Control and Stabilization of a Multiple Boiler Plant: An APC Approach

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Abstract: A multiple coal fired boiler house provides steam for utility usage in various production plants. Maintaining stable header pressure and boiler availability is of critical importance for downstream consumers. Advanced Process Control comprising of a G2 based expert system and Model Predictive Control was implemented to improve the boiler house performance. The results yielded improvements in the main header pressure stability, reduction in boiler saturation and significant saving in coal consumption.

Keywords: advanced process control, boiler efficiency, soot blowing, pressure stability, expert system.

1. INTRODUCTION

1.1 Background

Coal fired boilers are used in many industrial processes with the most prominent being steam generation for utilities and power plant turbines. The primary objective of a boiler is to achieve optimum operating efficiency of the equipment with high reliability and low cost. Optimizing boiler performance whilst simultaneously adhering to environmental constraints has lead to a large focus in industry over the past decade on techniques to improve boiler operation. Model predictive control has increasingly become a popular replacement for traditional boiler control and optimization (Majanne, 2005). The paper describes the implementation of a model predictive controller together with a G2 expert system on a boiler house consisting of seven boilers.

1.2 Literature Review

Advanced Process Control (APC), particularly Model Predictive Control (MPC) has been widely used in industry and has proven to stabilize and optimize plants (Quin *et al.* (2003)). Stable control on boiler key combustion parameters balances the burner management system reducing thermal stress factors and equipment degradation resulting from unstable control. Tight dynamic control of variables to increase boiler efficiency whilst reducing production of NOx is an interactive process which requires a multivariable controller. Environmental legislation requires power generation utilities to reduce harmful gases such as nitrous oxides (NOx) and carbon monoxide CO emissions from coal fired boilers. Model based APC was implemented to a coal fire power generation plant to adhere to regulations whilst maintaining the required load and efficiency. The results were a 48% and 75% reduction in NOx and CO emission respectively (Flower *et al.,* 2002).

Multiple boiler configuration plants also provide for significant efficiency improvement opportunities. Automatic controllers with cost objective functions for boilers that can shift loads accordingly can maximize efficiency and reduce energy costs. An example of this capability is the case of a chemical company operating two utility boilers used for generating steam where it was required to find the most efficient operating point for each boiler (InSyst, 2010). The boilers were analyzed and various relationships were developed. The boiler fuel to steam ratio was found to be quasi-concave and the marginal production curve was defined for each boiler. Optimal load switching and the use of APC on these boilers based on defined relationships resulted in a 3% decrease in fuel costs.

In another industrial application consisting of 4 utility boilers, the objective was to decrease NOx emissions to within environmental permits and reduce the fuel cost. Model based APC was implemented resulting in a reduction of 50%

NOx emissions and an energy efficiency improvement of 1% (Morrison, 2003). In yet another example, a synthetic fuel plant operating 18 boilers, which were used in driving turbines and generating utility steam, implemented MPC to optimize load and improve efficiency. A 15% reduction in NOx emissions as well as a 1.1% increase in efficiency were observed (Pekar *et al.*, 2006).

Studies have been conducted to evaluate the performance of advanced controllers as opposed to traditional regulatory controllers. Riggs *et al.* (1995) used nonlinear simulators to evaluate the performance of the MPC controller against regulatory proportional and integral (PI) controllers in reducing variability of the produced steam temperature under various upset conditions. The MPC control scheme reduced the variability of the steam temperature 3 to 5 times better than the PI controllers. Regulatory PI controllers provide acceptable steady state performance; however APC due to its ability to handle interaction provides more responsiveness and stable operation.

2. PROCESS

2.1 Process Description

The boiler house consists of seven twenty ton/hr fire tube boilers feeding into a common steam header (Fig.1). The primary objective of the boilers is to produce low and high pressure steam for utility usage, which includes continuous and batch processes. Production requirements of various downstream processes, particularly batch processes, cause large changes in steam demand. Regulatory control systems tend to be inadequate in satisfying operational demands, resulting in either a low steam supply pressure or waste of energy arising from undesirable opening of steam pressure release valves due to overcompensating.

