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M 12. IMPROVING COMBUSTION STABILITY IN SUGAR FACTORY BOILERS

By

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Abstract

Reliable operation of a sugar factory boiler station is essential for efficient and timely processing of the cane supply. Sugar factory boilers have to contend with changes in fuel quality caused by variations in performance of the extraction station, different cane varieties and associated agronomic factors along with fluctuations in factory steam demand. These variations can affect the stability of combustion in boiler furnaces leading to reductions in boiler steam output and large furnace pressure fluctuations that can cause serious damage. This paper investigates the causes of unstable combustion, discusses aspects of boiler design that make a boiler more susceptible to unstable combustion and uses modelling to evaluate different options for improving combustion stability.

Introduction

Sugar factory boilers have to handle a wide range of fuel conditions and steam flow requirements. Boilers in most other industries do not have to contend with such variability. Stable combustion needs to be maintained in boiler furnaces to consistently satisfy factory steam requirements. Fuel quality, fuel changes and variations in steam demand all make this very difficult. The pressure fluctuations caused by unstable combustion degrade boiler performance and pose serious risks. In some cases, the pressure fluctuations caused by unstable combustion have caused extensive damage to boilers that have resulted in significant down time. The cost of repairs can be several million dollars.

With the incentives provided for increased electricity generation from renewable sources, more sugar factories are generating electricity during the non crush period. Other renewable fuels used in sugar factory boilers such as wood chip, sawdust, camphor laurel and green waste often have markedly different combustion properties to bagasse. Even if bagasse is used during the non crush period, its combustion properties are likely to have changed during storage. Therefore fuel properties are likely to be more variable in the future and boilers firing different fuels are more susceptible to combustion stability problems.

Background

In the past, grate fired bagasse boilers were common (Lamb, 1979) but now nearly all sugar factory boilers in Australia burn bagasse in suspension with only a small proportion of the bagasse fuel burning on the grate (Dixon, 1984; Woodfield, 2001). This small amount of grate combustion assists with the ignition of the cloud of fine bagasse particles effectively acting as a pilot to the main flame in the furnace. However if too much bagasse lands on the grate then combustion cycling, where bagasse piles periodically build up on the grate and then burn off, often occurs (Naude, 2001; Woodfield *et al.*, 1998). Some of the newer boilers that need to utilise fuels that cannot be burnt in suspension (e.g. wood chip) have moving grates for burning those fuels while bagasse combustion still occurs predominantly in suspension (Palmer *et al.*, 2009). However combustion problems have occurred in these boilers when the fuel composition changes (Moller and Ironside, 2011).

In most cases combustion instability is initiated by piles of fuel building up on the grate and this can be brought about by:

- increases in fuel moisture or ash contents
- large particle sizes
- increases in fuel firing rates
- water from leaking tubes partially extinguishing the fire on the grate.

Increases in fuel moisture and ash contents reduce steam pressures and furnace temperatures until the boiler control system can compensate by increasing the fuel firing rate. If the fuel firing rate is increased the air to fuel ratio will temporarily reduce, possibly to sub stoichiometric levels, because the boiler draft system takes longer to respond than the fuel feeders. If the air to fuel ratio is sub stoichiometric in parts of the furnace, even for short periods of time, some combustible volatile matter will remain unburnt. When the unburnt volatile matter does eventually burn, this will cause a pressure surge or in some cases, an explosion.

All boilers will experience combustion instability if the fuel firing rate is high enough or the fuel quality poor enough. However some boilers are more susceptible to combustion stability than others. Boilers susceptible to combustion instability usually have one or more of the following:

- A high grate area heat release rate. The grate area heat release rate is usually defined as the fuel combustion energy divided by the grate area directly exposed to combustion in the furnace. The upper limits for grate area heat release rate used by boiler designers depend on a range of factors including fuel moisture content and combustion air temperature. For a fuel moisture content of 50% a typical grate area heat release rate limit is 3.1 MW/m^2 (Magasiner *et al.*, 2001).
- A water cooled grate. With these types of grate the energy removed from the grate by the cooling water is used to generate steam whereas for an air cooled grate the energy transferred from the grate to the cooling air remains in the furnace. Consequently temperatures near a water cooled grate are generally lower than temperatures near an air cooled grate or a grate without any cooling. Lower near-grate temperatures slow the fuel

drying, devolatilization and combustion rates and make unstable combustion more likely;

- Low combustion air temperature. This makes unstable combustion more likely by reducing near grate temperatures. For this reason boilers without air heaters tend to be more susceptible to unstable combustion than boilers with air heaters; and

- Fan capacity limitations. If the correct air to fuel ratio cannot be maintained when fuel quality deteriorates or when the fuel firing rate increases there will be more unburnt fuel which can give rise to unstable combustion.

