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A boiler simulator for improved operator training

Final report prepared by:	AP Mann
Chief Investigator(s):	AP Mann
Research organisation(s):	QUT
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ABSTRACT

A boiler simulator training package ready for use by industry has been developed during this project. After some fine tuning to accommodate site specific details and interaction with existing factory control systems (if requested by the sites), the simulator will be ready for use by factories for operator training.

Models of the different boiler station components that form the basis of the back end of the simulator were developed. These models calculate the heat transfer and steam generation through the different boiler components, water/steam, gas and air side pressure changes through the boiler along with shrink and swell in the boiler steam drum. These models can be incorporated into the distributed control systems (DCSs) of factories with the assistance of factory instrumentation staff.

A user manual describing the operation of the simulator along with a training program that goes through common scenarios encountered during operation of a sugar factory boiler has been written.

Use of the simulator will improve the skill level of operators and increase the effectiveness of operator training. There will be a reduced risk of damage to boilers and lost production. With improved operator performance the number of incidents should reduce. This will improve the financial performance of the industry, the public perception of the industry and in the long term, reduce insurance costs.

EXECUTIVE SUMMARY

Continuous, efficient and safe operation of a sugar factory depends on having competent and confident operators who can prioritise sometimes conflicting requirements and choose the best option under pressure. Most operators have another role during the maintenance season and there is anecdotal evidence from factories that issues arising from operator error are more common early in the crushing season when operators are getting back up to speed. This switching between different roles is more difficult for inexperienced operators and a suitable mentor may not be available when needed.

Recent incidents, attributed in part to operator error, that have cost factories several million dollars in boiler repair costs and lost production, have highlighted the importance of having boiler operators that have the understanding and skills to deal effectively with the many issues that can arise. In some other industries simulation packages are an integral part of operator training, maintenance of skill levels and assessment of competence. If the sugar industry lags behind in this area it is likely that such incidents will continue to occur.

A training simulator consists of a front end, the interface that the user interacts with, and a back end that carries out the calculations. The front end receives inputs from the user that are sent to the back end and the calculated results are returned to the front end, which displays the results in a suitable format. This work includes the development of both back end and front end components of a boiler simulator and the interfacing of the two components into an integrated generic simulator for boiler operators. The development of the simulator was guided by the industry at all stages of the project.

Boiler operator and industry surveys were carried at the start of the project to identify critical situations that occur during boiler operation, issues relating to operators changing roles, the experience and age distribution of the existing operator workforce, any past simulator use and simulator preferences. An industry workshop was held at Pleystowe Mill on the 24 February 2017. Boiler operators, engineering managers, training managers and instrumentation staff from Mackay Sugar, Tully Mill, Sunshine Sugar and Wilmar attended.

The back end development involves developing physically based sub-models (software code) of boiler station components that can predict the steam state and transient response of these components to different inputs and combining these sub-models into the simulator back end. The sub-models have adjustable parameters such as heat exchange surface areas to simulate the characteristics of specific boilers. The back end development was guided by input from respondents to boiler operator and industry surveys and participants in an industry workshop. DCS factory data was used in the development and evaluation of the back end.

The front end development involves the development of a generic user interface that has some features of a DCS used by boiler operators but will not represent all the graphical details of a DCS. In earlier feedback on this proposed work it was noted that having a generic interface too close to that of a mill DCS interface would cause confusion. Feedback on the generic user interface was received during an initial site visit at the Wilmar Townsville office on Friday 14 September, 2018. Staff from Wilmar, Tully Mill and Mackay Sugar attended. The attendees included boiler operators, boiler operator trainers, instrumentation staff and boiler engineers.

The updated simulator with the training program was demonstrated during a second site visit and feedback was used to update the simulator and training program. The second (follow up)

demonstration of the simulator took place at Millaquin Mill on Tuesday 28 May, 2019. Staff from Millaquin Mill, Bingera Mill, Isis Mill and Maryborough Mill attended the demonstration.

