THE EFFECTS OF BAGASSE MOISTURE VARIATIONS ON THE PERFORMANCE OF A 105 TPH BOILER

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Introduction

Bagasse moisture content has a significant effect on the performance of a bagasse fired boiler and even a relatively small variation of one or two per cent can have a noticeable effect on the boiler performance. The effects of fuel moisture are not limited to combustion stability and boiler efficiency, but also influence the erosion rate of the convective surfaces, absorbed power and various other factors which will be discussed in more detail.

The moisture content typically varies between 47 and 56%, but there are mills which have managed moisture contents as low as 43%. This may seem like a narrow band but one has to consider the energy required to evaporate the moisture, this translates into a significant difference in the reactivity of the fuel and the boiler efficiency.

A complete set of calculations were performed with the moisture content varying from 10 to 56%. Although not currently employed in the African sugar industry there is technology available which can reduce the fuel moisture by 8-13% depending on the boiler final gas temperature. Thus it is possible to reduce the fuel moisture below 40%. Dryer fuels such as wood chips may be blended in because of fuel availability and to reduce the average fuel moisture content.

The behaviour of the fuel changes drastically below 47% and factors such as slagging can become the determining factor in the boiler design. This effect will depend on the chemical composition of the fuel, which in turn is influenced by soil composition amongst other factors.

It is normally not practical to guarantee that the fuel moisture content will consistently remain below 50%. Therefore even if the plant is set up to produce lower moisture bagasse or when bagasse dryers are used the boiler would still be designed to burn 50% moisture bagasse.

The moisture content of the fuel influences the boiler design. Designing a boiler to cater for large variations in fuel moisture will therefore result in a more expensive boiler. The effects of fuel moisture on the boiler design will be discussed in greater detail.

Effects on Boiler Performance

For the purpose of this exercise a typical bagasse analysis was chosen (Table 1). The moisture content was varied over a range of 10 to 56% and the fuel composition was adjusted or diluted accordingly. The calorific value was calculated based on standard SMRI (Wienese, 2001) formulas, while the carbon loss and excess air ratio was adjusted based on John Thompson guidelines.
### Table 1. Base fuel, % mass.

<table>
<thead>
<tr>
<th>Element</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>21.71</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>2.68</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.02</td>
</tr>
<tr>
<td>Oxygen</td>
<td>20.77</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.16</td>
</tr>
<tr>
<td>Chlorine</td>
<td>0</td>
</tr>
<tr>
<td>Argon</td>
<td>0</td>
</tr>
<tr>
<td>Water</td>
<td>50</td>
</tr>
<tr>
<td>Ash</td>
<td>4.66</td>
</tr>
</tbody>
</table>

| Gross calorific value | kJ/kg | 8824 |
| Net calorific value  | kJ/kg | 7018 |

The fuel moisture has a significant influence on the boiler performance and the major effects can be grouped together under the following headings:

- **Efficiency**:
  - Moisture in gas loss
  - Excess air requirement
  - Carbon loss

- **Velocities**:
  - Increased gas and air side pressure drop
  - Increase in fan absorbed power
  - Increase in erosion

- **Dew point corrosion and deposits.**

*Moisture in gas loss*

The efficiency calculations are based on the input-output method as prescribed by ASME PTC 4 (2013) and FDBR (physical characteristics of combustion gases are calculated for a concrete composition in the given cross-section of the gas duct) method used for calculating the gas properties.

The moisture in the fuel is evaporated before the combustion process can commence. This process requires a lot of energy which is lost to the boiler because the moisture is not condensed in the boiler but rather emitted as gas along with the rest of the flue gas. This loss of energy is referred to as moisture loss. The moisture in gas loss is by far the biggest single loss in a bagasse fired boiler and as evident by Figure 1, there is a significant proportional change with variation in fuel moisture content.