The trends of oxygen concentration and furnace pressure recorded by boiler instrumentation are often useful indicators of combustion instability. Figure 1 shows the trends of oxygen concentration and furnace pressure over a one hour period during the 2011 crushing season for the Victoria Mill No. 11 boiler. This boiler has a very high grate area heat release rate at maximum continuous rating (MCR) (> 3.6 MW/m^2) and a water cooled stationary grate. This boiler is susceptible to unstable combustion. During the time period covered by the trends the average steam flow was approximately 225 t/h, which is close to the boiler's MCR of 230 t/h. Both the oxygen concentration and furnace pressure readings show large fluctuations. Over the time period of the readings the oxygen concentrations decrease while the furnace pressure increases. This indicates that combustion is deteriorating and the boiler control system is increasing the fuel flow but due to fan capacity limitations the air to fuel ratio cannot be kept constant (decreasing oxygen concentrations) and the suction in the furnace is decreasing (increasing furnace pressure).

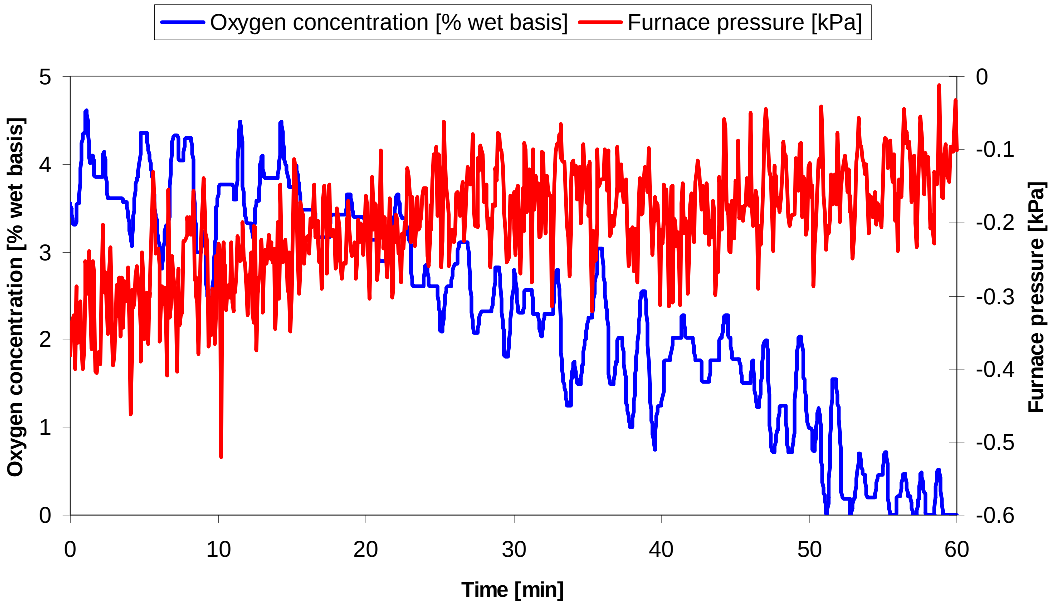

Fig 1 – Trends of oxygen concentration and furnace pressure from the Victoria Mill No. 11 boiler.

Figure 2 shows the oxygen concentration and furnace pressure trends over a one hour period during the 2011 crushing season for the Harwood Mill boiler. This boiler has a lower grate area heat release rate at MCR (< 2.9 MW/m^2) and an air cooled dumping grate. This boiler rarely experiences combustion stability problems. During the time period covered by the trends the average steam flow was approximately 120 t/h which is well below the boiler's MCR of 160 t/h. The oxygen and furnace pressure trends are both consistent with the boiler operating well within its limits. Compared with the trends for the Victoria Mill No. 11 boiler the oxygen concentration and pressure fluctuations are small. The readings show no clear trend of increasing or decreasing furnace pressures or oxygen concentrations.

