in a special oven following the methodology of ASME [1] and GOST [2]. In the same way, a_i refers to the ratios of ash in the fly ash, a_{fa}, ash hoppers, a_{ah}, and bottom ash, a_{ba} with respect to the total ash in the fuel, in $kg_{ash\ in\ refuse}/kg_{ash\ in\ fuel}$. From a mass balance of ash in the boiler, considering G_i as the refuse collected per time unit in the different locations in fly ash, G_{fa}, ash hopper, G_{ah}, and bottom ash, G_{ba}, respectively, in kg_{refuse}/s, the following equation can be written,

$$B\,A^P\ (\mathrm{kg_{ash}/s}) = G_{fa}\,A_{fa} + G_{ah}\,A_{ah} + G_{ba}\,A_{ba} \tag{6}$$

the different ash ratios a_i, in fly ash, a_{fa}, ash hoppers, a_{ah}, and bottom ash, a_{ba}, are defined by

$$a_i\ (\mathrm{kg_{ash\ in\ refuse}}\ /\mathrm{kg_{ash\ in\ fuel}}) = \frac{G_i\,A_i}{B\,A^P} \tag{7}$$

and hence,

$$1\,(\mathrm{kg_{ash\ in\ refuse}}\ /\mathrm{kg_{ash\ in\ fuel}}) = a_{fa} + a_{ah} + a_{ba} \tag{8}$$

To calculate the conduction heat loss, q_5, from the external wall to the surrounding area, the total heat lost (including radiation) has to be considered. In Eq. (5), λ_T is the total heat transfer coefficient in $kW/(m^2\,{}^oC)$, F is the total heat transfer area of the external wall in m^2, t_i and t_{ea} are the external wall and external air temperature (K), respectively. It has to be noted that in Eq. (5) the fuel consumption, B, has to be included for dimensional homogeneity. The unknown fuel consumption in eqs. (4) and (5) is calculated by an iterative procedure.

4.- Waste heat recovery scheme

The RETAL boiler was adapted from a German model that used pulverized coal as fuel. Over the years, the boiler has been redesigned, mostly by modifying its combustion systems according to the changes in fuel type. However, a careful study to optimize the waste heat recovery scheme has never been specifically attempted. It is for this reason that one of the aims of the present investigation was the determination of the most suitable combination of low-temperature heat transfer surfaces, from both thermal and economic viewpoints, to obtain the optimum waste heat recovery scheme.

Special attention has been paid to heat losses respect to the exhaust gas, because they can reach up to 30% of the total energy in the fuel. To obtain the optimal value for the exhaust gases temperature, it is necessary to use additional heat transfer surfaces such as an economizer, air heater, bagasse dryer, or some combination of them. However, the addition of new elements increases the investment and operating costs of the boiler. Hence the importance of establishing the optimal stack temperature.

To solve this problem, a minimum total cost (Z) has to be found through the equation:

$$Z\ (\$/\mathrm{yr}) = \sum P_i F_i + P_{ef} B_{ef} \tag{9}$$

where, i is the type of recuperative heat transfer surface (furnace water-walls, superheater, generating tubes, air heater, economizer, and bagasse dryer); P_i the annual cost of 1 m^2 of the surface i (*\$/(m*^{2} *year*)); F_i the heat transfer area of surface i (m^2), P_{ef} the equivalent fuel-oil cost (*\$ s/(year kg)*) and B_{ef} the equivalent fuel-oil consumption (*kg/s*). This fuel-oil equivalence means the amount of commercial fuel-oil, with an average heating power (Q_{ef}^P) of 41,868 *kJ/kg* (and its price at the oil market), needed to yield the same energy as the total bagasse consumed to produce a given steam power. Once the efficiency is determined using the indirect method previously described in Section III, the total bagasse consumption, B, is calculated by

$$B\ (\mathrm{kg/s}) = \frac{D_{sh}\left(I_{sh} - I_{ec}^{e}\right)}{\left(Q_l^P\, \eta\right)} \cdot 100 \tag{10}$$

where D_{sh} is the measured steam power in *t/h* and I_{sh} and I_{ec}^{e} are the superheated steam and the fed water enthalpy, respectively. The equivalent fuel-oil consumption B_{ef} is determined by,

$$B_{ef}\ (\mathrm{kg/s}) = \frac{B\, Q_l^P}{Q_{ef}^P} \tag{11}$$

Using the common methodology to calculate the minimum value of a function, the equation obtained to determine the optimal stack temperature, considering all the heat transfer surfaces is,

$$\frac{dZ}{dT_{eg}} = \frac{P_{ef}\, dB_{ef}}{dT_{eg}} + \frac{d(P_w\, F_w)}{dT_{eg}} + \frac{d(P_{sh}\, F_{sh})}{dT_{eg}} + \frac{d(P_{gt}\, F_{gt})}{dT_{eg}} + \frac{d(P_{AH}\, F_{AH})}{dT_{eg}} + \frac{d(P_{ec}\, F_{ec})}{dT_{eg}} + \frac{d(P_{bd}\, V_{bd})}{dT_{eg}} = 0 \tag{12}$$

In this equation, T_{eg} is the stack temperature; P and F define, respectively, the cost and area for all thermal surfaces considered. Subscript w indicates furnace water-walls; sh superheater, gt generating tubes; AH the air heater; ec the economizer, and bd the bagasse dryer.

Similar equations can be derived for hot air temperature and bagasse moisture optimization. The computer code developed for the optimization procedure is capable of performing the simultaneous optimization of the stack and hot air temperatures. At the same time, if a bagasse dryer is considered in the waste heat recovery scheme, the bagasse moisture can also be optimized. Obviously, as the available remaining heat has to be transferred to the water, as a consequence, an optimum water temperature is obtained as well. The equations have to be adapted according to the particular heat recovery scheme to be optimized. Five combinations of retrofitted heat exchangers have been considered in the present study. In naming the various configurations, the different surfaces are listed in their placement order following the flue gas flow direction. The examined cases are: Air heater-Economizer-Air heater (case **I**), Air heater-Economizer (case **II**), Economizer-Air heater (case **III**), Economizer (case **IV**), and Air heater-Economizer-Bagasse dryer (case **V**). In each case, the name of the first surface listed corresponds to that exposed to the highest gas temperature.