*Excess air requirement*

The moisture content also influences the optimum excess air requirement, operating the boiler below this point will result in increased carbon loss and high CO levels while operating it at a higher level will result in lower carbon loss it will result in higher dry gas and moisture in air loss. The higher the moisture content, the more combustion air is required to achieve ignition and an acceptable level of combustion. Although the type of combustion equipment influences the excess air requirement it will follow a similar trend regardless of the technology used. For the purposes of this exercise the excess air requirement is based on a standard spreader stoker fired boiler which is the most widely used technology in the Southern African sugar industry.
The excess air requirement remains fairly constant below 50% fuel moisture content but increases rapidly at higher moistures. Both the fuel reactivity and the physical characteristics e.g., propensity to lump together reducing the mixing of fuel and air, changes rapidly above 50% moisture content demanding a higher excess air ratio to ensure stable combustion and to limit the carbon loss. The air does not only provide the oxygen required for combustion but also helps to keep the fuel in suspension and to drive off the moisture.

![Figure 1. Dry gas loss and moisture in gas loss.](image)

It is evident from Figure 1 that although the excess air requirement influences the overall boiler efficiency it is overshadowed by the moisture loss. A higher excess air ratio will result in increased gas and air flow which in turn will result in increased velocities and pressure drop on both air and gas side of a boiler. The excess air ratio thus influences the FD and SA fan parasitic load which will be discussed later in this paper.

**Carbon loss**

The moisture content of the fuel has a significant effect on the unburned carbon loss and is mainly driven by the following factors:

- The fuel reactivity
- Upwards velocity in the furnace
- Physical fuel properties.

As mentioned earlier, the moisture is evaporated before the combustion process can commence. The rate of this process is a function of the temperature, which is a function of the amount of refractory in the boiler, and the undergrate air temperature, as well as the fuel particle size.

The majority of bagasse boilers rely on suspension firing, making the upwards or up-flow velocity in the furnace a very important variable. The gas volume and as a result upwards velocity in the furnace is a function of the amount of combustion gasses released and the excess air ratio which both decrease with fuel moisture. The lower the upwards velocity the more time the fuel spends in the furnace (residence time) allowing more complete burnout, thus less unburned carbon and ash are carried over from the furnace.
At higher moistures the fuel tends to lump together resulting in a larger portion of the fuel burning on the grate thereby reducing the mixing of the fuel and the combustion air. This is where the type of stoker and the secondary air system start to play a role in the boiler efficiency. A well designed and setup secondary air system will help to reduce the carbon loss while a continuous ash discharge stoker (CAD and vibrating grate) will allow better burn out of the fuel that lands on the grate compared to a batch wise ash removal system (pin hole grate and dump grate). However, when burning bagasse with moisture contents in excess of 54% and typical ash content in a furnace designed for combustion in suspension, could result in the fuel blocking the airflow through the grate sufficiently to prevent effective combustion of these piles of bagasse on the grate, even in the case of a moving grate. This will result in a large percentage of unburned fuel leaving the furnace with the coarse ash.

It is important to note that the carbon loss is calculated based on experimental data obtained under ideal operating conditions and will in fact be higher under normal operating conditions.

Although the carbon loss is significantly less than the moisture and dry gas losses respectively it is something that can be reduced and will translate into a noticeable fuel saving.

**Boiler efficiency**

Figures 2 and 3 and the aforementioned factors prove that the fuel moisture has a significant influence on the boiler efficiency and ultimately the fuel consumption. Figure 2 contains two lines, the top one is the actual fuel consumption of the boiler at given moisture content while the bottom one is the bone dry fuel consumption, note the fuel still contains ash.

![Figure 2. Boiler fuel consumption.](image-url)
Figure 3. Boiler efficiency relative to fuel moisture content.

Table 2 displays the typical fuel moisture range attainable with current technology, and the associated boiler performance. A fuel moisture content of 40% can comfortably be achieved using a bagasse dryer however, anything lower than this would be more difficult to achieve. Maintaining stable combustion becomes problematic once the fuel moisture exceeds 52% and the additional energy required to evaporate this moisture becomes impractical when combusting biomass with moisture content exceeding 56%. Bagasse drying is unpacked in more detail later in this paper.

