EFFICIENCY ANALYSIS OF A BOILER FOR SUSPENSION BURNING OF SUGAR CANE BAGASSE

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The present paper describes the results of the retrofitting of a bagasse-fired boiler (RETO CV-25-18) in the sugar mill "Amancio Rodriguez", located in Las Tunas, Cuba. The boiler was modified in order to implement a suspension-burning configuration. Among other modifications, the distribution of combustion air along the furnace was redesigned in order to obtain a large-scale swirling-flow pattern above the grate. As a result, the new aerodynamic organization of the fuel-air mixture within the furnace was significantly improved.

The combustion efficiency of the boiler before and after the retrofitting is analyzed in this paper. The results of the analysis show that the gross efficiency calculated for the modified boiler increased by 1.91%. This difference is due mainly to the decrease of the heat losses by mechanical unburned matter from about 4% before the retrofitting to 1.95% with the new configuration.

Keywords: Furnace; Efficiency; Combustion; Bagasse; Suspension burning; Heat losses.

INTRODUCTION

The Sugar Industry in the Cuban Economy

The importance of the sugar industry for the Cuban energy budget may be appreciated from the data in Table I (CNE, 1993; MINAZ, 1995). Nearly one fourth of the energy consumed in Cuba in 1995 was generated by the sugar industry. That situation has not changed in the last years, and the bagasse constitutes the main energy source after the imported petroleum.

To increase the efficiency in steam generation is an important objective within the sugar industry, and a program aimed at the optimization of the old plants has been initiated.
TABLE I  Energy budget of Cuba in 1995 (compiled by Silva and Barreda, 1997)

<table>
<thead>
<tr>
<th>Energy source</th>
<th>$10^3$ tef</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imported fuel-oil</td>
<td>7200</td>
<td>61.6</td>
</tr>
<tr>
<td>National fuel-oil</td>
<td>1287</td>
<td>11.01</td>
</tr>
<tr>
<td>Bagasse</td>
<td>2600</td>
<td>22.24</td>
</tr>
<tr>
<td>Others</td>
<td>600</td>
<td>5.15</td>
</tr>
<tr>
<td>Total</td>
<td>11687</td>
<td>100.0</td>
</tr>
</tbody>
</table>

tef* — tons of equivalent fuel-oil

The following data give an idea of the relevance and possibilities of bagasse as an energy source in Cuba:

1. The energy potential of bagasse is estimated in 1120–1600 GJ.
2. 85% of the Cuban sugar mills are connected to the electricity distribution system.
3. 74% of the energy demand in the Cuban sugar industry is covered by the combustion of bagasse.

Figure 1 shows the ratio between the energy generation capacity currently in the Cuban sugar mills and the energy consumption in these plants, between 1989 and 1999. The ratio increased in 1994 due to the installation of 42 new steam turbines, accounting for an increment of 100 MW in the installed capacity. Nevertheless, the energy consumption still exceeds the generation capacities. Also, Figure 1 displays the ratio between the electricity generated and consumed in the Cuban sugar mills. The values of this ratio are lower than 1 in all the cases, indicating that the mills are consuming energy from the national electricity distribution network. Since energy is mainly obtained from imported petroleum, a decrease of the net electricity consumption in the sugar mills is of the utmost importance for the Cuban economy.

The combustion equipment installed in the sugar mills by the end of the 1980's consisted of horseshoe furnaces, with combustion in layer or pile, not suitable to achieve high capacities or efficiencies. The main disadvantages of these combustion systems are the following (Horton, 1980; Watkins, 1993):

- High maintenance cost for furnace brickwork.
- Necessity to maintain a high excess air in the furnace, in order to avoid a high level of heat losses due to incomplete burned from chemical and mechanical causes. This results in low gas temperature inside the furnace and, consequently, in a poor heat exchange by radiation.
- High heat losses in the flue gases due to both poor heat exchange inside the furnace and to the increased gas flow rate caused by the high excess air.
EFFICIENCY ANALYSIS OF A BOILER

FIGURE 1 Evolution of electricity generated/consumed and installed/consumed in the Cuban sugar industry for the harvests between 1989 and 1999.

air. An increased power consumption of forced and induced draught fans is also observed.

- A great amount of bagasse is piled up on the grate causing a high inertia of the system and consequently a slow response to load changes. It is difficult to introduce reliable combustion regulation systems.
- Poor control of combustion air, with leakage through the bagasse feeding chutes.

The introduction of new combustion technologies in those boilers can result in more efficient steam generators, allowing an increased capacity of the existing bagasse-fired boilers. As a result, the contribution of the sugar industry to the Cuban energy budget may be increased, reducing the dependence on imported oil for electricity generation. All these benefits can be achieved with a simultaneous reduction of pollutant emissions to the atmosphere.