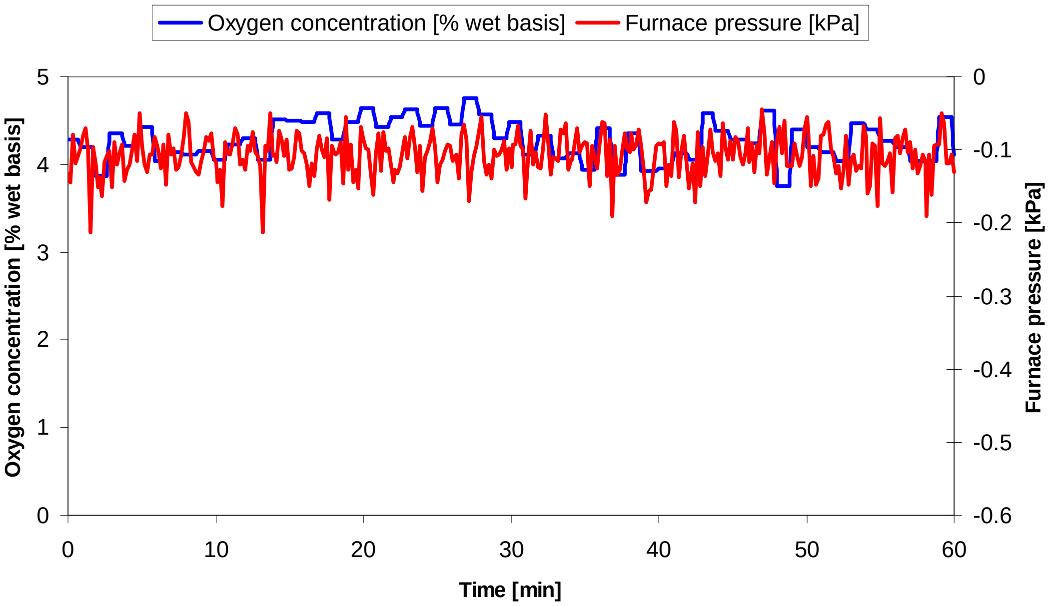

Fig 2 – Trends of oxygen concentration and furnace pressure from the Harwood Mill boiler.

Procedure

The grate area heat release rate, the grate type and combustion air temperature are set by the boiler design and in most cases cannot be changed without significant capital expenditure. Two options that do not involve major changes to the boiler structure that have been used to improve combustion stability are:

- extensive refractory coverage of furnace wall tubes
- reducing the fraction of total combustion air entering through the grate.

In this work the effects of these two options were investigated computationally for the Harwood Mill boiler. The FURNACE CFD code (Boyd and Kent, 1986; Chen *et al.*, 1992; Luo *et al.*, 1997; Mann *et al.*, 2003) was used to model the effects of refractory addition and changed air flow distribution on the flow patterns and gas temperature distributions in the furnace while the lumped parameter BOILER model (Dixon *et al.*, 1998; Plaza *et al.*, 2006) was used to simulate the effects of refractory addition on the boiler heat transfer performance. The Harwood Mill boiler was modelled in this work because the author had been studied several times over the last few years (Mann and Scott, 2011) and FURNACE and BOILER model representations of the boiler have been developed in previous work (Mann and Dephoff, 2006).

The FURNACE model representation of the Harwood Mill boiler used approximately 390 000 cells for the gas flow, combustion and convection heat transfer calculations. A more coarse grid with 3 500 cells was used for the furnace radiation calculations that were based on the discrete transfer method (Lockwood and Shah, 1981). The motion of bagasse/ash particles through the boiler was approximated by tracking 12 960 representative trajectories using the particle source in cell method (Crowe *et al.*, 1977).

The Harwood Mill boiler has had extensive refractory coverage of the furnace wall tubes since it was installed. The purpose of this refractory coverage was to improve combustion stability when the boiler was fired with poor fuel. The FURNACE code was modified in previous work (Mann and Dixon, 1998) to simulate the effect of refractory addition on furnace wall tubes. The earlier work assumed that the refractory layer is in thermal equilibrium with its surroundings so that the heat transfer via convection and radiation from the gas at T_g to the refractory layer with surface temperature T_s is equal to the heat conducted through the refractory layer to the tube wall at temperature T_w. This can be expressed as

$$\frac{k_{ref}}{\delta x}\left(T_s - T_w\right) = h\left(T_g - T_s\right) + \sigma\varepsilon_{ref}\,(T_g^4 - T_s^4) \tag{1}$$

where k_{ref} and ε_{ref} are the thermal conductivity and emissivity of the refractory layer respectively. σ is the Stefan Boltzmann constant, h is the heat transfer coefficient for the gas adjacent to the refractory surface and δx is the thickness of the refractory layer. The above equation can be solved for for T_s which can then be used instead of the wall temperature in the flow and radiation calculations.