Table 1. Boiler performance comparison.

<table>
<thead>
<tr>
<th>Fuel moisture content</th>
<th>%</th>
<th>40</th>
<th>50</th>
<th>56</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross calorific value</td>
<td>kJ/kg</td>
<td>10588</td>
<td>8824</td>
<td>7765</td>
</tr>
<tr>
<td>Net calorific value</td>
<td>kJ/kg</td>
<td>8910</td>
<td>7018</td>
<td>5882</td>
</tr>
<tr>
<td>Dry gas loss (%)</td>
<td>%</td>
<td>4.99</td>
<td>5.5</td>
<td>6.81</td>
</tr>
<tr>
<td>Moisture in Gas Loss</td>
<td>%</td>
<td>20.31</td>
<td>25.6</td>
<td>30.36</td>
</tr>
<tr>
<td>Boiler NCV efficiency</td>
<td>%</td>
<td>88.88</td>
<td>86.5</td>
<td>82.81</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>t/h</td>
<td>36.2</td>
<td>47.2</td>
<td>56.8</td>
</tr>
<tr>
<td>Dry fuel consumption</td>
<td>t/h</td>
<td>20.58</td>
<td>22.734</td>
<td>24.24</td>
</tr>
<tr>
<td>Fuel consumption relative to 50% moisture</td>
<td>%</td>
<td>76.7</td>
<td>120.3</td>
<td></td>
</tr>
<tr>
<td>Fuel saving on dry basis</td>
<td>%</td>
<td>9</td>
<td>0</td>
<td>-7</td>
</tr>
</tbody>
</table>

**Velocity and pressure drop**

The moisture content has a significant influence on the amount of flue gas released. Thus an increase in fuel moisture will translate into increased gas volume flow, gas velocity and pressure drop over the convective surfaces of a boiler (figures 4, 5 and 6). As explained above the optimum excess air is a function of the fuel moisture, thus an increase in moisture translates into increased gas and air side velocities. The pressure drop, erosion rate and fan absorbed power all depend on velocity. Therefore, the effects of fuel moisture extend well beyond the boiler efficiency.
The moisture content has a particularly large impact on the erosion rate. Not only is it velocity dependant but the lower furnace velocity when burning dryer fuels and reduction in fuel consumption result in a reduction in ash carried over from the furnace. Thus even a relatively small variation in moisture content will have a significant influence on the erosion rate of the convective heating surfaces and downstream equipment.

**Figure 4. Flue gas velocities.**

**Figure 5. Gas side pressure drop.**
Dew point corrosion and deposits

It is evident from Figure 7 that the variation in the water and the acid dew point temperature, across the typical bagasse moisture range seen in industry, can be ignored. The bagasse moisture typically varies between 48 and 52% with a water dew point temperature increasing from 68 to 69°C. The drop in water dew point temperature only becomes notable below 40% moisture content in fuel, which is currently not achieved in the industry.

Figure 6. Fan absorbed power based on nominal fan efficiencies and an ESP (60 and 70% efficiency for FD and ID respectively)

Figure 7. Dew point temperature, sulphuric acid dew point temperature calculated based on the Ganapathy (1993) method.
Design Implications

Although boilers are designed to handle a range of fuels, modifications may be required if there is a significant variation in the fuel moisture. The areas most affected are:

- Furnace refractory
- Superheater
- Airheater size vs economiser size
- Grate design:
  - CAD
  - Vibrating grate
  - Dump grate
  - Pinhole grate

Boilers designed to combust high moisture fuels have a refractory band in the furnace to create a high temperature zone to accelerate the water evaporation rate in order to improve combustion stability. If a boiler is purposefully designed to burn low moisture fuels the size of the refractory band will reduce accordingly. However, it is generally not possible to guarantee constant low moisture in a sugar mill.