A boiler simulator with a generic interface and a training program has been developed in this project that can be used for operator training. Some of the component models of the simulator back end can be incorporated into factory DCSs. Use of the simulator will improve the skill level of operators and increase the effectiveness of operator training and operator refresher training. There will be a reduced risk of damage to boilers and lost production. With improved operator performance the number of incidents should be reduce. This will improve the financial performance of the industry, the public perception of the industry and in the long term, reduce insurance costs.

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1.1. Project rationale

Continuous, efficient and safe operation of a sugar factory depends on having competent and confident operators who can prioritise sometimes conflicting requirements and choose the best option under pressure. Most operators have another role during the maintenance season and there is anecdotal evidence from factories that issues arising from operator error are more common early in the crushing season when operators are getting back up to speed. This switching between different roles is more difficult for inexperienced operators and a suitable mentor may not be available when needed.

Recent incidents, attributed in part to operator error, that have cost factories several million dollars in boiler repair costs and lost production, have highlighted the importance of having boiler operators that have the understanding and skills to deal effectively with the many issues that can arise. In some other industries simulation packages are an integral part of operator training, maintenance of skill levels and assessment of competence. If the sugar industry lags behind in this area it is likely that such incidents will continue to occur.

1.2. Literature review

To thrive in an increasingly competitive market and to comply with more stringent environmental requirements, industries depend on well trained, competent operators that can adapt quickly to process changes and respond appropriately to uncommon situations. It is widely acknowledged the experience is the best teacher and that people learn from their mistakes, in many industries it is difficult to get sufficient 'hands on' experience and mistakes can be catastrophic. While in the past, operator training using dynamic simulation was seen as an expensive luxury, the improved profitability, enhanced plant operations, extended equipment life and favourable insurance considerations that can result along with the reducing cost of computing power has made it very attractive to many industries (Stawarz and Sowerby, 1995).

Commercial and military aviation training has used dynamic simulation extensively for more than seventy years (Ortiz, 1994; Salas et al., 1998). A meta-analysis by Hays et al. (1992) found that training using simulators and aircraft training consistently produced better results than aircraft training alone which is consistent with the study by Ortiz (1994) on college students without aviation training. Aviation flight simulators have been modified to be used extensively for manned spacecraft training where training under operational conditions is impossible (Abbey, 1974).

The fossil fuel power industry has long recognised the benefits of simulators for operator training. In fossil fuel boilers, simulators are estimated to save millions of dollars over the life of the simulator (Fray, 1995). These saving are due to reduced operating (fuel, maintenance, stoppages) and capital costs (longer lasting power station components). More effective and faster training of operators is another well documented area of savings (Fray, 1995). It has been noted that far more has been spent on reducing equipment failures than training operators even though preventable human error contributes almost as much to lost power production (Fray, 1995). Simulators are even more critical in the power industry as electricity networks become more complicated (Spanel et al., 2001; Waight et al., 1991) and operators have to balance power plant requirements against the variable requirements of the electricity grid. Simulators can be used to optimise boiler control parameter (Pelusi et al., 2013) as a less risky alternative to boiler tuning during plant operation.

In the nuclear power industry, plant failure can lead to loss of life and long lasting environmental consequences. Simulators have long been used for operator training and evaluation of operator performance in nuclear power plants (Dudley et al., 2008; Noji et al., 1989). In some companies simulators are used to provide training not only to operators but to shift crews as well, both individually and as groups (Noji et al., 1989). Today all nuclear power plants are required by law to have and maintain a full scope operator training and simulation system because theory and academic qualifications have been shown to be no longer enough to satisfy the requirements for competence (Dudley et al., 2008).

Simulators are widespread in process industries for operator training (Cox et al., 2006; Drozdowicz et al., 1987; Kano and Ogawa, 2010; Niemenmaa et al., 1998; Ylén et al., 2005) and to evaluate operator performance (Lee et al., 2000). In many industries process simulators are an integral part of day to day operation (Cox et al., 2006). For existing plants, simulator training can complement traditional 'hands on' training under the guidance of a mentor but for a new plant that is not possible. Simulators are required to develop and evaluate procedures for start-up, shutdown and dealing with emergencies and then for training the operators in these procedures.