5.- Results and discussion

5.1.- Bagasse heating value determination

In general, bagasse has a broad range of heating values, extending from 6,500 to 9,150 *kJ/kg* (as received). Due to the importance of this parameter in the determination of the efficiency of a boiler, it was carefully determined using a calorimeter on more than 1,000 samples collected during the tests. Results yielded an average heating value for the bagasse of 7,738±100 *kJ/kg*, as received. However, in most sugar mills it is not possible to carry out such a determination in their laboratories. An alternative method has been considered, calculating the heating value using the well-known equation [2],

$$Q_l^P \text{ (kJ/kg)} = 339.15\,C^p + 1{,}256.10\,H^p - 108.86\,O^p - 25.12\left(H^p + W_L\right) \tag{13}$$

taking into account the general chemical composition given by Hugot [3], but considering bagasse moisture and ash contents from the samples measured in the laboratory tests. As an example, the following relation is used to modify the carbon composition,

$$\frac{C^p}{100 - W_L - A_L^p} = \frac{C_H^p}{100 - W_H - A_H^p}$$

where C^p is the carbon content in the bagasse, and W and A are the bagasse moisture and ash contents. Subscripts H and L indicate values given by Hugot and those experimentally determined in the laboratory analysis, respectively. Similar equations can be written for the other chemical components, *i.e.* hydrogen and oxygen.

It was found that the lower heating values calculated using Eq. (13) differed from experimental measurements by less than 1%. The fact that experiments were performed in two different sugar mills, having widely different methods of harvesting and cane varieties, indicates that Eq. (13) provides a means for quickly determining the heating value of bagasse (as received) with a high confidence level, good accuracy, and avoiding the more difficult and time-consuming experimental measurements. In contrast to the ultimate fuel analysis, bagasse moisture and ash contents are relatively easy to measure and are accessible to every sugar mill.

5.2.- Optimization of the boiler operation

With the present experimental investigation, an adequate methodology to determine the efficiency of bagasse boilers was established, adapting the ASME and GOST test code evaluations to this particular fuel and type of boiler. The principal drawback of the ASME and GOST methods is the large time required and the high cost, including personnel, of each test, as can be inferred from the description in Section III. For this reason, a special effort has been devoted to optimize both the test itself and the boiler operation. Important general rules have been extracted from the complete regular tests, and, as a result, a simplified Bagasse-boilers Industrial Test Code [4] has been elaborated. In short, the stationary regime should be reached only one hour before, and during the whole test, allowing maximum fluctuations of 15% for the prescribed steam power and its temperature, 3% for the water temperature and 7% for the steam pressure and the stoichiometric ratio. The determination of the bagasse moisture and ash contents need to be performed only once during the test. The analysis of exhaust gas composition is measured at the beginning and at the end of the test. Validity of the simplified test code has been demonstrated in more than 30 boilers.

To carry out the boiler optimization for different operational regimes, experimental measurements have been obtained from the full tests according to the ASME [1] and GOST [2] procedure. Special attention was devoted to obtain general charts relating measured parameters, such as the stoichiometric ratio, steam power, etc., to the overall boiler efficiency (η). As a consequence of the experimental results, some important simplifications on both the fixed carbon loss, q_4, and conduction heat loss, q_5, are considered. At the same time, attention has also been focused to obtain the needed statistical models, with a high level of confidence but keeping them as simple as possible, in order to ease the efficiency evaluation of the boilers by engineers at the sugar mill factory.

Determination of the conduction heat loss, q_5, in an exact way is quite difficult, requiring the measurement of all external wall temperatures as well as the determination of the heat transfer coefficient as commented in Section III. From the experimental tests, it is concluded that q_5 only shows a strong dependence on steam power. For this reason, a simplified equation relating q_5 with the steam power commonly used in this type of boilers [2] was considered, namely,

$$q_5\ (\%) = \left(\frac{D_{sh}^{nom}}{D_{sh}} \right) \sqrt{\frac{100}{D_{sh}^{nom}}} \tag{14}$$

Results obtained using both Eq. (5) and Eq. (14) demonstrated a very good agreement between the complete thermal analysis and the simplified one. It is for this reason the Eq. (14) was included in the recommended simplified *Bagasse-boiler Industrial Test Code*, and also included in the computer code used to optimize the boiler operational regime, with the only measurement of the steam power to determine this heat loss.

Considering the physical influence of the fixed carbon loss (q_4) on the remaining heat losses (q_2 and q_3), it must be the first of all the heat losses to be evaluated in the efficiency calculation. For the terms inside the brackets in Eq. (4), experimental measurements during the tests performed demonstrated the validity of the following inequality,

$$a_{fa} \frac{(100 - A_{fa})}{A_{fa}} >>> a_{ah} \frac{(100 - A_{ah})}{A_{ah}} + a_{ba} \frac{(100 - A_{ba})}{A_{ba}} \tag{15}$$

which means that the terms corresponding to ash hopper and bottom ash can be neglected when compared to the fly ash one.

The terms (100-A_i) in Eqs. (4) and (15) are, by definition, the unburned fuel (carbon) for the refuse collected in the different locations. Having in mind that q_4 is expressed as an unburned loss, it is convenient at this moment to introduce the relation $C_{uf} = 100 - A_{fa}$ as the unburned carbon in the fly ash. For this reasons, Eq. (4) can be rewritten as

$$q_4\ (\%) = \frac{\Delta H_C^C\ A^P}{Q_l^P} \left(\frac{C_{uf}}{100 - C_{uf}} \right) \tag{16}$$

In this equation, a_{fa} has been considered equal to 1 (see Eq. (8)) taking into account the experimental results and calculations, with a high confidence level.

It can be observed that the above simplifications to calculate for q_4 and q_5, reduce and simplify the number of statistical models to be fitted to obtain the claimed efficiency chart. In the next paragraph, the statistical models fitted to calculate C_{uf}, $CO/(CO+CO_2)$ and stack temperature, T_{eg}, will be discussed. It should be noted that the last parameter, T_{eg}, is needed to calculate the exhaust gases enthalpy in Eq. (2).