The modified version of the FURNACE code (Mann and Dixon, 1998) was used to simulate the Harwood Mill boiler at 120 t/h steam output and 37% excess air for the following three cases:

- current boiler configuration with extensive refractory coverage of furnace wall tubes
- refractory removed
- refractory removed and 20% of the grate air flow redirected to enter the furnace through additional secondary air nozzles high on the rear furnace wall.

Extensive refractory addition will significantly reduce furnace heat transfer. To estimate how much this affects overall boiler performance, BOILER model simulations of the Harwood Mill boiler were carried out with extensive refractory coverage of the furnace walls (the current configuration) and with the refractory removed. The bagasse and air flows calculated by the BOILER model for each of these cases were used in the FURNACE simulations.

The likely effects of refractory addition or changed air flow distribution on combustion stability can be assessed by comparing the mean gas temperatures in different parts of the furnace before and after the change. Figure 3 shows the different zones in the furnace where cell volume weighted mean gas temperatures were calculated.

Zone 1 is where bagasse drying is expected to occur while devolatilization and ignition of the volatiles is expected to occur in zone 2. Much of the energy for bagasse drying is expected to come from the hot gas above the spreaders (zone 3). Zone 4 is the near grate region.

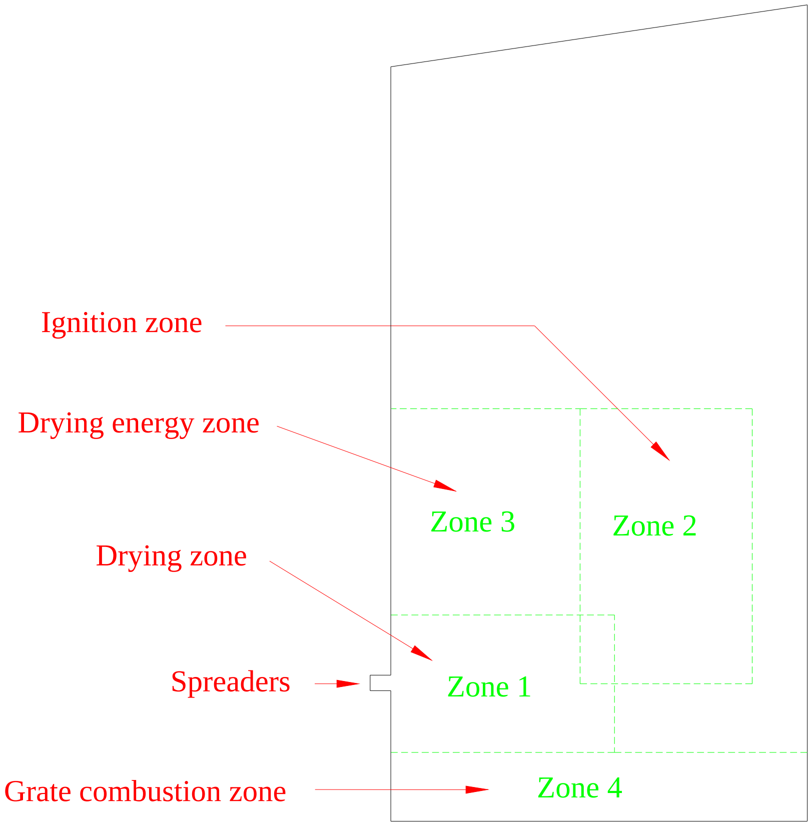

Fig 3 – Location of different furnace zones relative to the spreaders used to assess the effect of refractory addition and changed air flow distribution on combustion stability.

Results

Side elevation views of the predicted gas velocity distributions through the Harwood Mill boiler furnace for the three cases are shown in Figure 4. The corresponding gas temperature predictions are shown in Figure 5. When the refractory is removed the furnace gas temperatures are significantly lower; this delays the drying and ignition of the bagasse particles which makes to main flow closer to the rear wall of the furnace. Note that with the refractory removed the boiler efficiency will be higher and the bagasse and air flows will be lower; this will reduce the grate air flow which will also contribute to the main flow being closer to the rear wall of the furnace.