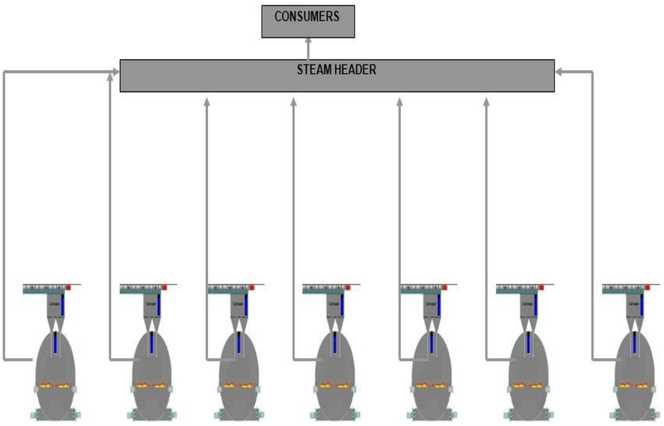

Figure 1: Boiler house configuration.

The boilers utilize lignite coal that is stored in a coal bunker located adjacent to the boiler house. The calorific value (HHV) of coal is calculated using the formula

$$\text{HHV (kJ/kg)} = 337C * 1442(H - O/18) + 93S, \qquad (1)$$

where C, H, O and S are the mass fractions of carbon, hydrogen, oxygen and sulphur respectively. The average calorific value of coal supplied to the boilers is 15MJ/kg.

The coal is transported from the bunker to storage bins located at the top of each boiler by screw feeders. The coal thereafter gravitates into two stoker hoppers situated on the left and right side at the front end of each boiler. Each stoker hopper feeds coal onto a grate which conveys the coal through the boiler forming a coal bed. Coal is ignited by ignition arches as it transits from stoker to the grate. The length of the coal bed on the grate is determined by the speed of the each stoker. The use of PID controllers on the stoker speeds has yielded little success in achieving performance goals.

Figure 2 is a schematic representation of the process showing the equipment and controllers.

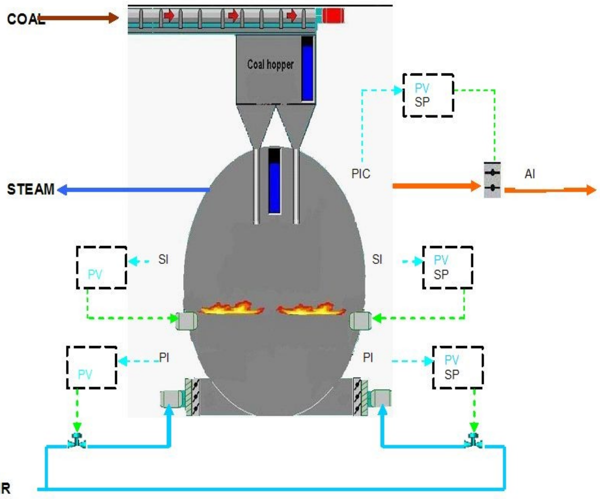

Figure 2: Individual boiler schematic.

Each boiler has two Forced Draft (FD) fans situated on the left and right side at the rear end the boiler. The FD dampers control the forced draught into the boiler and are used to regulate the furnace pressure. The flue of each boiler is equipped with an oxygen analyzer and Induced Draft (ID) fan which controls the boiler steam pressure. To prevent the flames from burning outside the boiler, the boiler must be kept at a slight negative interior pressure. The ID damper essentially determines the steam demand of the boiler. The boiler off gas stream is treated by scrubber columns to limit escape of hazardous gases into the atmosphere. The scrubbers reduce emissions of suspended particles and sulphur dioxide. Water is supplied via de-aerators, which consists of treated recycled condensate and municipal water. The supply water conductivity to the boilers is monitored to prevent scaling of boiler tubes.