In order to obtain a simplified model, the influence of the stoichiometric ratio in the furnace (α_f) and steam power (D_{sh}) on the unburned carbon in the fly ash, C_{uf}, has been plotted. Results of the experimental measurements are depicted in Fig. 2. As can be seen, the unburned carbon increases with increasing steam power and decreases with increasing stoichiometric ratio in the furnace. As steam power is raised at a constant stoichiometric ratio, both the amount of bagasse fed and the combustion air flow rate increase, since the air volumetric flow rate per unit weight of bagasse is fixed. This, in turn, increases the average gas velocity in the furnace and the fraction of fuel that burns in suspension, rather than in the bed on the stationary grate. The shorter residence time available for combustion in suspension results in an increased unburned carbon carryover and poorer combustion performance. Therefore, when steam power and bagasse consumption are increased, a higher stoichiometric ratio in the furnace is needed to achieve the same carbon conversion (C_{uf}). Taking into account all the experimental data, a statistical model is fitted

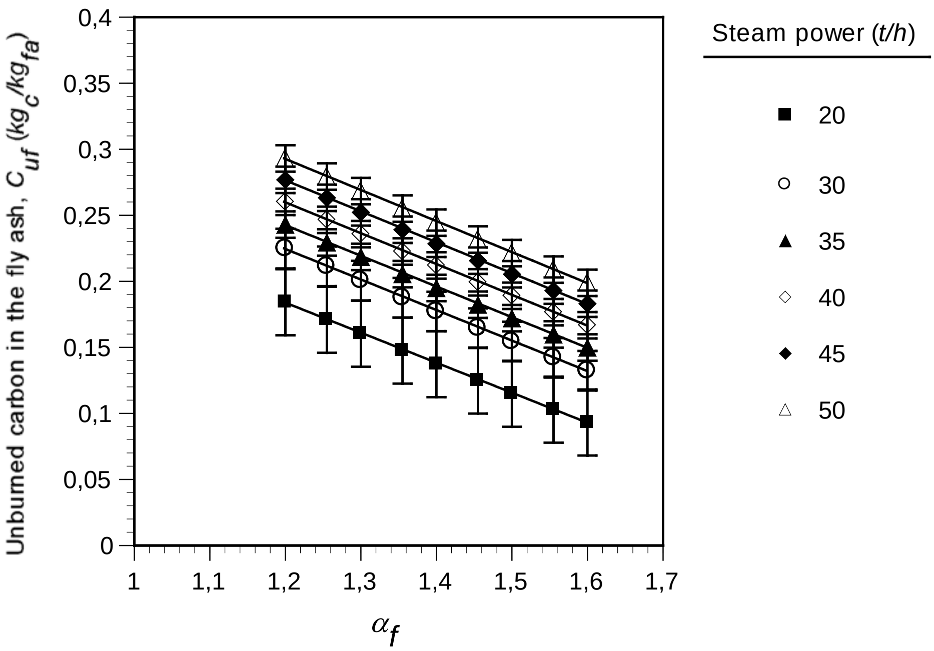

Fig. 2. Performance of the unburned carbon in fly ash vs. stoichiometric ratio at the exit of the furnace (α_f) for different values of steam power. The depicted solid lines correspond to the different steam powers given by Eq. (17).

$$C_{uf}\ (\mathrm{kg_c}\ /\ \mathrm{kg_{fa}}) = 0.854965 + 0.002724\, D_{sh} - 0.592243\sqrt{\alpha_f + \frac{1.3416}{\sqrt{D_{sh}}}} \tag{17}$$

reproducing the experimental dependence of C_{uf} on both the stoichiometric ratio at the furnace, α_f, and the steam power, D_{sh}. In this equation D_{sh} has units of *t/h*.

Once q_4 is calculated, q_3 and q_2 can also be evaluated. To determine the chemical carbon heat loss (q_3), the parameter $R_{CO/f}$ needs to be calculated by the equation

$$R_{CO/f} = \mu_{CO/C}\left(\frac{C^p + 0.375S^p}{100}\right)\left(\frac{CO}{CO+CO_2}\right)\left(\frac{100-q_4}{100}\right),$$

$\mu_{CO/C}$ being the *CO*-to-*C* molecular weight ratio. C^p and S^p are the carbon and sulfur contents of bagasse from ultimate analysis (as received). CO and CO_2 are the carbon monoxide and dioxide concentration in the stack gases, respectively. Substituting $R_{CO/f}$ on Eq. (3), only the term containing CO and CO_2 remains to be determined from the experiments in order to establish a correlation for the chemical carbon loss, q_3. Results are presented in Fig. 3, showing a linearly decreasing dependence of this term for increasing stoichiometric ratio, and a weak influence of the steam power. For clarity, in this plot, error bars are only displayed for the measurements corresponding to steam powers of 20 and 50 *t/h* respectively. The remaining experimental points represent the mean values for the different stoichiometric ratios and steam powers analyzed. The statistical model relating carbon monoxide, expressed as a fraction of the total carbon oxides, to both α_f and D_{sh}, is

$$\frac{CO}{CO+CO_2} = 0.0275 - 0.01485\,\alpha_f - \frac{0.0165}{\sqrt{D_{sh}}} \tag{18}$$

It is important to note that the physical parameters measured in the tests are the O_2, CO and CO_2 concentration in the exhaust gases, which are used to calculate the stoichiometric ratio, α_b, at the exit of the boiler applying the equation [2],

$$\alpha_b = \frac{1}{1 - 3.76\left(\dfrac{O_2 - 0.5CO}{100 - O_2 - CO_2 - CO}\right)} \tag{19}$$

where O_2, CO and CO_2 are the stack gases composition analysis. This equation is obtained using the combustion reactions as a function of the mole number, following the definition of the stoichiometric ratio previously stated in Section III.

