DETERMINATION OF THE OPTIMUM GAS EXHAUST TEMPERATURE IN BAGASSE BOILERS

By

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Abstract

This paper presents the results of the optimal gas exhaust temperature evaluation in bagasse boilers. Four different options for modifying the construction of an APU 50 boiler, manufactured by Caldema Industrial Equipments Ltda., were considered, as well as different scenarios for bagasse prices and for the commercialisation of the obtained electricity surplus. The boiler’s thermal calculations were carried out by using the software SBC-Steam Boilers Calculation. The analysis was implemented based on two approaches: considering the annual incremental cost of boiler operation (approach I) and the commercialisation of the electricity surplus (approach II), the latter using Gate Cycle version 5.5.1 for simulating a sugar mill typical steam cycle and for obtaining the amount of generated electricity. The most important conclusion of this study is that the results obtained by approach II should be given preference. The reason for this is the variability of the bagasse market prices, which are now much lower than the equivalent price of the fuel-oil. The optimal value of the gas exhaust temperature (120–130°C) is much smaller than the value now practised by boiler manufacturers (about 160°C), showing the existence of a potential for increasing the efficiency of bagasse boilers.

Introduction

The increase in the cogeneration installed capacity in the Brazilian sugar and alcohol industry is a trend that has been confirmed over the past few years. Now, the installed power is approximately 2500 MW, out of a thermodynamic and economic potential of 5584 MW and 4020 MW, respectively.

In this context, we can highlight the technological modernisation that accompanies this process, which is characterised by:

- implementation of high steam pressures (6–8 MPa) with condensing/extraction turbine units;
- evaluation and implementation of technologies allowing the reduction in the in-process steam consumption;
- mills electrification;
- installation of more efficient systems for the removal of solid particles from boiler exhaust gases.

The current steam boilers, with net thermal efficiencies ranging between 82% and 83%, have considerable potential for efficiency increase, mainly by means of a reduction in the temperature of the exhaust gases, which today is approximately 220°C.

Another way of improving the efficiency of these boilers, that was not taken into account in this work, is the use of more efficient combustion systems, which could result in gains of 1–2% as a consequence of the reduction of solid products of incomplete combustion.

Barroso et al. (2003) present the methodology and the results of the determination of the optimal temperature of the exhaust gases for the case of the RETAL-Cuban boiler. This work is based on the price of the sugarcane bagasse calculated as fuel-oil, its energy equivalent.
The resulting gas exhaust temperature of 85°C is low, as a consequence of the extremely low cost of the convective heating surfaces and of the cost of the fuel-oil taken as reference. These values coincide with the range of values for the dew-point temperature of the bagasse combustion gases: 60–90°C (Magasiner, 1996).

A more accurate approach to explain this subject could be based on the determination of the real cost of sugarcane bagasse by using thermo economics as a tool.

In this paper, the analysis of the optimum gas exhaust temperature is carried out based on two approaches: considering the annual incremental cost of boiler operation (approach I) and the commercialisation of the electricity surplus (approach II).

These results provide the answer to the question concerning the efficiency goal in bagasse boilers coupled to modern cogeneration systems, which constitutes the main objective of this work.

The modeling of different constructive options for the boiler was carried out with the help of the SBC – Steam Boilers Calculation Software developed in the NEST at the Federal University of Itajubá – UNIFEI in the State of Minas Gerais, Brazil. For the calculation of the cogeneration system, the software Gate Cycle version 5.51.0r was used (GE Entersoftware).

**The SBC software**

By using this software, it is possible to carry out the thermal and aerodynamic calculation of steam boilers burning sugarcane bagasse. The calculation methodology that was used corresponds to what was proposed in the Russian normative method for thermal and aerodynamic calculations of steam boilers (TsKTI, 1977).

The scheme, composed of a furnace, gas and air ducts, water and steam tubes, fans, soot blowers and a chimney, can be set up from different elements, surfaces and ducts using a friendly interface.

Silva et al. (1992) present the values of the necessary typical coefficients for the thermal calculation of bagasse boilers.