2.2 Regulatory Control

The objective of the base layer control is to stabilize the process using PI feedback control loops. The FD dampers control the forced draught via pressure PI controllers. Invariably, sticktion (mainly from the coal ash present in the boiler house) has a tendency to accumulate on the final control elements of the FD dampers causing pressure cycles. These pressure cycles are further amplified by the location of the pressure transmitter for each FD damper. The pressure transmitters are located on a common arch, thus a change in left pressure will cause the right pressure to change and vice versa. The ID damper regulates the boiler steam pressure via a PI controller. The water level of the boiler is controlled using feed water into the boiler via a proportional integral and derivative (PID) controller. This ensures no water overflows into the steam header.

The structural properties of the coal grating induces large time delays in the process, which require controllers to be detuned to an extent that disturbance rejection and reference tracking performance becomes unacceptable (Marlin, 2000). This could lead to large amounts of hot coals being thrown off the grate at the exit and would result in a loss of fire inside the boilers. Thus the stoker speeds are controlled manually. The varying steam demand and manual control of the stokers results in inadequate reference tracking performance of the regulatory control.

3. ANALYSIS

3.1 Interaction

A boiler is a multiple input multiple output (MIMO) plant. If a change in one input affects more than one output, the plant is considered as interacting (Skogestad *et al.*, 1996). If a MIMO plant is non-interacting, that is if one input only affects one output, decentralized manipulated variable-control variables pairing can be used. There exist various techniques in designing decentralized controllers for MIMO systems. Robust design of decentralized controllers takes into account off diagonal dynamics of plant as uncertainty. Labibi *et al.* (1996) implemented robust decentralized control on an industrial boiler which showed improved performance than previous PID control. The relative gain array (RGA) is a measure of interaction for decentralized control. The RGA is also a measure of the plant model sensitivity to input uncertainty such as actuator dynamics (Skogestad *et al.*, 1996). For each boiler the manipulated variables (MVs) available are:

- Left FD dampers (LFD)
- Right FD dampers (RFD)
- Left Stoker Speed (LST)
- Right Stoker Speed (RST)

The available control variables (CVs) are:

- Left and Right FD pressures
- Steam produced
- % O2 in the off gas

The ID damper is considered as a disturbance variable. The RGA at steady for one of the seven boilers present in the boilers house is shown in Table 1.

Table 1. Boiler RGA

	Left Pressure	Right Pressure	Steam	Off gas %O2
LFD	0.75	-0.16	0.34	0.07
RFD	-0.17	0.90	0.13	0.15
LST	0.75	0.34	0.94	-1.03
RST	-0.33	-0.07	-0.41	1.82

Large RGA elements in Table 1 indicate potential control difficult with input sensitivity. The RGA matrix elements depict interaction with no clear MV-CV paring thus having a limited ability to achieve optimization by using decentralized control.

3.2 Key Performance Indicators (KPI's)

Identifying KPI's and target setting is crucial in achieving an efficient operating plant and realizing the monetary benefits. For boiler performance monitoring, KPI's were defined so as to identify targets the process should be driven to. The KPI's are defined below,

3.2.1 Steam to Coal ratio

The boilers use coal to create steam and the steam to coal (S/C) ratio is calculated according to,

$$S/C = Ms / Mc, \tag{2}$$

where Ms is the mass (in ton/hr) of steam produced and Mc is the mass (in ton/hr) of coal utilized.

3.2.2 Boiler Efficiency

The boiler efficiency (ηe) is calculated as

$$\eta e\ (\%) = 100\% - F_L - DS_L \tag{3}$$

where F_L is the fixed loss and DS_L is dry stack loss. The F_L is assumed to be the industry average of 5%. DS_L is determined by the Siegert formula, i.e.

$$DS_L = 0.63*(To - Ti) / \%CO_2 \tag{4}$$

where Ti is the ambient temperature and To and $\%CO_2$ are the temperature and % carbon dioxide in the offgas.

3.2.3 Thermal Efficiency

The thermal efficiency (ηt) is defined as

$$\eta t\ (\%) = Ms(hs - hw) / (Mc * HHV) \qquad (5)$$

where hs and hw are the enthalpy of steam and water respectively and HHV is the calorific value of coal as defined in equation 1.