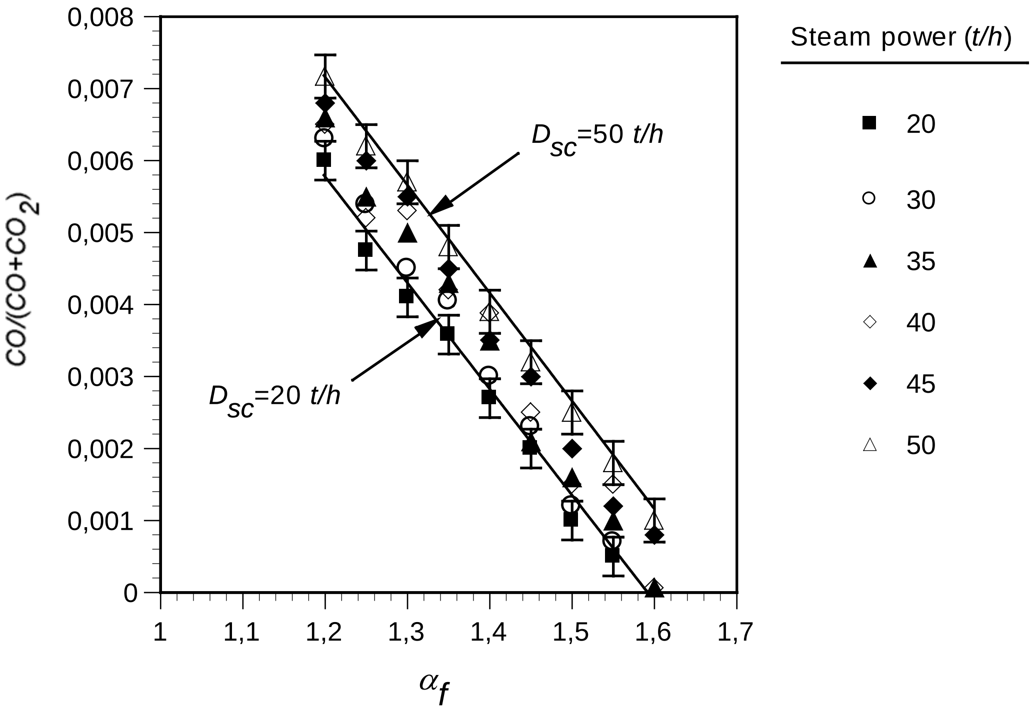

Fig. 3. Behavior of CO and CO_2 concentration in the stack gases as a function of stoichiometric ratio at the exit of the furnace (α_f) and steam power. The fitted lines correspond to Eq. (18) for values of the steam power of 20 and 50 *t/h* (lower and upper lines).

However, equations (17) and (18) are correlated to the stoichiometric ratio at the furnace exit, α_f, because of the physical dependence of both C_{uf} and CO on α_f rather than on α_b. These two stoichiometric ratios are closely related throughout the air in-leakage, $\Delta\alpha$, by

$$\alpha_b = \alpha_f + \Delta\alpha \tag{20}$$

Air in-leakage, $\Delta\alpha$, represents the leakage of surrounding air, due to non air-tightness, into the boiler and can be calculated by [5]

$$\Delta\alpha = \Delta\alpha^{nom} \sqrt{\left(\frac{D_{sh}^{nom}}{D_{sh}}\right)} \tag{21}$$

where $\Delta\alpha^{nom}$ is the air in-leakage at the nominal steam power (D_{sh}^{nom} = 45 *t/h*). This parameter, $\Delta\alpha^{nom}$, was previously determined for all boilers tested and yielded a roughly constant value of 0.2.

Finally, to calculate the exhaust gases heat loss, q_2, the exhaust gas enthalpy, I_b, needs to be known. This enthalpy depends on the stack temperature, T_{eg}. The experimental data show a linear dependence of T_{eg} on the stoichiometric ratio, as seen in Fig. 4. As in Fig. 3, errors bars are only depicted for the lowest and highest values of the steam power (20 and 50 *t/h*). Fitting a curve to the measurements relating T_{eg} to α_f and D_{sh}, the following equation is obtained

$$T_{eg}\ (^{\circ}\mathrm{C}) = 172.32 + 24.76\alpha_f + \frac{43.22}{\sqrt{D_{sh}}} - 0.213\left(D_{sh}\right)^{0.33} \quad (22)$$

as shown in Fig. 4 by the solid lines for 20 *t/h* and 50 *t/h* respectively. Even when the dependence of T_{eg} on D_{sh} is weak, it is noteworthy that the stack temperature is raised as the steam power decrease. When the steam power is decreased for a constant stoichiometric ratio at the furnace, combustion air flow rate also decreases, reducing the average gas velocity in the furnace as well as the heat transfer in the waste heat recovering scheme. As a result, a higher exhaust gases temperature is measured at the exit of the boiler.

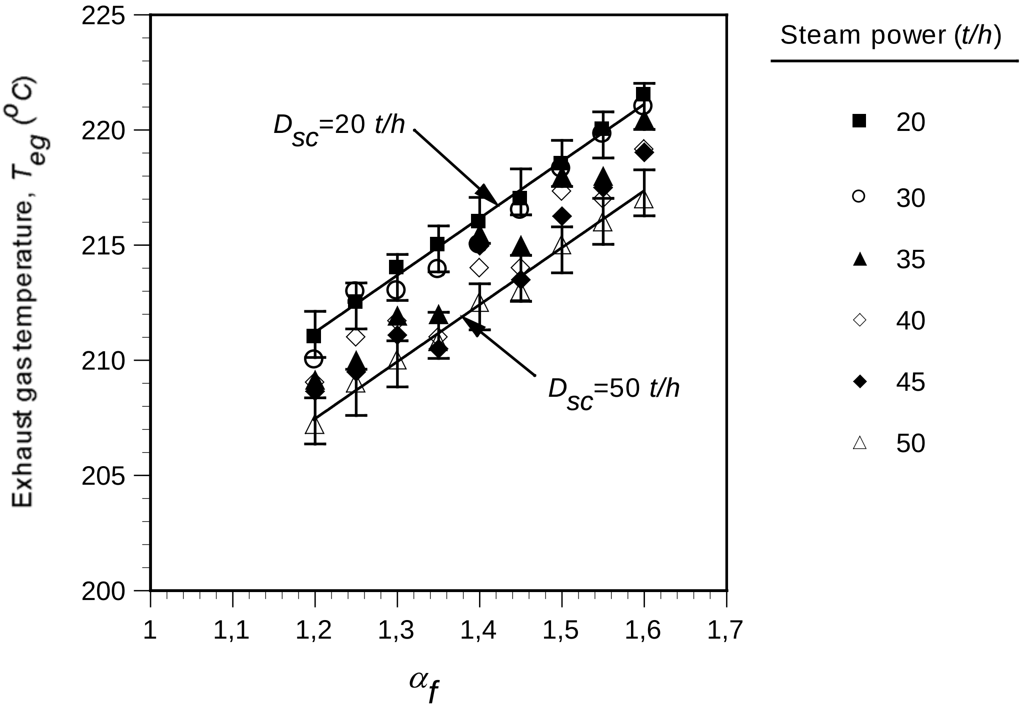

Fig. 4. Influence of the steam power and the stoichiometric ratio on the stack gases temperature. Solid lines correspond to Eq. (22) for values of the steam power of 20 and 50 *t/h*.