With the refractory removed and 20% of the grate air flow redirected to the additional upper rear wall secondary air nozzles, the flame is predicted to be much lower in the furnace due to the reduced grate air flow. The reduced grate air flow also makes the air to fuel ratio closer to stoichiometric near the grate and gas temperatures in this region will therefore be higher. The air entering through the additional secondary air nozzles on the upper rear wall of the furnace pushes the flame back towards the front furnace wall.

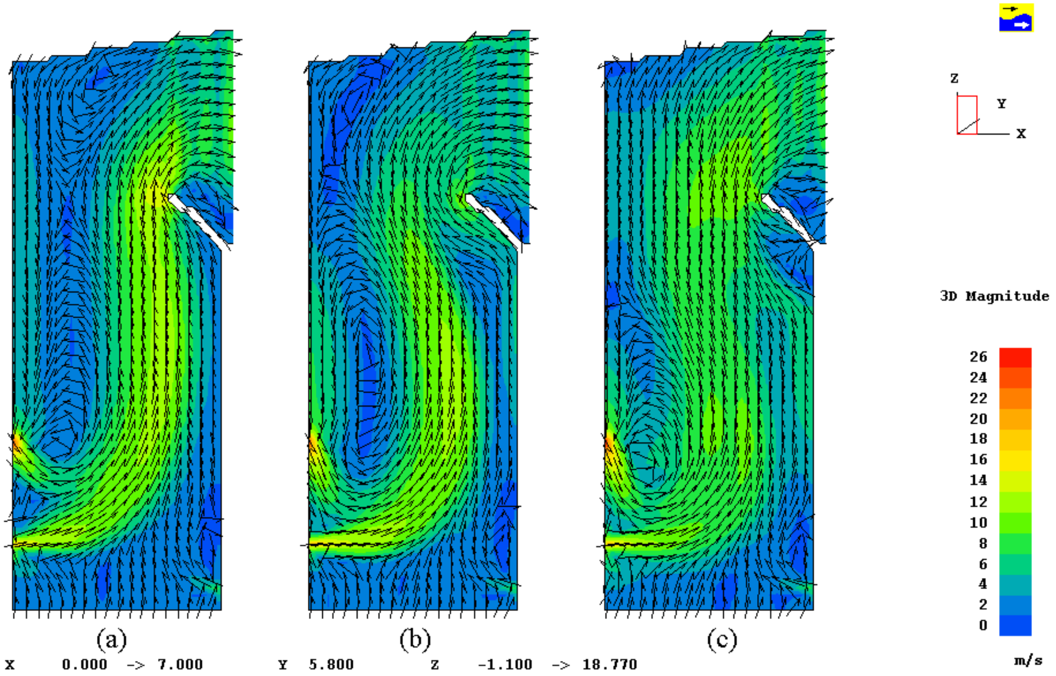

Fig 4 – Side elevation views of the predicted gas velocity (m/s) distribution through the Harwood Mill boiler furnace with (a) current extensive refractory coverage (b) refractory removed and (c) refractory removed and 20% of the grate air flow redirected to enter through additional secondary air nozzle high on the rear furnace wall.