3.2.4 Boiler Saturation

Saturation of the boiler (bs) occurs when the ID damper, the left stoker (LST) and the right stoker (RST) are at their upper limits, i.e. the boiler is at maximum steam production.

$$bs = \max(ID)\ \&\ \max(LST)\ \&\ \max(RST) \qquad (6)$$

3.3 Objective

The objective of the controller is to improve the header pressure stability and KPI's defined in (2) to (6) above.

4. ADVANCED CONTROL SOLUTION

4.1 Architecture

The intricate behaviour and relationships associated with boilers present widespread challenges in achieving optimal performance. Regulatory PI controllers provide acceptable steady state performance. However, advanced process control (APC) provides more stability and responsiveness in operation due to its ability to handle interaction. An APC system was installed to optimize the combustion system. This included a GenSym G2 expert system toolkit specifically developed for Anglo Platinum (and, therefore, referred to as the Anglo Platinum Expert Toolkit (APET)), and a DMCplus model predictive controller. The real time expert system, APET, is an object orientated environment which includes a representation of plant equipment in the form of a knowledge base as shown in Figure 3.

All plant variable values are continually updated via OPC communications to the plant control system. APET forms the platform for the APC solution, interfacing between the plant control system and DMCplus controller. The APET system used has been configured to continuously monitor the communication links, reviveing the communication automatically when a failure occurs. The flexibility of APET allows the ability to include equations such as KPI's defined previously. This feature together with the knowledge base has been further enhanced to create an offline reporting tool. APET has many advantages, the most prominent feature exploited for the boiler APC is the use of real time calculations.

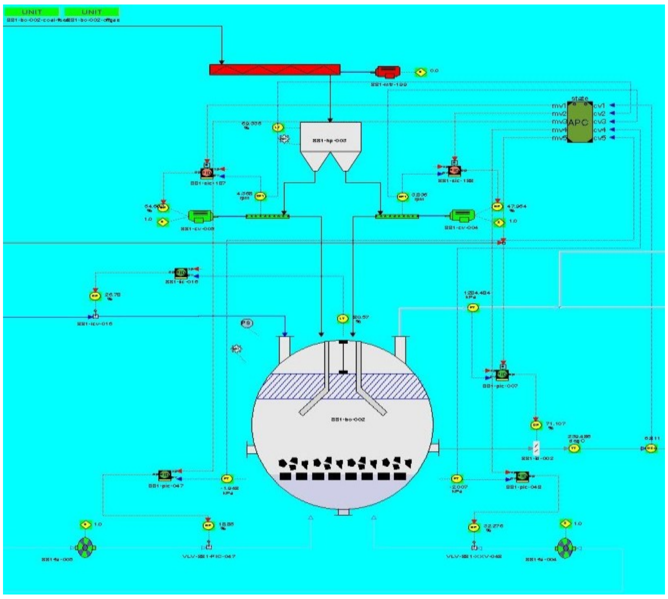

Figure 3: Individual G2 based APET boiler schematic.

4.2 Implementation

The APC controller consisted of a main steam header controller and individual boiler MPC controllers. The steam header MPC controls the steam header pressure by manipulating the ID damper of each boiler. Each boiler ID damper would determine the steam demand of the boiler. The change in steam demand would cause the header pressure to change accordingly and thus the MPC will manipulate the ID dampers to maintain the header pressure. There are seven boilers and one steam header pressure; hence the MPC is over specified. Each boiler affects the steam header pressure thus proving the main steam header to be highly interactive.