The three formulae, (17), (18), and (22), based on the expected physical relations among the parameters, were obtained using the STATVIEW commercial code [6], and are valid for steam power values ranging from 20 to 50 *t/h* and for stoichiometric ratios at the furnace exit, α_f, from 1.2 to 1.6. All the experimental measurements were included in the statistical fitting process and the regression coefficients R^2 were always greater than 0.9.

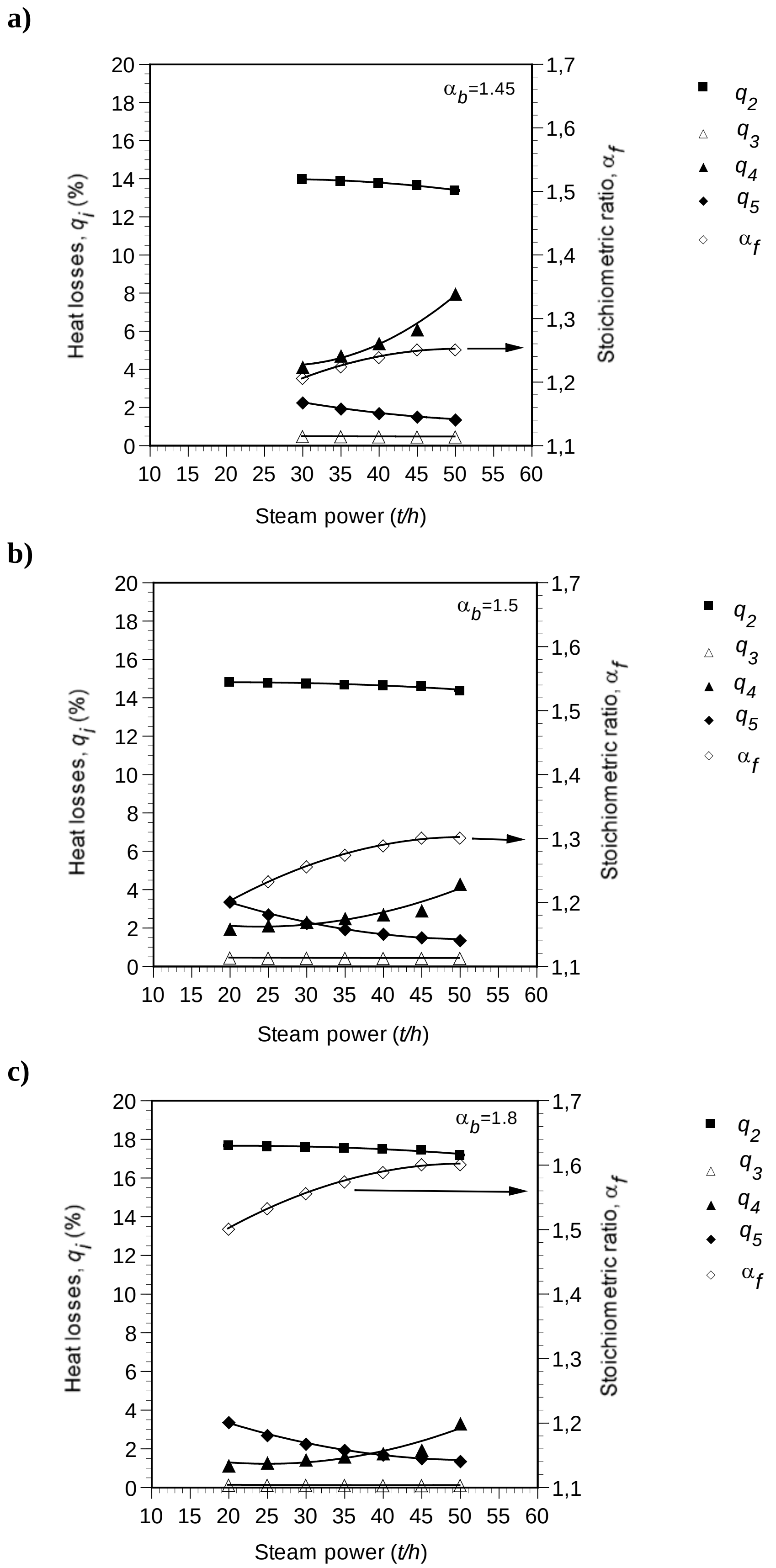

Fig. 5. Calculated heat losses (q_2; q_3; q_4; q_5) vs. steam power for three levels of stoichiometric ratio at the exit of the boiler (α_b) : (a) 1.45, (b) 1.5 and (c) 1.8. A 50% of bagasse moisture and an (dry) ash content of 4% have been considered.

If the set of equations (17), (18) and (22) is introduced into the methodology to calculate the heat losses q_4, q_3 and q_2, their individual contributions to the overall boiler efficiency can be analyzed. This influence is shown in Fig. 5 a), b) and c) for three different levels of stoichiometric ratio at the exit of the boiler, α_b: 1.45, 1.5 and 1.8 respectively, considering a fixed constant bagasse moisture of 50% and an ash content of 4% (dry). In all these figures, the stoichiometric ratio at the furnace exit, α_f, has also being included. The evolution of α_f as a function of steam power derived from eqs. (20) and (21) and its dependence on the level of the stoichiometric ratio at the boiler exit, α_b, can be easily verified. Comparing the three figures, it is evidenced that, as the stoichiometric ratio at the exit of the boiler increases the heat losses have different behavior; the exhaust gases heat loss, q_2, undergoes a significant rise, while q_3 and q_4 decrease. Even though equations (17), (18) and (22) are valid for D_{sh} of 20 *t/h*, it can be seen that for low stoichiometric ratios, see Fig. 5a) (α_b = 1.45), experimental data is only available for steam flows above 30 *t/h*. During the experimental tests, it was checked that if the stoichiometric ratio at the furnace exit, α_f, is reduced below 1.2 the boiler starts to work in an unstable regime and, at the end, combustion stops. In this case, a stoichiometric ratio at the furnace exit, α_f, of 1.2 corresponds to a steam flow of 28.8 *t/h*.