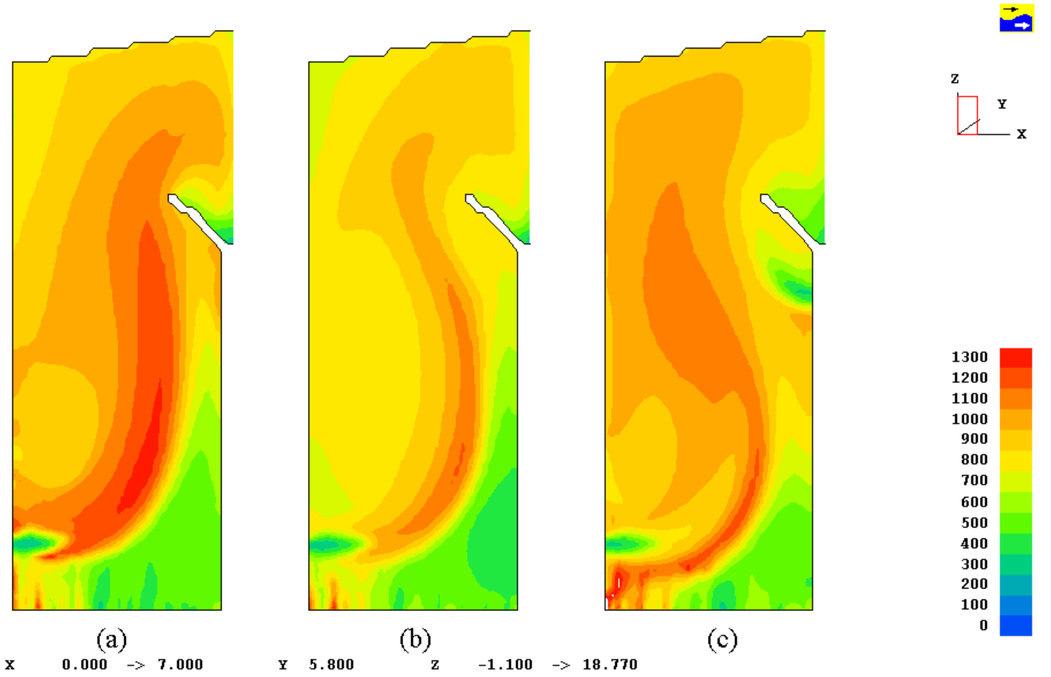

Fig 5 – Side elevation views of the predicted gas temperature (°C) distribution through the Harwood Mill boiler furnace with (a) current extensive refractory coverage (b) refractory removed and (c) refractory removed and 20% of the grate air flow redirected to enter through additional secondary air nozzle high on the rear furnace wall.

Table 1 compares the gas temperatures in the different furnace zones and radiant heat transfer to the grate for the different cases. When the refractory on the furnace walls is removed the zone 1 (drying zone), zone 2 (ignition zone) and zone 3 (drying energy zone) gas temperatures and radiant heat transfer to the grate all decrease while there is a small increase in the zone 4 gas temperature. These results suggest that extensive refractory coverage works by assisting with the drying and ignition of bagasse particles while they are in suspension.

With the refractory removed and 20% of the grate air flow redirected to enter the furnace through additional nozzles on the upper rear furnace wall, all the temperatures and the radiation to the grate are predicted to be higher than for the case with refractory removed and no changes to the air flow distribution. With no refractory and the changed air flow distribution the predicted zone 1 and zone 4 gas temperatures are higher than for the current configuration with extensive refractory coverage of the furnace wall tubes. This suggests than many of the benefits of extensive refractory coverage can be achieved with changes to the air flow distribution.

Table 1 – Calculated cell volume weighted mean gas temperatures in the different furnace zones and radiation to the grate for the Harwood Mill boiler furnace with current extensive refractory coverage, refractory removed and refractory removed and 20% of the grate air flow redirected to enter through additional secondary air nozzle high on the rear furnace wall.

		With refractory	Without refractory	Without refractory and 20% of grate air flow redirected to additional upper rear secondary air nozzles
Zone 1 temperature	(°C)	918	880	933
Zone 2 temperature	(°C)	1004	932	973
Zone 3 temperature	(°C)	966	853	906
Zone 4 temperature	(°C)	604	609	738
Radiation to grate	(kW)	2 873	1 555	2 208

Table 2 compares the thermal performance of the Harwood Mill boiler at 120 t/h steam output and 37% excess air with and without extensive refractory coverage of the furnace wall tubes. Without refractory coverage the furnace heat transfer increases so the convection bank exit and air heater gas exit temperatures decrease. The air heater air exit temperature decreases because the gas entering the air heater is cooler. With the refractory removed the boiler efficiency is predicted to increase by 1.7 percentage points and bagasse consumption is predicted to reduce by 2.4 t/h. At 120 t/h steam output the furnace is well within the normal design limits with extensive refractory coverage. When the refractory is removed the furnace residence time increases and the grate area heat release rate and volumetric heat release rate both decrease which means the furnace will operate within normal design limits by an even greater amount.

Note the steam temperature is predicted to decrease when the refractory is removed. Without refractory the furnace gas temperatures are lower which reduces radiant and convective heat transfer to the superheater tubes. If refractory addition is considered as a means of improving combustion stability then the increased steam temperature should be taken into account.

Table 2 – Calculated thermal performance of the Harwood Mill boiler with and without extensive refractory coverage of the furnace wall tubes.