Each ID damper was used as a feed forward to the respective individual boiler MPC, determining the load required by each boiler. The boiler MV's are,

- Left Stoker Speed
- Right Stoker Speed
- Left FD Damper
- Right FD Damper

The boiler CV's are,

- Left FD Pressure
- Right FD Pressure
- Off Gas % O2
- Left Stoker Target
- Right Stoker Target

To increase the production of steam, the ID damper is opened. This will let through more air, increasing combustion, increasing the production of steam. This will also cause the coal on the grate to be consumed quicker, causing the burn zone to shift towards the rear of the boiler. The boiler controllers reacted to changes in the ID damper position by increasing or decreasing the stoker speeds, to maintain a ratio between the ID damper position and the length of the coal bed on the grate. This kept the fire in the correct position in the boiler. The ID Damper Stoker is an MV-MV relationship, y, which was defined by the following linear relationship

$$y = mx + c + \text{bias} \qquad (7)$$

with m is given by

$$m = \Delta ID / \Delta ST \qquad (8)$$

where ΔID and ΔST are the operational ranges of the ID damper and the stoker speed respectively. The parameter c is obtained according to

$$c = (m * \mathrm{IDL}) / \mathrm{STL}) \qquad (9)$$

where IDL and STL are the lower bounds on the operational range of the ID damper and the stoker speed respectively. The coal bunker is not covered; thus moisture build up from, for example rain, requires the coal to dry and remain on the grate for an extended period of time before combustion. Hence, a bias was added to compensate for such scenarios. These controller calculations were implemented in APET. The output of (7) was added as CV's to the controller as left and right stoker targets.

The boiler MPC manipulated the FD damper pressure set points by maximising FD pressure while ensuring that no flames exit the boiler. The controller had a limited ability to minimize the off gas % O_2 due to the sticktion present on the FD dampers.

5. RESULTS

The performance of the boiler house was evaluated over a ten month period consisting of five months with no APC and five months with APC. Figure 4 below illustrates the performance of the header pressure.

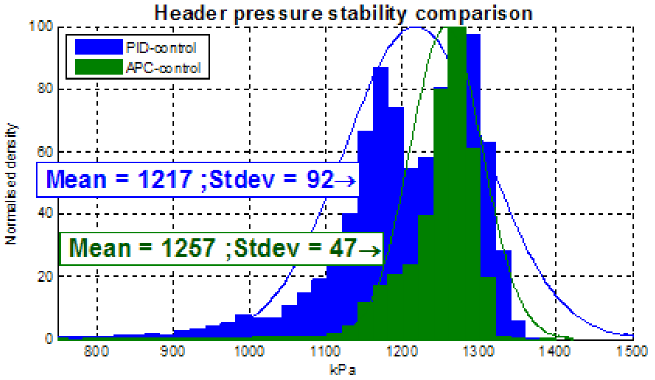

Figure 4: Header Pressure Stability

There was a significant improvement in the steam header pressure stability with the APC solution, reducing the pressure standard deviation (μ) by 50%, Figure 4. The boiler house steam to coal ratio improved from 9.07 to 9.98 as shown in Figure 5.