The combustion temperature and the furnace exit temperature both vary inversely with the fuel moisture (Figure 8) and can lead to slagging on the refractory or even the superheater (Magasiner, 1987). This is normally not a problem since the concentration of the alkali metals is generally low, but the risk will increase should brown leaf be blended with the bagasse or if the soil stuck to the cane should contain unwanted elements that could contaminate the bagasse.

![Figure 8. Furnace exit temperature.](image)

The heat transfer rate in the superheater is a function of the gas temperature and the volume flow rate. The volume flow rate varies with fuel moisture while the furnace exit temperature is inverse to the fuel moisture making them opposing variables.

In order to ensure stable combustion, high moisture fuels require hot combustion air. The air accelerates the evaporation process of the moisture, hence the hotter the air the more stable the combustion would be. However, the boiler grate relies on the primary combustion air passing through it for cooling. Thus, besides the cost of a larger airheater and FD fan which
is required to achieve higher temperatures, the temperature is limited by the grate. Due to the aforementioned trade off the combustion air temperature is typically limited to 250°C.

The under grate air temperature influences the furnace temperature, in other words higher under grate air temperature will result in increased furnace and furnace exit temperature.

This increases the risk of grate level slagging for lower moisture fuels and therefore if a boiler is designed for low moisture biomass the air temperature is reduced and less refractory is used to allow for more heat absorption through the water-cooled membrane walls. To maintain the boiler efficiency the size of the economiser is then increased.

The backend of the majority of the boilers in the African Sugar industry consist of an airheater followed by an economiser. This configuration is widely used since it greatly reduces the risk of dew point corrosion while a high enough under air temperature can be achieved. Since both the dew point temperature and the required under grate air temperature, to achieve stable combustion, reduces with fuel moisture the backend layout can be changed around with the economiser located before the airheater should the moisture content be reduced sufficiently, below 40%.

A lower final gas temperature and consequently higher boiler efficiency can be achieved when an airheater is the last heat recovery bank opposed to an economiser. To ensure sufficient under grate air temperature, when the moisture content exceeds 40%, the airheater has to be located upstream of the economiser. When the desired efficiency cannot be achieved with this arrangement a second airheater can be installed after the economiser. The air will pass through this second unit before going to the unit located upstream of the economiser. To ensure longevity special design features has to be incorporated in the design of the second airheater, there are papers available on this design (Moor, 1985; Kotze, 2016). The additional ducting required to connect the two airheaters makes it a more expensive design. Therefore a low final gas temperature can be achieved on low moisture fuel without the added complexity of a second airheater.

The allowable grate rating, energy released per square meter of grate area, is a function of the fuel moisture content and drops off significantly when the moisture content exceeds 50%. It is due to the fraction of fuel burning on the grate increasing rapidly beyond this point and it is one of the main reasons why there is an increase in carbon loss beyond this point.

It should be noted that the carbon loss is determined under ideal test conditions with the secondary air system setup at the optimal point, stable load and the grate is not dumped (dump grate) or steam-blown (pin hole grate) during this period.

Grates such as a dump grate and a pinhole grate, where the ash is removed in batches, will result in a large amount of unburned fuel being discharged with the coarse ash. The piles that form during the combustion of high moisture fuel will end up in the sluice system as floating particulate and can cause chokes as well as pose a fire risk in chutes. This is of particular concern when operating a dump grate since a fire in the under grate hopper can cause overheating of the linkages.

A continuous ash discharge stoker allows the piles more time to burn out resulting in a lower carbon loss and is therefore preferred when burning high moisture fuels. A vibrating grate has the added bonus of levelling the piles to create a more even covering of the grate, that in turn prevents preferential air flow and reduces the carbon-in-coarse-ash loss.

Reducing Bagasse Moisture

The most cost-effective way to reduce the moisture content is to ensure that the plant milling tandem or drying mills are setup optimally. It is evident from the calculations that even a 1% reduction in fuel moisture yields a noticeable improvement in efficiency (refer to Figure 3).
There are also alternative technologies available to reduce the bagasse moisture. One type of flash dryer is installed in the hot flue gas path after the boiler gas clean up plant in case of a dry gas cleaning system and if a wet scrubber is used would be bypassed and the dryer will act as gas clean-up plant as well.