Figure 1 shows a lateral view of an APU 50 boiler cut drawing, manufactured by Caldema Industrial Equipments Ltda, which was used as the basis for the calculations.

Figure 2 illustrates a typical functional scheme of the boiler set up in the SBC interface. Its steam capacity is 150 t/h and the steam parameters are 6.3 MPa and 480°C.

**Scheme alternatives for the analysed boiler**

The boiler presented in Figure 3, for its original version, has the following convective surfaces:

- secondary air pre-heater;
- primary air pre-heater;
- economiser.

In order to obtain lower temperatures for the boiler exhaust gases, a preliminary air pre-heating stage was added after the economiser was added, and the height of the primary air pre-heater as well as the economiser surface were varied (Figure 3b).

By varying the duct width, it was possible to have three values of speed of the gases: 17.3, 12.1 and 8 m/s respectively.

Four groups of boiler modification options were analysed. In each case, the reduction of the temperature of the gases is achieved by increasing the economiser surface. There are 24 calculation cases. The four groups of modifications are:

1. Option A—Cases 1–6: with an additional air pre-heating stage after the economiser (1 m high and 519 m² of surface);
2. Option B—Cases 7–12: with an additional air pre-heating stage after the economiser (1.5 m high and 779 m² of surface);
3. Option C—Cases 13–18: with an additional air pre-heating stage after the economiser (2 m high and 1038 m² of surface);
4. Option D—Cases 19–24: Without air pre-heater after the economiser.
Fig. 1—Lateral view of the APU-50 boiler, which was used as reference for the calculations. 1: Furnace, 2: horizontal gas duct, 3: convective duct, 4: fuel belt transporter, 5: grate, 6: bagasse distributors, 7: drum, 8: convective superheater, 9: screen, 10: ash separator, 11: air pre-heater I, 12: air pre-heater II, 13: economiser first stage, 14: economiser second stage, 15: scrubber (wet ash separator), 16: induced draft fan, 17: chimney.

Fig. 2—Typical boiler scheme implemented at SBC screen.
Methodology

Two approaches have been used to determine the optimum gas exhaust temperature in bagasse boiler: These are considering the annual incremental cost of boiler operation (approach I) and the commercialisation of the electricity surplus (approach II). In both approaches, the following costs of the heating surfaces were adopted: economiser - 400 R$/m² and air pre-heating - 100 R$/m². In order to consider the costs of *in situ* assembly these values were multiplied by 1.25. Following are the details regarding the methodology.

In Approach I (based on the annual incremental cost of boiler operation), the minimum value of the annual operation cost is calculated, taking the reduction in the consumption of fuel, and the investment increment as a consequence of the gas exhaust temperature reduction into account. It is assumed that the sugarcane bagasse is purchased at a cost corresponding to its own price, which is about 5–7 US$/t (15–21 R$/t). Besides the increase in the cost of the fuel-oil, recent investments in combined heat and power plants have caused the current price of the sugarcane bagasse in the market to reach 30 R$/t. This value is still much smaller than the price calculated for the energy equivalent in oil, according to current levels of fuel-oil price, being is about 120–150 R$/t. The annual incremental cost of boiler operation, $\Delta Z$, is composed of the annualised additional investment in convective surfaces (considering the amortisation and the interest rates) and the reduction in the annual expenses for fuel, taking as reference the original version of the boiler (See equations 1 to 3).

$$\Delta Z = \Delta I_{\text{ANNUAL}} + \Delta C_{\text{FUEL}}$$

where:

$$\Delta I_{\text{ANNUAL}} = (C_{\text{H}}^\text{AP} \cdot \Delta H_{\text{AP}} + C_{\text{H}}^\text{ECO} \cdot \Delta H_{\text{ECO}}) \left[ \frac{i \cdot (1+i)^n}{1-(1+i)^n} \right]$$

and

$$\Delta C_{\text{FUEL}} = c_{\text{FUEL}} \cdot \Delta C_{\text{FUEL}} \cdot n_{\text{TEAR}}$$
In Approach II (based on the commercialisation of the electricity surplus), the techno-economic viability of the modifications in the boiler is determined, based on the additional profit obtained from the sale of the electricity surplus. The turbine always generates the same power because the generated steam flow is always the same. Then, it was considered that the ‘saved’ sugarcane bagasse would be used for electricity generation for a few hours during the off-season period (See equations 4 to 6). Table 1 shows the data adopted regarding the techno-economic assessment for both approaches.