On the other hand, as can be observed in this figure, at higher steam powers, q_5 decreases, as predicted by Eq. (14). As the total heat transfer area is a fixed value (for each boiler) and the external wall temperature is roughly constant irrespective of the steam power, then the total heat lost to the surroundings (in *kW*) is nearly constant as well. However, as an increase in the steam power is related to a higher fuel consumption, a reduction in the conduction heat loss is finally achieved, according to the behavior also predicted by Eq. (5).

All these features are summarized in Fig. 6, where the overall efficiency, η, is plotted as a function of the stoichiometric ratio at the exit of the boiler and the steam power, demonstrating the global effect of heat losses on boiler efficiency (see Eq. (1)). Data for only four values of the stoichiometric ratio are displayed, for clarity. It is concluded that the highest efficiency is reached for a steam power value in the vicinity of the nominal one, 45 *t/h* and for low values of α_b (1.45). This result is supported by the fact that the largest heat loss in these boilers is that corresponding to the exhaust gases, q_2. However, again for this value of α_b, a decrease of the steam power below 30 *t/h*, causes the unstable combustion regime described before, which finally results in flame extinction. On the contrary, for α_b of 1.5 and 1.6 a nearly flat behavior of the efficiency respect to the steam power is reached, for the whole range, with values quite close to those achieved for the lowest stoichiometric ratio, α_b. It is for this reason that, including in the analysis the results obtained for all the boilers tested, the optimal value of the stoichiometric ratio at the exit of the boiler, α_b, has been determined to range from 1.5 to 1.55, which allows for a full coverage of the whole range of steam powers. It should also be noted that, prior to this experimental research, engineers and boiler operators used to run the boilers at higher stoichiometric ratio values at the exit of the boiler, even exceeding 1.8, loosing a large amount of thermal energy which resulting in a lower efficiency.

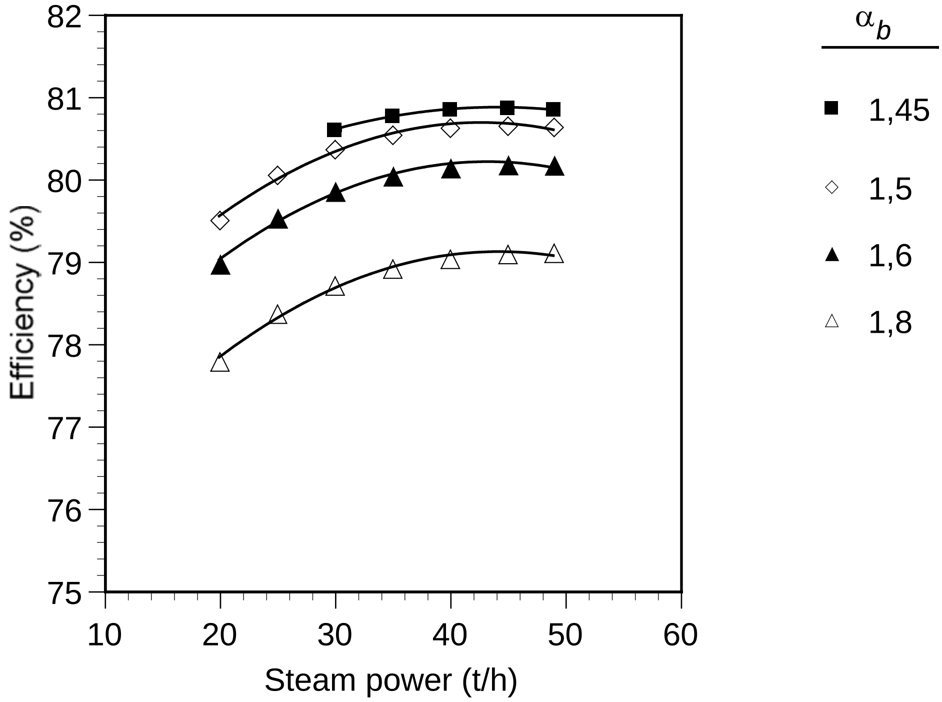

Fig. 6. Overall boiler efficiency calculated using Eq. (1), and experimental data vs. steam power for four different stoichiometric ratios at the exit of the boiler, α_b; with the same conditions considered in Fig. 5.

5.3.- Optimization of the heat recovery scheme

As commented in Section IV, and considering the results obtained in the boiler efficiency analysis in the previous section, to the importance of the exhaust gases heat loss, q_2 on the overall combustion efficiency has been evidenced. In this section the optimization of the stack temperature will be analyzed, for its strong influence on the exhaust gas enthalpy and, therefore, on q_2.

Boiler design optimization is a very complex problem [7], requiring some assumptions to simplify its mathematical treatment. In this study, to optimize the waste heat recovery scheme, the speed of the flue gas, steam, water and air flow are supposed to have their optimal values for all the heat transfer surfaces studied. At the same time, the furnace exit gas temperature is kept constant at 900 ℃ and the steam power is fixed at the nominal value of 45 *t/h*. It is also necessary to consider the specific heat at the exit of the boiler and its average value at the different heat transfer surfaces to be independent of the stack temperature. The heat transfer coefficients should also be considered as independent of the optimized temperature.

To solve equations (9) and (12) a thermal analysis of all the heat transfer surfaces in the boiler was first performed followed by a coupled mathematical and graphical analysis. The overall heat transfer coefficient (*k*) of each individual heat transfer surface considered in the analysis was initially computed using its own thermal equation. These equations are slightly different depending on the type of construction, flow arrangement, core configuration, etc., but they are always a function of local heat transfer coefficients, γ_1 and γ_2, and the thermal efficiency, Ψ, according to the relation,

$$k\left(\mathrm{kW/m^2\ K}\right) = \Psi \frac{(\gamma_1 \gamma_2)}{(\gamma_1 + \gamma_2)} \tag{23}$$

where subscript *1* means hot gas and *2* refers to the cold fluid (water, steam or air). A summary of the heat transfer coefficients for the different surfaces studied is presented in Table 1. Note that for the bagasse dryer, the volumetric heat transfer coefficient is given in $kW/(m^3K)$.