SUSPENSION BURNING IN BOILER RETO CV-25-18

The retrofitting of installed boilers to implement suspension burning of bagasse-fuel is one of the alternatives proposed to the Sugar Ministry in order to improve their performance. These firing systems have the following advantages (Beaton, 1994; Oliva et al., 1991; Brito and Beaton, 1997):

- The high turbulence in the combustion chamber guarantees a good mixing between the bagasse particles and the air, as well as a more intense convective heat exchange.
- The high levels of furnace temperatures and the long residence time of the fuel particles create favorable conditions for an efficient combustion.
- The suspension burning of bagasse results in a fast response to changes in steam demand.
The research group of the University of Oriente developed a physical model to study the combustion process in suspension. In a subsequent stage, the sugar mill "Amancio Rodriguez" was retrofitted to implement and test a configuration of suspension burning.

Cuban engineers of the Mechanical Design Company in collaboration with Russian specialists designed the original boiler. In this design, the bagasse burns on a dumping grate, with a capacity of 25 ton/h, a pressure of 1.8 MPa and a superheated steam temperature of 600 K. Other design parameters are summarized in Table II. This boiler was denominated RETO CV-25-18, and the Cuban industry has installed this boiler from 1982.

The implementation of suspension burning in a boiler RETO was achieved by modifying the injections of bagasse and air (Brito and Beaton, 1997). Figure 2 shows a schematic of the furnace after the retrofitting. Bagasse and a fraction of the combustion air are supplied through pneumatic distributors located in the front wall. The rest of the air is injected through overfire air nozzles installed at differ-

### TABLE II Design and operating parameters of the boiler RETO, (I) before and (II) after the retrofitting

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>I</th>
<th>II</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Steam generation</td>
<td>Ton/h</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>2. Bagasse moisture</td>
<td>%</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>3. Feed water temperature</td>
<td>°C</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>4. Bagasse low caloric value</td>
<td>kJ/kg</td>
<td>7954</td>
<td>7954</td>
</tr>
<tr>
<td>5. Available heat</td>
<td>kJ/kg</td>
<td>8009</td>
<td>8009</td>
</tr>
<tr>
<td>6. Drum pressure</td>
<td>MPa</td>
<td>2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>7. Superheated steam pressure</td>
<td>MPa</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>8. Superheated steam temperature</td>
<td>°C</td>
<td>320</td>
<td>354</td>
</tr>
<tr>
<td>9. Flue gas exit temperature</td>
<td>°C</td>
<td>199</td>
<td>212.5</td>
</tr>
<tr>
<td>10. Excess air in flue gases</td>
<td>%</td>
<td>1.54</td>
<td>1.62</td>
</tr>
<tr>
<td>11. Loss q2</td>
<td>%</td>
<td>13.4</td>
<td>14.0</td>
</tr>
<tr>
<td>12. Loss q3</td>
<td>%</td>
<td>0.5</td>
<td>0.14</td>
</tr>
<tr>
<td>13. Loss q4</td>
<td>%</td>
<td>4</td>
<td>1.95</td>
</tr>
<tr>
<td>14. Loss q5</td>
<td>%</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>15. Bagasse consumption</td>
<td>kg/s</td>
<td>2.89</td>
<td>3.9</td>
</tr>
<tr>
<td>16. Gross efficiency</td>
<td>%</td>
<td>80.9</td>
<td>82.81</td>
</tr>
</tbody>
</table>

$q_2$=Heat losses in flue gases
$q_3$=Heat losses due to incomplete burning from chemical causes
$q_4$=Heat losses due to incomplete burning from mechanical causes
$q_5$=Heat losses to the surroundings
The studies performed indicate that the fuel particles behave differently depending on their size. The bigger particles burn mainly in the lower part of the furnace. The finer fractions, as well as low-density partially-burned particles, are entrained into the upwards gas flow, and their combustion takes place in a "vertical flame" over the upper part of the furnace (Oliva et al., 1991).

The main modifications carried out in the furnace of the boiler RETO to implement a suspension-burning configuration are:

- Lengthening of the rear and front walls.
- Reduction of the surface area of the grate in 50%.
- Installation of pipe and nozzles for the supply of air.
- Substitution of the mechanical feeder by a pneumatic feeder.
- Change of fans.

Before the retrofitting, most of the combustion took place on the grate, where bagasse was deposited forming a pile. After the retrofitting, a much larger fraction of the fuel burns in suspension and the area of the grate could be re-
duced by about 50% to 8.04 m\(^2\). With the new configuration, only the bigger particles are deposited and burn on the grate.

The walls of the retrofitted furnace are covered by tubes of 57 x 3.5 mm. This represents a heat-transfer surface of 151 m\(^2\). The tubes of the rear and front walls at the height of 3 to 5 m and 5.67 to 6.6 m respectively have been curved forming two "noses" in order to increase the gas path length inside the combustion chamber and a longer residence time of the bagasse particles.