\[
\Delta C_{\text{INCREMENTAL}} = (E_{\text{EI}} - E_{\text{SPLUS}}) \cdot C_{\text{EP}} 
\]  

\[
\text{NPV} = \sum_{n=1}^{\text{Year}} \left( \Delta C_{\text{INCREMENTAL}} - \Delta I_{\text{ANNUAL}} \right)_{\text{YEARMZERO}} 
\]

Or

\[
\text{NPV} = \sum_{n=1}^{\text{Year}} \left( \Delta C_{\text{INCREMENTAL}} \right)_{\text{YEARZERO}} - I_{\text{TOTAL}} 
\]

**Table 1—Data for the techno-economic assessment.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Season period, days</td>
<td>210</td>
</tr>
<tr>
<td>Operation factor</td>
<td>0.85</td>
</tr>
<tr>
<td>Mill capacity, tcf/h</td>
<td>210</td>
</tr>
<tr>
<td>Steam consumption in process, kgsteam/tc</td>
<td>450</td>
</tr>
<tr>
<td>Electricity consumption in process, kWh/tc</td>
<td>18</td>
</tr>
<tr>
<td>Interest rate, %</td>
<td>15</td>
</tr>
<tr>
<td>Investment life, years</td>
<td>5</td>
</tr>
<tr>
<td>Electricity commercialisation price</td>
<td>R$/MWh 70–120</td>
</tr>
<tr>
<td></td>
<td>US$/MWh 21–40</td>
</tr>
<tr>
<td>Net cycle power generation, MW</td>
<td>40.48</td>
</tr>
<tr>
<td>Condenser pressure, kPa</td>
<td>15</td>
</tr>
<tr>
<td>Net efficiency (LHV basis), %</td>
<td>25.43</td>
</tr>
<tr>
<td>Specific steam consumption (Heat rate), kJ/kWh</td>
<td>14 158</td>
</tr>
</tbody>
</table>

Additionally, in approach II, for the determination of the optimum gas exhaust temperature in the boiler, it was assumed that it included a combined heat and power plant, which is composed of a condensing-extraction steam turbine operating at 6.0 MPa and 500°C. Figure 4 shows the thermal scheme of the cogeneration plant. Previous work determined that, for generation projects with high steam pressures, the optimum pressure was 6.0 MPa (Carpio and Silva, 2002).

![Thermal scheme of a cogeneration plant with Gate-Cycle software results.](image-url)
The commercialisation electricity prices that were researched (70–120 R$/MWh) considered the maximum values based on the Program of Incentive to Alternative Energy -PROINFA that ranges from 89 to 120 R$/MWh (Brasil Energia, 2004).

**Results**

Figures 5 and 6 show the general results related to the variation of the fuel consumption, the power consumed by the fans and the boiler efficiency with the reduction of the gas exhaust temperature. The fuel consumption decreases slightly as a consequence of the increase in the boiler efficiency (See Figure 5). The power consumed by the induced draft fan increases with the gas exhaust temperature reduction, as a consequence of the increase in the duct aerodynamic resistance caused by the installation of additional heating surfaces. The power consumed by the forced draft fan falls due to the reduction in the fuel consumption and the necessary air flow. Each 10°C of reduction in the gas exhaust temperature corresponds to an increase of 0.7% in the efficiency of the boiler.