Table 1. Heat transfer coefficients used for the different surfaces studied.

	Generating tubes	**Air heater**	**Economizer**	**Superheater**	**Bagasse dryer**
k *(kW/(m²K))*	0.041	0.014	0.057	0.054	0.1014*

*This entry has units of $kW/(m^3\ K)$.

The economical cost of the individual heat transfer surface per area unit was calculated according to the principle of scaling economy [8] carefully detailed in Barroso *et al.* [9], using the equation,

$$\frac{P_2}{P_1} = \left(\frac{F_2}{F_1}\right)^a \tag{24}$$

where the same nomenclature as in Eq. (9) has been used. In this equation, subscript *1* is assigned to the known heat transfer surface and *2* refers to that to be calculated; *a* is a scaling exponent determined with the known cost and heat transfer area. Results for the individual heat transfer surfaces considered in this study are depicted in Table 2. For the case of the bagasse dryer, a cost of 300 $\$/m^3$ is obtained. For all the calculations, a recovery coefficient of 0.26 $year^{-1}$ for the furnace, and 0.28 $year^{-1}$ for the rest of heat transfer surfaces, has been considered.

Table 2. Cost of the individual heat transfer surfaces obtained from the scaling behavior given by Eq. (24)

	Generating tubes	**Water walls**	**Air heater**	**Economizer**	**Superheater**
P_i ($\$/m^2$)	32	134	16	26	87

A typical value for the stack temperature for boilers that burn common fuel oils and coal ranges between 150-300°*C* to avoid acid corrosion. However, as stated in section II, sulfur contents in bagasse are negligible, yielding a low dew point temperature for the exhaust gases, around 60°*C*, based on experimental determinations. Therefore, keeping the external pipe temperature in the last equipment over 70°*C* (or the stack temperature over 80°*C*) the problem of acid deposition is avoided. Five heat recovery schemes, previously described in Section IV, were considered, to reduce the stack temperature to its optimal value. The non-linear relations given by equations (9), (12) and (24) were solved for the different waste heat recovery schemes using a computer code based on TKSOLVER software [10] through the coupled thermal and economical analysis. The behavior of the total cost curve against the stack temperature is depicted in Fig. 7 for case **III**. As can be observed, the optimal stack temperature was found to be 86°*C* for this particular waste heat recovery scheme, with an optimum value of 88°*C* for the hot air temperature.

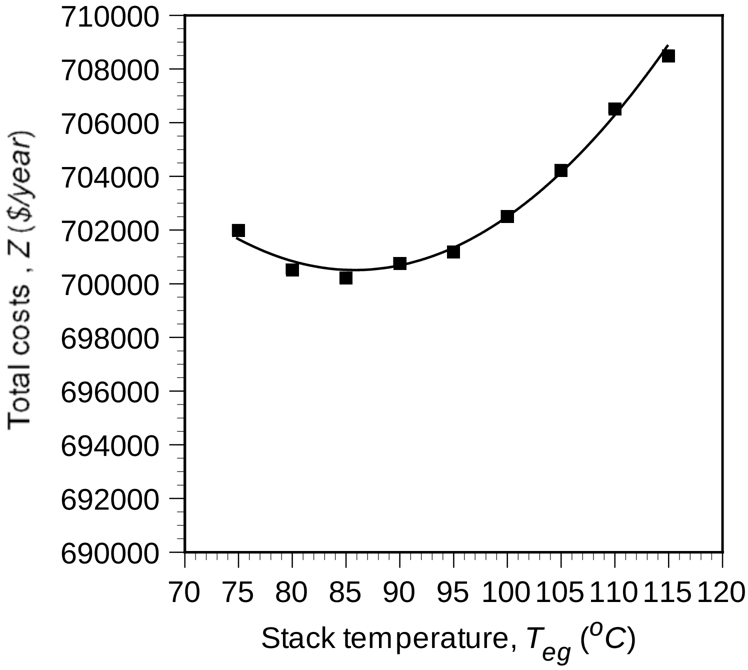

Fig. 7. Results obtained for the optimization of the stack temperature for case **III.**

Results for all of the heat recovery schemes studied are displayed in Table 3. It is observed that the optimal stack temperature, T_{eg}, varies between 80°*C* and 100°*C* for all the cases analyzed, except when a bagasse dryer is taken into account (Case **V**). For case **V**, the optimal stack temperature is slightly higher than 60°*C*; which is permissible when the last recuperative piece of equipment is the bagasse dryer, because acid deposition on the previous heat transfer surface (in this case the economizer) will never occur. The optimal value for bagasse moisture, *W*, is near 41% when a bagasse dryer is taken into account (case **V**). The optimal hot air temperature, T_{AH}, reaches the highest value for case **II,** as expected. Finally, if the thermal results presented in Table 3 are coupled with the total cost displayed in the last column, the most efficient combination of heat surfaces can be obtained. In this sense, the optimal heat recovery scheme is case **III** formed by an economizer followed by an air heater, in the exhaust gas flow direction.

Table 3. Optimization results for the different combinations studied (see notation in text)

Combination	T_{eg} (°C)	T_{AH} (°C)	W (%)	**Efficiency,** η (%)	**Cost,** Z (*$/year*)
Case **I**	83.6	150.0	50.0	87.9	709 436
Case **II**	98.6	257.0	50.0	86.8	716 418
Case **III**	86.0	88.0	50.0	87.8	700 206
Case **IV**	98.0	25.0	50.0	86.9	701 385
Case **V**	62.6	145.0	41.4	90.5	816 553