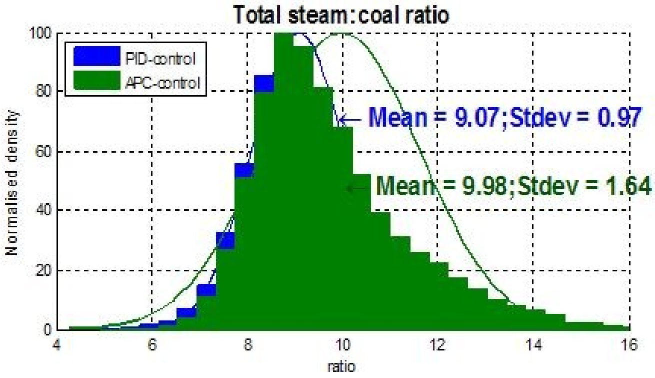

Figure 5: Overall Steam to Coal Ratio

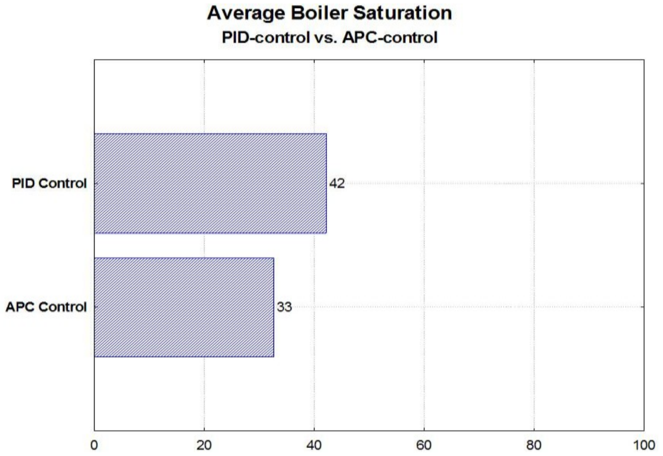

Figure 6: Boiler Saturation

The average boiler saturation was reduced during APC although there is no significant difference in the amount of steam produced over the comparison period, Figure 6. A one way ANOVA was used to evaluate significant difference in PID control versus APC control and summary of the results are presented in Table 2.

Table 2: ANOVA Results. Hypothesis: $\mu_{PID} \neq \mu_{APC}$ with 0.99 confidence level (CL) and significance level of p=0.05

Indicator	PID control μ	APC control μ	p-value
Header Pressure-kPa	1217.5	1257	0.00
Steam/Coal	9.07	9.98	0.00
Saturation	42	33	0.05

Figures 7 and 8 below show the improvement in combustion and thermal efficiency respectively.

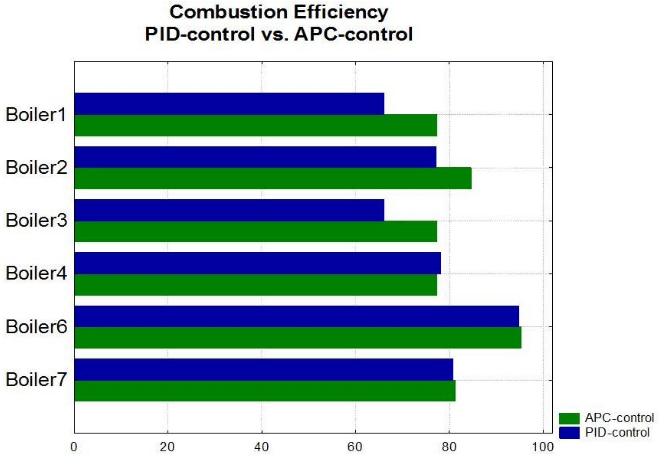

Figure 7: Combustion Efficiency

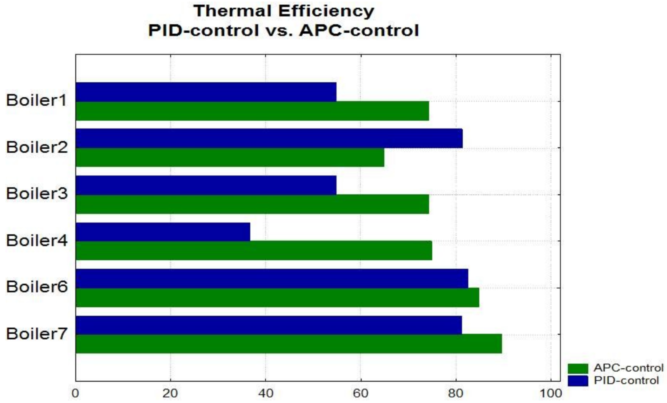

Figure 8: Thermal Efficiency

The improvement in steam to coal ratio resulted in a 7.27% reduction in coal usage with a significant monetary saving.

6. CONCLUSION

The implementation of a MPC together with the APET expert system has stabilized the steam header pressure. This resulted in overall improvement in the boiler operation, with the most prominent benefit being the coal saving. The features of APET in automatic communication revival allows for ease of maintenance and increased APC run time. The continuous reports generated by APET readily provide personnel with information to further optimize assets. The replacement of the current FD dampers to a system that is less prone to sticktion will allow the MPC controller to provide further benefits by minimizing oxygen in the off gas.

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