**Approach I**

The main results obtained from this approach are shown in Figures 7, 8 and 9. Figure 7, for a bagasse cost of 30 R$/t, shows the variation of the annualised investment and the fuel expenses with the reduction in the gas exhaust temperature for the different values of heat exchange surfaces that were
adopted. The rise in the incremental investment is observed as a logical consequence of the increase in the heat exchange surfaces in the air pre-heating and economiser. The variation in the expenses related to the ΔZ shows a tendency towards reduction values ranging between 140°C and 150°C, which soon are increased as a consequence the significant rise in the power consumed by the fans.

A similar curve, corresponding to the annual total cost of operation, shows optimum value of the gas exhaust temperature of approximately 155°C (Figure 8). The consolidated results of the dependence between the optimum exhaust gas temperature and the cost of the fuel are shown in Figure 9. It is confirmed that, for the sugarcane bagasse market price of 30 R$/t, the optimum exhaust gas temperature corresponds to 155°C.

Fig. 7—Dependence of the annualised investment and the expenses with fuel, at 30 R$/t, with the reduction in the gas exhaust temperature for the different values of heat exchange surfaces that were adopted.

Fig. 8—Dependence of the annual boiler operation cost with the reduction of the gas exhaust temperature for a fuel cost of 30 R$/t and the different values of heat exchange surfaces that were adopted.

Fig. 9—Dependence between the optimum gas exhaust temperature and the sugarcane bagasse price.
Approach II

As a tool for the analysis of the different investment cases in this approach, the Net Present Value (NPV) was used, being given preference to the option that presents the largest value for this parameter. Figure 10 shows the relation between the NPV and the gas exhaust temperature for the 4 modification options. It is observed that option C presents the best feasibility. Figure 11 shows the relationship between the NPV and the gas exhaust temperature for different electricity surplus commercialisation prices. From this graph, it can be concluded that the optimum value for the gas exhaust temperature ranges between 120 °C and 130°C.

![Graph showing the relation between NPV and gas exhaust temperature for different modifications and electricity surplus commercialisation prices.](image)

Fig. 10—Relation between the NPV and the gas exhaust temperature for the four modification options for 120 R$/MWh of electricity surplus commercialisation price.

![Graph showing the relation between NPV and gas exhaust temperature for different electricity surplus commercialisation prices.](image)

Fig. 11—Relation between the NPV and the gas exhaust temperature for different electricity surplus commercialisation prices.
Conclusions
The evaluation and comparison of the results of approaches I and II lead to the following conclusions:

- Each 10°C of reduction in the gas exhaust temperature corresponds to an increase of 0.7% in the boiler efficiency.
- The value of the gas exhaust temperature obtained from the analysis that used the annual cost of operation (approach I) for a market bagasse price of 30 R$/t corresponds to 155°C.
- The value of the gas exhaust temperature obtained from the analysis using the electricity surplus (Approach II) ranges from 120°C – 130°C.
- The variations in the bagasse market price relative to the equivalent fuel-oil price makes the results obtained from approach I less reliable than the ones obtained from approach II. However, a bagasse market price, giving the same exhaust gas optimal temperature as obtained in approach II, could be considered as a ‘real’ value of bagasse for a given economic scenario.
- The optimum value of the gas exhaust temperature obtained from approach II is much smaller than the values now used by manufacturers, approximately 160°C, showing the existence of a potential for an increase in the efficiency of the boiler that operates in combined heat and power plants that generate an electricity surplus.

