Applications of CFD (computational fluid dynamics) modelling on boilers in the sugar industry

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Abstract There are numerous well-documented phenomena that plague the efficient operation of bagasse boilers. Key parameters that influence boiler combustion and operation are studied with the aid of computational fluid dynamics. Combustion stability and efficiency has been linked to various parameters such as fuel moistures and air temperatures supplied to the boiler and are investigated in this paper as part of a case study. With the benefit of computational fluid dynamics (CFD) simulations, the influences of secondary air, fuel spreader geometry and air distribution were evaluated. The result of the high sand loading in bagasse is that sugar mills have accepted erosion in boilers as normal wear over the years. This leads to high maintenance cost. This paper details a case study that focused on reducing erosion on an economiser by testing different geometries of ducting. Flow maldistribution is common in boilers, especially in the sugar industry where large air heaters are used. This leads to inefficient heat exchange, blockages, erosion and corrosion. A quasi-2D thermodynamic model has been developed to determine the gas velocities and tube metal temperatures. The output data is used to modify the air heater to increase the gas velocity which considerably reduced the probability of fouling.

Key words Bagasse combustion, spreader, secondary air, stability, CFD

INTRODUCTION

As hardware resources become more affordable, computational fluid dynamics (CFD) simulations are becoming more standard practice for designers and developers alike. CFD combustion modelling is also becoming more popular with the power-generation industry driving the complexity and accuracy of the modelling strategies.

We present three case studies in this paper to illustrate the use of CFD in solving boiler-related problems in the sugar industry. Case 1 details the CFD combustion modelling of a boiler to solve a stability problem. Case 2 details the approach used to solve an erosion problem with CFD and Case 3 evaluates the effects of blockages.

The objective of the research in Case Study 1 was to investigate the effects of fuel and air distribution on boiler performance. The boiler performance was measured by the heat flux absorbed in the furnace, CO concentration at the furnace outlet and average temperature in the furnace. The methodology followed was to simulate an existing boiler with commercial CFD software and investigate the effects of undergrate air distribution, fuel spreaders and overfire air on the combustion performance. The CFD model accounts for all the physics related to combustion and aerodynamics and are an extension of the model used by du Toit and van der Merwe (2014). The boundary conditions such as velocities into the boiler and air distribution on the grate were measured during boiler operation.

In recent years harvesting methods had to be pushed to the limits in order to maximize agricultural yields. Thus sugarcane is cut closer to the ground, resulting in higher sand content bagasse causing erosion in boilers, especially in the heat recovery equipment such as the economiser and air heater. Case Study 2 introduces the use of CFD in designing economic and robust solutions that can be used to minimize erosion in the heat recovery equipment, thus increasing the equipment’s life span. We discuss the use of several hopper designs to remove the ash from the gas stream before reaching heat recovery equipment, thus minimizing erosion.

Due to the high moisture content in bagasse, large air heaters are required in order to achieve stable combustion. Careful considerations of flow effects become important in such systems. In Case Study 3, we investigated blockages in an airheater positioned after an economiser. The analysis is simplified by using a lumped parameter and a one-dimensional CFD approach.
CASE STUDY 1

We conducted a study to identify potential improvements of combustion instabilities due to high moisture (56% moisture) bagasse. The geometry and dimensions of the boiler were known and were created in the three-dimensional volume (Fig. 1). The model included a dumping grate, bagasse spreaders, furnace and secondary air nozzles.

Fig. 1. Three-dimensional model of the boiler as utilised in the combustion simulations.

The three-dimensional combustion model was solved for a single geometry as depicted by the following case permutations:

- Datum case – with geometry and combustion controls as is in the current state.
- Additional secondary air case – added higher-level secondary air to introduce mixing.
- Increased lower-level secondary air case – additional mixing on grate level.
- Altered undergrate zone – added baffles to the undergrate zones to aid the even air distribution on the grate.

Sub-models were solved for the following cases:

- Spreader geometry to investigate alterations.
- Undergrate zone to determine the pressure drop over the grate.

Results of CFD modelling

The boundary conditions were measured on site during normal boiler operation. Prior to the combustion modelling the undergrate air distribution predicted by the CFD were validated (Fig. 2a,b). Combustion parameters considered were CO, average furnace temperature and heat flux to the furnace.
Combustion results

The resulting combustion temperature contours are shown in Figure 3 for the datum case. Although there was adequate combustion, the simulation showed high CO concentrations leaving the boiler. The high CO concentration noted in this simulation is typical for the amount of secondary air used.