**EFFICIENCY ANALYSIS**

The efficiency of steam boilers can be determined by direct and indirect methods. The direct method is rarely used for the study of bagasse-fired equipment due to the difficulty in having a continuous measure of fuel mass-flow rate. The equation for efficiency calculation by the indirect method is:

\[
\eta = 100 - \sum_{i=2}^{6} q_i
\]

where \(\eta\) is the gross efficiency of the boiler (in %), and is calculated from the different heat losses:

- \(q_2\) = Heat losses in the flue gases, %.
- \(q_3\) = Heat losses due to incomplete burning from chemical causes, %.
- \(q_4\) = Heat losses due to incomplete burning from mechanical causes, %.
- \(q_5\) = Heat losses to the surroundings, %.
- \(q_6\) = Heat losses by the sensible heat of the slag, % (in bagasse-boilers this contribution is negligible).

The main results of the tests carried out in the reconstructed boiler are presented in Column II of Table 2. Column I in the same table indicates the design values of the boiler RETO before the retrofitting. The comparison of both data series shows the advantages obtained after the retrofitting. Nevertheless, this is even a conservative estimate, since the operation parameters of the boiler before the modifications were much worse than the design values (e.g., the actual efficiency was about 76 to 78%, instead of the nominal value of 80.9%).

A remarkable result of the reconstruction is that the nominal steam generation-capacity could be increased from 25 to 35 ton/h (40 %), due to a better use of the furnace volume and to the increase of the heat transfer surface in the furnace.
The suspension burning allows burning a higher quantity of fuel compared to the combustion of bagasse on the grate in the previous configuration. On the other hand, convective heat transfer to the furnace walls is enhanced in the new geometry due to the higher velocity of the gases.

The gross efficiency of the boiler has increased by 1.91% as a result of the retrofitting, due mainly to the decrease of the heat losses due to unburned matter from mechanical causes ($q_4$ is reduced from 4% to 1.95%) as a result of the retrofitting. The uncertainty associated to the determination of $q_4$ has been estimated as 0.86%, and therefore the reported difference is considered a reliable result. The reduction of 2.05% in $q_4$ is attributed to the improved aerodynamic organization of the flow inside the combustion chamber achieved with the suspension-burning configuration. This effect also leads to a decrease of heat losses due to incomplete burning from chemical causes ($\Delta q_3 = -0.357\%$). These benefits overcome the increase of the heat losses in the exit gases by +1.3 %. The increase of this parameter was caused by the high value of the excess air measured ($\alpha_{eg} = 1.6$) compared to the nominal value before the retrofitting ($\alpha_{eg} = 1.54$) together with the increase of the exit gas temperature (199°C before, and 212.5°C after the retrofitting).

![Temperature field inside the reconstructed boiler (°C).](image)
The temperature distribution inside the combustion chamber was measured for a steam generation of 35 ton/h and is shown in Figure 3. The maximum temperature zone (1250°C) is located in the central and lower parts of the furnace. No contact between the flame and the tubes of the wall is observed, which guarantees normal conditions of heat transfer (Brito and Beaton, 1997).

The gas temperature measured at the furnace exit for the load of 35 tons/hr is 875°C, similar to the value obtained before reconstruction (850°C) for the load of 25 tons/hr. The flame is distributed over the furnace volume completely, which explains the fairly uniform temperature distribution measured in the combustion chamber.

Figure 4 shows the oxygen distribution measured inside the combustion chamber before and after the retrofitting. Significant differences in the patterns of oxygen isolines for the two cases can be observed. Such effects are consistent with the different combustion strategies. In the original boiler, the oxygen concentration decreases gradually as the flow moves downstream from the grate, until a final value around 5%. On the contrary, the measurements of oxygen in the
retrofitted boiler reproduce the swirling-flow pattern, with a minimum at the center of the lower flame. Downstream, the oxygen concentration is higher near the rear wall, where overfire air is injected, and the values at the exit are in the range of 5 to 10%.

CONCLUSIONS

- As a result of the reconstruction of the boiler, the steam generation and combustion efficiency were increased from 25 to 35 ton/hr and from 95.5 to 97.5%, respectively. The high gas velocity in the furnace leads to an enhancement of heat and mass transfer and, consequently, to a higher capacity of the furnace and a higher efficiency of the process.
- In particular, the flow pattern achieved within the retrofitted boiler causes a more intense air/fuel mixing, leading to a reduction by a factor of 2 of the solid unburned material leaving the furnace.
- The high gas velocity in the furnace enhances the convective heat transfer, contributing to the increase of the boiler capacity.
- The reconstruction includes the reduction of the grate area by 50%, with most of the fuel being burnt in suspension. Nevertheless, the combustion of a fraction of bagasse still takes place on the grate, which helps to prevent a loss of pressure in the event of an interruption in the supply of bagasse to the furnace.
- A more homogeneous temperature field in the combustion chamber is observed. In particular, this effect reduces the thermal stresses in the tubes, which are the cause of frequent failures in bagasse-fired boilers.

The encouraging results obtained support the convenience of the retrofitting of the old boilers in the Cuban sugar industry. The reconstruction of two other steam boilers for burning bagasse in horizontal swirl are being carried out in the sugar mills "Amancio Rodriguez" and "Los Reynaldos."

References

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