REFERENCES

Nomenclature
\( \Delta I_{\text{ANNUAL}} \) Annualised incremental investment, R$/year;
\( \Delta Z \) variation of the annual fuel expenditures, R$/year;
\( C^0_{\text{AP}} \) Air pre-heater heat transfer unit surface cost, R$/m²;
\( C^0_{\text{ECO}} \) Economiser heat transfer unit surface cost, R$/m²;
\( \Delta H^0_{\text{AP}} \) Air pre-heater additional heat transfer surface in relation to the reference case, m²;
\( \Delta H^0_{\text{ECO}} \) Economiser additional heat transfer surface in relation to the reference case, m²;
\( i \) Annual discount rate (interests);
\( n \) Installation useful life, years;
\( c^0_{\text{FUEL}} \) Fuel market price, R$/t;
\( \Delta C^0_{\text{FUEL}} \) Fuel consumption reduction in relation to reference case, t/h;
\( n_{\text{YEAR}} \) Sugar mill annual operation, hours;
\( E^0_{\text{ES}} \) Electricity surplus for the incremental case, kWh/year;
\( E^0_{\text{SBASIS}} \) Electricity surplus for the original case (base), kWh/year;
\( \Delta C^0_{\text{SINCRCENTRAL}} \) Incremental revenue due to electricity surplus commercialisation, R$/year;
\( C^0_{\text{FP}} \) Electricity commercialisation price, R$/kWh;
\( \text{NPV} \) Net Present Value, R$;
\( \Delta I^0_{\text{ANNUALIZED}} \) Annualised value of the incremental investment (Air pre-heater and economiser increase in heat transfer surface), R$/year.
LA TEMPÉRATURE OPTIMALE POUR LE GAZ D’ÉCHAPPEMENT DE CHAUDIÈRES A BAGASSE

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MOTS CLEFS: Chaudière, Efficience, Cogeneration, Bagasse.

Résumé

On présente une évaluation de la température des gaz d’échappement provenant de chaudières a bagasse. Quatre options différentes pour modifier la construction d’une chaudière APU 50, construite par Caldema Industrial Equipments Ltda, ont été considérées ; en même temps on a étudié les effets du coût de la bagasse et de la commercialisation de l’électricité produite a partir de la bagasse. On s’est servi du logiciel SBC- Steam Boilers Calculation pour les calculs et l’analyse est basée sur deux approches. La première utilise le coût incrémental annuel d’opération de la chaudière ; la seconde utilise la commercialisation de l’électricité produite et se sert du Gate Cycle 5.51.0r pour la simulation de la consommation de vapeur et la production d’électricité dans une sucrerie de canne. La conclusion la plus importante de cette étude est que la seconde approche est la meilleure ; cette conclusion est causée par la variabilité des prix de la bagasse qui sont maintenant bien plus faibles que les prix équivalents de l’huile. La valeur optimale de la température des gaz est 120 à 130°C, ce qui est plus bas que la valeur habituelle (160°C) produites par les chaudières commerciales. Il existe donc une possibilité pour une amélioration de la performance des chaudières a bagasse.

DETERMINACIÓN DE LA TEMPERATURA ÓPTIMA DE ESCAPE DEL GAS EN LAS CALDERAS DE BAGAZO

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PALABRAS CLAVE: Caldera, Eficiencia, Co-generación, Bagazo de Caña de Azúcar.

Resumen

Este documento presenta los resultados de la evaluación de la temperatura óptima de escape de gas en las calderas de bagazo. Se consideraron cuatro distintas opciones para modificar la construcción de una caldera APU 50, fabricada por Caldema Industrial Equipments Ltda., así como distintos escenarios para los precios del bagazo y para la comercialización del excedente de energía eléctrica obtenida. Los cálculos térmicos de la caldera se llevaron a cabo usando el programa de cómputo SBC- Steam Boilers Calculation [Cálculo para Calderas de Vapor – SBC]. El análisis se implementó basándose en dos enfoques: considerando el costo incremental anual de la operación de la caldera (enfoque I) y considerando la comercialización el excedente de electricidad (enfoque II). Para este último se empleó Gate Cycle [Ciclo de Compuertas] versión 5.51.0r, con el fin de simular un ciclo típico de vapor de un molino de azúcar y para obtener la cantidad de energía eléctrica generada. La conclusión más importante de este estudio es que debe darse preferencia a los resultados obtenidos por el enfoque II. La razón de lo anterior es la variabilidad en los precios del bagazo en el mercado, que en la actualidad son mucho más bajos que el precio equivalente para el petróleo. El valor óptimo de la temperatura de escape de gas (120–130°C) es mucho menor que el valor que actualmente se emplea por los fabricantes de calderas (alrededor de 160°C), lo cual muestra la existencia de un potencial para incrementar la eficiencia en las calderas de bagazo.