In the case with secondary air added to the rear wall higher level, combustion was improved from the datum case. Combustion showed increased temperatures throughout the furnace (Fig. 4). The CO concentrations were also decreased when compared to the datum case.

Fig. 2. (a) Velocity contours as calculated by the computational fluid dynamics (CFD) model in m/s, (b) Velocity contours as measured on site in m/s.

Fig. 3. Contours of static temperature through a plane of the boiler in K for the datum case.
The case with increased secondary air on the lower level, showed similar levels of CO concentrations on the furnace outlet. The average furnace temperature was higher than the previous case resulting in a higher heat flux to the furnace walls (Fig. 5).

**Fig. 4.** Temperature contours for the case with added higher level secondary air in K.

**Fig. 5.** Temperature contours for the case with increased lower level secondary air in K.
The addition of a perforated baffle in the undergrate zone showed similar temperature contours as the previous case. However, the most notable difference was in the CO concentration, heat flux absorbed and average furnace temperature (Table 1).

**Table 1.** Comparison between the performance parameters of the combustion cases.

<table>
<thead>
<tr>
<th>Performance</th>
<th>Top SA</th>
<th>Top and Bottom SA</th>
<th>Altered undergrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO at outlet [mg/kg]</td>
<td>- 58%</td>
<td>- 54%</td>
<td>- 63%</td>
</tr>
<tr>
<td>Ave heat flux to furnace [kW/m²]</td>
<td>+14.5%</td>
<td>+ 30.8%</td>
<td>+ 40.6%</td>
</tr>
<tr>
<td>Average temp in furnace</td>
<td>+33°C</td>
<td>+ 85°C</td>
<td>+105°C</td>
</tr>
</tbody>
</table>

**Sub-models**

The pneumatic spreaders installed in the boilers have been modified and included an unnecessary air slot. Simulations of the spreader showed that the spreading velocity could be increased by 16% when the slot is closed (Fig. 6). With the slot closed the spreading efficiency can be increased drastically.

![Velocity comparison between the case with the bottom nozzle open and the other where the nozzle is closed: (a) nozzle open, (b) nozzle closed.](image)
Case study 1 - Conclusions

The effect of additional secondary air was paramount to reduce the CO concentration and increase the combustion temperature. The increased mixing in the furnace brought by the additional secondary air increased the combustion temperature and increased the heat flux to the furnace (Table 1).

The importance of an adequate air distribution over the grate is also highlighted.

All the solutions presented will aid furnace stability and could increase boiler efficiency. The importance of spreader air velocity is also highlighted and can contribute to combustion stability.

CASE STUDY 2

A boiler in the sugar industry had severe erosion problems on the top rows of the economiser situated below the air heater.

Having established a good correlation between the CFD model and observations from site, a mud-drum hopper and a throw-out hopper were added to the CFD model with minimal ducting modifications.

The two hoppers were able to capture 13% of total mass flow of particles injected, but a large amount of the particles ranging from 150 to 400 μm is not captured (Fig. 7).

In order to capture some of the particles in the range stated above, a ramp was introduced to accelerate smaller particles into the throw-out hopper. The secondary objective of the ramp was to trap more of the larger particles in the mud drum hopper. This was achieved by modifying the ducting as shown in Figure 8.

The large particles are diverted into the mud drum hopper (Fig. 8) - only particles below 200 μm are not captured. The total amount captured is 25%, thus doubling the amount of particles captured in the first design iteration.
The resulting erosion patterns on the economiser and air heater were then analysed and compared to the as-is case. As seen in Figures 9 and 10, erosion has been reduced by the hoppers. It should be noted that the 23% reduction in average erosion is believed to be conservative as a fine size distribution was used. The actual size distribution could be coarser.
Figure 11 shows the change in amount of particles captured as the size distribution becomes coarser. As the size distribution increases, the mud drum hopper performance increases dramatically. However, from an average diameter of 425 µm, the increase in particles captured in the mud drum hopper actually causes the throw-out hopper performance to decrease.

We observed that as the amount of particles captured increases, erosion rate decreases. For example when operating at point ‘B’ (if the average particle size is 425 µm; Fig. 11), 52% of the particles will be captured. This will result in approximately 50% reduction in erosion. As the sand content in the bagasse increases, it is believed that the operating point shifts from the conservative particle size distribution ‘A’ to a coarser size distribution ‘B’, therefore the hoppers will be more effective.