		With refractory	Without refractory
Steam load	(t/h)	120	120
Steam temperature	(°C)	255	231
Convection bank gas exit temperature	(°C)	347	310
Air heater gas exit temperature	(°C)	235	211
Air heater air exit temperature	(°C)	199	180
Furnace residence time	(s)	2.65	3.35
Grate area heat release rate	(MW/m^2)	1.85	1.76
Volumetric heat release rate	(kW/m^3)	116	110
Boiler efficiency (GCV[1] basis)	(%)	65.2	66.9
Bagasse flow	(t/h)	48.9	46.5
Air flow	(t/h)	188.5	179.1

[1] Gross calorific value.

Conclusions

A number of factors can contribute to combustion instability in sugar factory boilers. Some boiler designs are more prone to unstable combustion than others. This modelling work suggests that extensive refractory addition and changed air flow distributions will both improve combustion stability but the refractory addition option can significantly reduce boiler efficiency. Changing the air flow distribution into the furnace is therefore a preferred option for improving combustion stability.

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REFERENCES

Boyd RK, Kent JH (1986) Three-dimensional furnace computer modelling. *Proceedings of the Combustion Institute* **21**, 265-274.

Chen JY, Mann AP, Kent JH (1992) Computational modelling of pulverised fuel burnout in tangentially fired furnaces. *Proceedings of the Combustion Institute* **24**, 1381-1389.

Crowe CT, Sharma MP, Stock DE (1977) The particle-source-in-cell (PSI-Cell) model for gas-droplet flows. *Journal of Fluids Engineering* **99**, 325-332.

Dixon TF (1984) Preliminary measurements in the flame region of a bagasse fired boiler. *Proceedings of the Australian Society of Sugar Cane Technologists* **6**, 165-171.

Dixon TF, Joyce KN, Treloar R (1998) Increasing boiler capacity by dried bagasse firing. *Proceedings of the Australian Society of Sugar Cane Technologists* **20**, 445-452.

Lamb BW (1979) Combustion of bagasse. PhD thesis, University of Sydney, Sydney.

Lockwood FC, Shah NG (1981) A new radiation solution method for incorporation in general combustion prediction procedures. *Proceedings of the Combustion Institute* **18**, 1405-1414.

Luo M, Stanmore BR, Dixon TF (1997) Modelling combustion in corner-fired sugar mill boilers. *Proceedings of the Australian Society of Sugar Cane Technologists* **19**, 466-472.

Magasiner N, Alphen Cv, Inkson MB, Misplon BJ (2001) Characterising fuels for biomass - coal fired co-generation. *Proceedings of the South African Sugar Technologists' Association* **75**, 282-291.

Mann AP, Dephoff RM (2006) Reducing bagasse consumption at Harwood Mill. *Proceedings of the Australian Society of Sugar Cane Technologists* **28**, 389-397.

Mann AP, Dixon TF (1998) Predicting the effect of refractory addition on combustion stability in a bagasse-fired furnace - poster paper. *Proceedings of the Australian Society of Sugar Cane Technologists* **20**, 564.

Mann AP, Plaza F, Dixon TF (2003) Improving the prediction of convection bank heat transfer. *Proceedings of the Australian Society of Sugar Cane Technologists* **25**, (CD-ROM) 11 pp.

Mann AP, Scott SJ (2011) Optimisation of low load boiler operations. *Proceedings of the Australian Society of Sugar Cane Technologists* **33**, (electronic format) 6 pp.

Moller D, Ironside R (2011) Advanced controls for a biomass boiler. *Proceedings of the Australian Society of Sugar Cane Technologists* **33**, (electronic format) 5 pp.

Naude DP (2001) Combustion of bagasse and woodwaste in boilers for integration into a cogeneration steam cycle. *Proceedings of the Australian Society of Sugar Cane Technologists* **23**, 384-389.

Palmer C, Farrell RM, Hurt J (2009) The development of cogeneration projects at Condong and Broadwater mills. *Proceedings of the Australian Society of Sugar Cane Technologists* **31**, 401-409.

Plaza F, Mann AP, Joyce KN (2006) Improved estimates of boiler performance by combining empirical and CFD models. *Proceedings of the Australian Society of Sugar Cane Technologists* **28**, 409-414.

Woodfield PL (2001) Combustion instability in bagasse-fired furnaces. PhD thesis, University of Sydney, Sydney.

Woodfield PL, Kent JH, Dixon TF (1998) Computational modelling of a bagasse-fired furnace - effects of moisture. *Proceedings of the Australian Society of Sugar Cane Technologists* **20**, 458-464.