Another important aspect is to ascertain the influence of both heat transfer area and conventional fuel costs on the optimized parameters (stack temperature, hot air and bagasse moisture). To obtain the optimum value as a function of a certain individual cost, a similar procedure to that described above to optimize the stack gas temperature, has to be followed. For example, to analyze the influence of the air heater cost on the optimum value for the stack gas temperature in case **III**, the optimum value from the total cost chart is obtained for a first air heater cost, then for a second one and so on, until the range under study is completed. In this case, the optimal stack gas temperature is obtained as a function of the air heater heat transfer area cost curve, as depicted in Fig. 8a). The rest of the heat transfer areas and the conventional fuel costs, previously calculated, are kept constant at the values given in Table 2. In a similar way, an analysis was performed to determine the influence of the conventional fuel cost on the stack temperature, and the results are shown in Fig. 8 b). As can be observed, if the conventional fuel cost is increased, the optimum value for the stack temperature decreases. This behavior can be explained because the reduction in the consumption of conventional fuel becomes more significant if its price is raised, and, therefore, the optimum stack temperature is lower. On the other hand, if the cost of air heater heat transfer area increases, the optimum value for the stack temperature also increases, as depicted in Fig. 8a), because a further increment in the heat transfer area to reduce the stack temperature becomes more expensive. Hence, the optimum stack temperature displaces to lower values, if either a reduction in the cost of air heater heat transfer area or an increase in the conventional fuel cost, occurs.

a)

b)

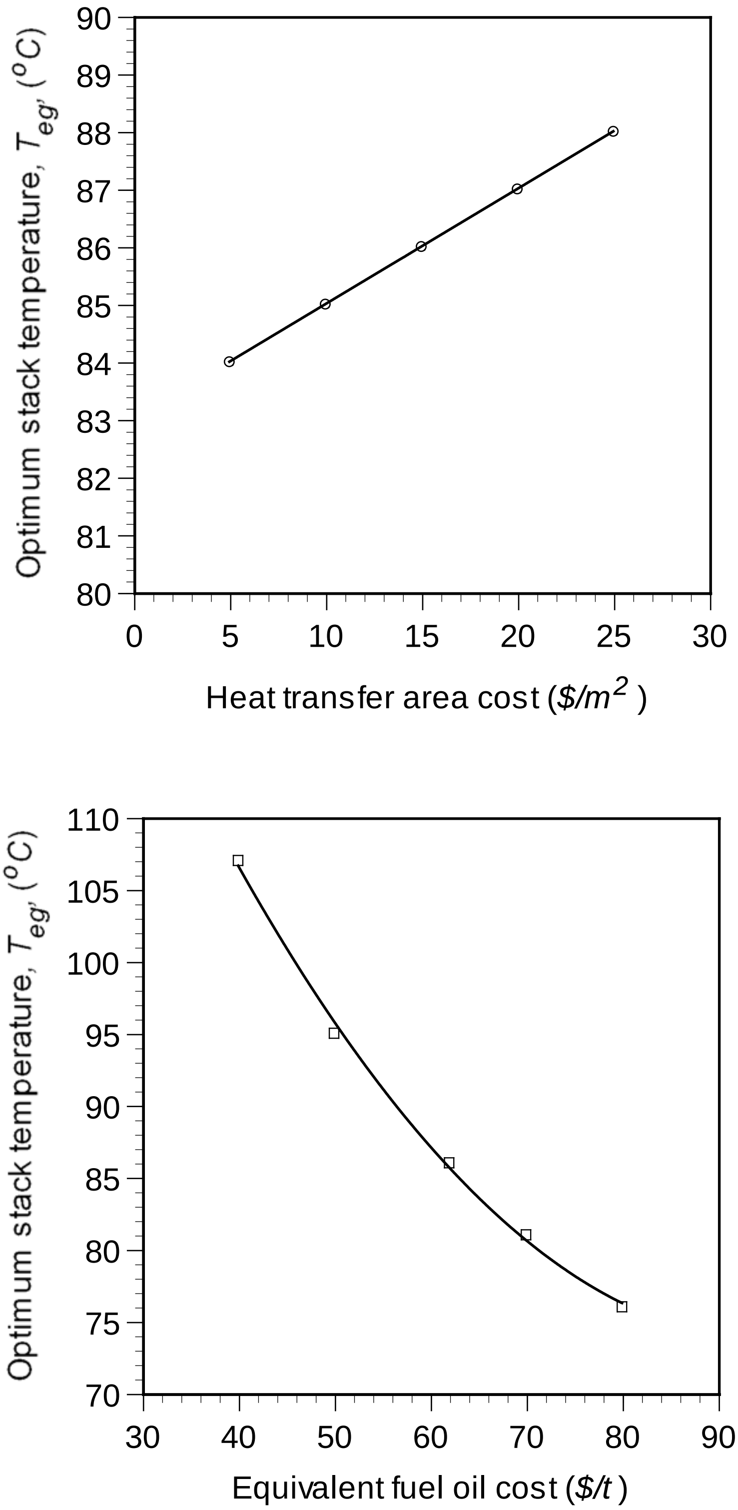

Fig. 8. Individual dependence of the optimum stack temperature with respect to heat transfer surface area cost (**a**) and conventional fuel cost (**b**) for the economizer-air heater heat recovery scheme (case **III**).

VI.- Conclusions

A methodology for the determination of heat losses and efficiency of RETAL boilers has been established, and a simplified *Bagasse-boiler Industrial Test Code* has also been implemented for the evaluation of boilers using bagasse as fuel. The use of this methodology requires a 10-hour test to evaluate and optimize the operation of a boiler, saving a lot of time when compared with the nearly 81 hours needed when the ASME or GOST methodologies are applied.

Three statistically-based models, Eqs. (17), (18) and (22), have been obtained, which are used to calculate the fixed carbon, chemical carbon, and exhaust gas heat losses, as a function of the stoichiometric ratio at the furnace, α_f, and the steam power, D_{sh}. The individual contributions of all heat losses on the overall boiler efficiency have been determined, yielding an efficiency chart for these bagasse boilers and the range of optimal stoichiometric ratio at the exit of the boiler, α_b. For all the boilers analyzed the optimal value of this parameter ranges between 1.5 and 1.55, for the whole range of steam power, contrasting with the 1.8 typically used prior to this study. This result greatly simplifies the decision-making and workload of the engineers and boiler operators, who can now easily control the boiler for optimum performance in different operating regimes.

To optimize the retrofit waste heat recovery scheme, several computer codes have been developed. The optimal stack temperature lies in the range between 60°*C* and 100°*C*, much lower than the 200°*C* commonly measured in most of the boilers installed in the Cuban sugar-cane industry. According to a coupled thermal and economic analysis, the optimal heat recovery scheme is that formed by an economizer followed by an air heater, in the direction of the exhaust gas flow, giving an optimal stack temperature of 86°*C*, with a hot air temperature of 88°*C*.

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