We conducted an additional study focusing on the top two rows of the economiser as the erosion was concentrated in this area on site. The CFD results indicated that the particles exiting the air heater were ‘jetting’ on to the top row of the economiser (Fig. 12) resulting in a high rate of erosion.

Fig. 11. Particles captured versus size distribution.

Fig. 12. Particles exiting the air heater.
In light of this observation, we increased the gap between the air heater and the economiser to allow the particles to lose momentum before entering the economiser, thus reducing particle velocity and erosion. The results of this change can be observed in Figure 13. The higher velocity particle impingement is not present with the increase gap and therefore the erosion would be reduced. This modification combined with the installation of hoppers and modified boiler outlet duct resulted in 41% reduction in average erosion in the CFD model compared to the as-is case.

![Image of particles exiting the air heater with increased gap between the air heater and economiser.](image)

**Fig. 13.** Particles exiting the air heater with increased gap between the air heater and economiser.

**Case study 2 - Conclusions**

A reliable CFD erosion model was developed. This model can be used by a designer to develop solutions to extend the life span of heat recovery components in a bagasse fired boiler.

Historically, the economizer of the boiler in the case study had erosion problems and was replaced every 6 months. After the erosion study was conducted and the solution implemented, the erosion was reduced resulting in no economizer tube leaks in 2 years.

**CASE STUDY 3**

Here we investigated blockages in an air heater of a bagasse-fired boiler. The entire boiler lumped parameter model was set up and from these results a quasi-2D detailed thermal-hydraulic model was created. From this model the gas velocities and tube-metal temperatures were determined.

Heavy fouling in an air heater is due to a two-part mechanism comprised of condensation and low gas velocities. If the metal temperature is within a certain limit below the saturation temperature at the partial pressure of the moisture in the flue gas, the particles will not stick to the condensate film if the gas velocity is high. This is because of the high momentum of the flue-gas particles. At low gas velocities and low tube-metal temperatures a sticky film develops (because of condensate and particle agglomeration) on the inside of the air heater tubes, especially on the air inlet side of the air heater, where the gas and air temperature is lowest.

The developed model is a quasi-2D thermodynamic model of each tube row, taken as a control volume with the heat transfer between the gas and air.

The boiler lumped parameter model was used to determine the combustion gas constituents and the mass fractions. These fractions were then used to determine the mole fraction of the moisture in the flue gas. The partial pressure and corresponding saturation temperature were then determined (Table 2).
Table 2. Gas mass fractions, mole fractions and saturation temperature of moisture.

<table>
<thead>
<tr>
<th>Gas constituent</th>
<th>X mass fraction</th>
<th>M molecular weight</th>
<th>X/M</th>
<th>Y mole fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>0.1908</td>
<td>18.02</td>
<td>0.010588235</td>
<td>0.287469</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.1891</td>
<td>44.01</td>
<td>0.004296751</td>
<td>0.116656</td>
</tr>
<tr>
<td>N₂</td>
<td>0.4632</td>
<td>28.013</td>
<td>0.01653518</td>
<td>0.448927</td>
</tr>
<tr>
<td>Air</td>
<td>0.1568</td>
<td>28.97</td>
<td>0.005412496</td>
<td>0.146948</td>
</tr>
<tr>
<td>SO₂</td>
<td>0</td>
<td>64.063</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>0.9999</td>
<td></td>
<td>0.036832662</td>
<td>1</td>
</tr>
<tr>
<td>Partial pressure</td>
<td>29023.78 Pa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturation temperature</td>
<td>68.33708°C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From Table 2 it is seen that if the tube metal temperature falls below 68.3°C, the moisture will start to condense on the inside of the air heater tubes. Firstly, the current air heater arrangement was modeled to determine the gas velocities and tube metal temperatures. Figure 14 shows the tube metal temperatures for each row.

![Fig. 14. Tube metal temperatures of air heater tubes for current design.](image-url)

From Figure 14 it is seen that on the air inlet side, tube rows 1-12 is below saturation temperature, thus moisture in these tubes will start to condense. The reason for this is that the outside (air side) heat transfer has a much lower thermal resistance than the inside (gas side) thermal resistance. Therefore, the tube metal temperature is closer to the air temperature. The thermal resistance is a function of the density, velocity, viscosity, specific heat and flow arrangement. The velocities inside the tube across the depth of the air heater were calculated at 6 m/s.