The bagasse is introduced into the exhaust gas and relies on the heat in the flue gas to evaporate some of the moisture. This type of dryer consists of two sections, a drying section and a collector. A cyclonic collector is used to capture and remove the bagasse from the flue gas after the drying section.

With a final gas temperature of 140°C the moisture content can be reduced by 8-10%, and when the final gas temperature is 160°C and above, the moisture content can be reduced by 10-13%.

Although this type of plant is not currently used in Southern Africa it is starting to gain popularity in other parts of the world such as India. Although not all flash drying plants installed around the world have been successful some designs have proven to operate reliably and are yielding significant savings.

The three most common concerns about driers which inject the bagasse into the flue gas are:

- Increase in parasitic load: A cyclonic collector is employed to capture and remove the bagasse from the flue gas after the dryer adding to the gas side pressure drop.
- Loss of bagasse fines: If the collector is not designed correctly some of the bagasse will escape with the flue gas.
- Fire hazard: On lower efficiency boilers where the final gas temperature is high and there is an increased risk of burning embers reaching the drier, which can lead to a fire.

As mentioned earlier there are dryers in operation which managed to overcome these problems. Although the dryer adds to the plant parasitic load in some ways, e.g. additional pressure drop through the cyclone(s), additional conveyors, it also reduces the boiler parasitic load in other ways e.g. lower flue gas volume flow due to reduced water vapour in the gas and improved boiler efficiency. Furthermore, air side power consumption reduces due to a reduction in combustion air requirement due to lower fuel consumption and lower excess air requirement. There is a significant reduction in the gas side power consumption due to lower pressure drop and volume flow rate. The saving in boiler parasitic load will offset, or at least help offset the bulk of the dryer's parasitic load.

A well-designed bagasse dryer will not only prevent bagasse from escaping with the flue gas but will reduce the boiler emissions. The bagasse in the dryer will capture some of the particles reaching the dryer while the lower moisture content will result in a reduction in carbon loss.

A pre-collector can be installed on older less efficient boilers to capture and remove any unburned embers that may be emitted from the boiler but as stated above the dryer will reduce the unburned carbon in fly ash loss, largely due to a reduction in fly ash carry-over. In other words, by installing a bagasse dryer the amount of unburned embers escaping from the boiler is reduced significantly.

Due to the advances in bagasse drying technology and advantages (lower fuel consumption, reduced carbon loss, and lower erosion). This should be considered at plants having to burn coal as a supplementary fuel.
Conclusion

It can be concluded that the moisture content has a significant effect on the boiler in more than one way and that a significant variation in the fuel moisture will impact the boiler design.

The moisture loss is the single biggest loss on a bagasse fired boiler. Both the moisture and the carbon loss are directly linked to the fuel moisture so it can be concluded that reducing the moisture content will yield a significant efficiency improvement. Furthermore, it also impacts the pressure drop and the erosion rate across the boiler thus both the maintenance and the parasitic load reduce along with the moisture content.

Bagasse drying technology has not been used in Africa but there are plants operating abroad which have proven to be economically viable. There are site specific and economic factors such as the price of coal and electricity which have a major influence on the feasibility of a bagasse dryer. However, due to the potential fuel saving it is worthwhile for plants burning coal to consider the feasibility of a bagasse drying plant. For those plants burning little to no coal, effort should be spent on reducing the moisture content of the bagasse by means of optimising the milling setup of the milling tandems or drying mills to achieve the correct bagasse moisture without affecting the cane throughput.

REFERENCES

American Standard of Mechanical Engineers (2013) ASME PTC4, Section 5-7: Fired Steam Generators. Performance Test Codes - Efficiency.


Kotze C (2016). Four ways of improving boiler efficiency: Pg.1-2