These gas velocities are well below the standard design value, thus it is clear that the air heater is going to foul badly and that is what we observed on site. The air heater gas cross-sectional flow area is much larger than what is required, thus the low velocities causes high thermal resistances on the inside of the tubes. Therefore, there are too many air heater tubes and the 76.2 mm diameter tubes should have been 63.5 mm to maximize gas-side heat transfer.
Case study 3 - Conclusions

The design outcome was to increase the gas side velocity to the design value for bagasse fired boilers; this was done by reducing the amount of tubes.

Although the gas velocities of the new design are much higher, the temperatures are still below the saturation line. This is because the total heat transfer area has now been reduced and therefore the heat transfer rate has decreased, although the heat transfer coefficient inside the tubes has increased due to the higher velocity. The final air temperature dropped from 130°C to 100°C. The higher gas velocities reduced the probability of fouling considerably.

In conclusion the position of the air heater should have been above the economiser to protect the air heater against fouling due to higher gas temperatures. In this arrangement the preferred minimum combustion air temperature for bagasse firing of 180°C would also have been achieved.

CONCLUSIONS

We have presented solutions to increase the efficiency, stability, reliability and life span of bagasse fired boilers. The solutions investigated were the most cost effective with the largest gains. CFD was an instrumental tool in each case study in order to conceptualise the solutions and quantify the performance gains.

REFERENCES


Applications de la CFD (computational fluid dynamics), modélisation des chaudières de l’industrie sucrière

Résumé. Il y a nombreux phénomènes bien documentés qui affectent le bon fonctionnement des chaudières de bagasse. Les paramètres clés qui affectent la combustion de la chaudière et son fonctionnement sont étudiés à l’aide de la dynamique computationnelle des fluides. L’efficacité et la stabilité de la combustion sont liées à des facteurs tels que l’humidité du carburant et la température de l’air dans la chaudière ; ces paramètres sont étudiés dans ce document. À l’aide de simulations par la dynamique computationnelle des fluides (CFD), les influences d’air secondaire, de la distribution des carburants et leur géométrie, et de l’air ont été évaluées. Le résultat de la présence du sable dans la bagasse est que les sucreries ont accepté l’érosion dans les chaudières comme une usure normale au cours des années. Cela conduit à un coût d’entretien élevé. Cet article décrit une étude portant sur la réduction de l’érosion dans un économiseur en testant différentes géométries. La mauvaise distribution des gaz est commune dans les chaudières, surtout dans l’industrie sucrière où des réchauffeurs d’air de grande taille sont présents. Cela conduit à la corrosion, aux blocages, érosion et a des échanges de chaleur inefficaces. Un modèle thermodynamique quasi-2D a été développé afin de déterminer les vitesses des gaz et les températures des tubes métalliques. Les données de sortie sont utilisées pour modifier le réchauffeur d’air afin d’augmenter la vitesse des gaz, ce qui réduit considérablement la probabilité de l’encrassement.

Mots-clés: Combustion de la bagasse, épandeur, air secondaire, stabilité, CFD

Aplicación de la modelación dinámica de fluído computacional (CFD en inglés) en calderas de la industria azucarera

Resumen. Hay numerosos fenómenos, bien documentados, que afectan la eficiente operación de las calderas de bagazo. Con el auxilio de la dinámica de fluído computacional se estudian parámetros claves que influyen tanto la combustión como la operación. La estabilidad de la combustión y la eficiencia se enlazan a varios parámetros como la humedad del combustible, y la temperatura del aire que se aplica a la caldera, los que se investigan en el artículo, como parte del caso de estudio. Con los beneficios que ofrece la simulación de la dinámica de fluido computacional se evalúan la influencia del aire secundario, la geometría de los distribuidores y la distribución del aire. Como resultado de la elevada carga de arena en el bagazo los ingenios azucareros han aceptado, a lo largo de los años, como un deterioro normal la erosión en las calderas. Esto ha conducido a altos costos de mantenimiento. Este artículo detalla un estudio de caso enfocado a reducir la erosión en un economizador mediante la prueba de diferentes geometrías de los ductos. La errónea distribución de flujos es común en las calderas, especialmente en la industria azucarera donde se emplean grandes calentadores de aire. Esto induce un ineficiente intercambio de calor, bloqueos, erosión y corrosión. Se ha desarrollado un modelo termodinámico (cuasi-20) para determinar
la velocidad de los gases y la temperatura del metal de los tubos. Los datos obtenidos se emplean para modificar los calentadores de aire para incrementar la velocidad de los gases que reduce considerablemente la posibilidad de incrustaciones.

Palabras clave: Combustión de bagazo, distribuidores, aire secundario, estabilidad, CFD.