While there is some published work on developing a simulators for sugar factories (Santos et al., 2008) there is little evidence in the open literature of widespread use of such simulators in sugar factories. There is however a strong push to improve the training of operators in sugar factories, from factory management wanting to reduce lost time and damage to equipment and from regulatory authorities wanting to eliminate the workplace health and safety and environmental consequences of operator error. The SOTrain system, recently developed by QUT (Broadfoot et al., 2015) provides background theory and exercises to enhance the knowledge and decision making skills of operators but cannot provide the level of detail and testing capability of an operator training simulator. Operator training simulators take operator training to the next level which needs to happen because boiler operators in particular often have to balance the demands of maintaining production and avoiding catastrophic damage to boiler plant (Rodman and Banweg, 2013).

For boiler simulators or any other type of process simulators to work effectively, the back end of the simulator must accurately represent all the important processes. Part of the boiler design process involves using lumped parameter heat transfer models (Dixon et al., 1998; Stultz and Kitto, 1992; Verbanck, 1997) to size the heat transfer surfaces. These models can be quite complex; users of these models need to be familiar with the heat transfer processes occurring in a boiler and for accurate predictions detailed geometric information about all the heat transfer components is required.

Computational fluid dynamics (CFD) is a widely used tool for simulating the gas, particle and air flow patterns through a boiler (Dixon et al., 2005; Mann et al., 2001; Mann and Rasmussen, 2011) and evaluating boiler design modifications. Both lumped parameter and CFD models are used by experienced engineers but are too complex to be used as operator training tools. By contrast the models that sit behind boiler simulation interfaces are often, but not always, comparatively simple and do not take account of the physical processes that occur. Therefore the simulation interfaces tend to be specific to a particular boiler and therefore costly to apply to a new boiler.

2. PROJECT OBJECTIVES

- Develop a boiler station simulator back end based on thermodynamic and heat transfer models of the boiler station components. It would simulate the water/steam, gas and air flow paths and would predict the transient and steady state response of the boiler station to changes in factory and fuel conditions and failure of boiler hardware. This back end would sit behind either a generic interface or the mill specific distributed control system (DCS) interface. This simulator would model the behaviour of the boiler station and how process variables change in response to events such as factory starts and stops, turbine trips, bagasse chute chokes and unstable combustion.

- Develop a generic front end for the simulator that would provide a user friendly graphical user interface (GUI) for operators to change inputs and observe the modelled response of the boiler station to the changed inputs.
- Include a training program with the generic front end. This training program would require the boiler operator to respond to scenarios such as a factory stop, a turbine trip, an increase in fuel moisture, the onset of unstable combustion, a sudden reduction in increase in factory steam demand and electricity grid disturbances.

3. OUTPUTS, OUTCOMES AND IMPLICATIONS

3.1. Outputs

A boiler simulator training package ready for use by industry has been developed during this project. The simulator was demonstrated during a site visit to Millaquin Mill on the 28 May 2019. After some fine tuning to accommodate site specific details and interaction with existing factory control systems (if requested by the sites), the simulator will be ready for use by factories for operator training. The target audiences are boiler operators, trainee boiler operators, shift supervisors and instrumentation staff. The simulator front end uses the SysCAD plant simulation software and a licence fee to the software supplier (KWA Kenwalt Australia) will apply to use the simulator.

There is no adoption of project outputs yet because the simulator has just been developed but there is strong interest in using the simulator.

Models of the different boiler station components that form the basis of the back end of the simulator were developed. These models calculate the heat transfer and steam generation through the different boiler components, water/steam, gas and air side pressure changes through the boiler along with shrink and swell in the boiler steam drum. These models can be incorporated in into the DCSs of factories with the assistance of factory instrumentation staff.

A user manual describing the operation of the simulator along with a training program that goes through common scenarios encountered during operation of a sugar factory boiler has been written.

3.2. Outcomes and Implications

The simulator will be used primarily as a training tool, both for new operators as well as experienced operators that have worked elsewhere and need to re familiarise themselves with boiler operation. The simulator can also be used to assess the skill level of operators before resuming duties at the start of the crushing season in conjunction with input from trainers.

Instrumentation staff can incorporate the back end of the simulator to work behind their existing DCSs. This approach would allow their existing DCSs to be operated in simulate mode. When operating in this mode the user will be able to find out how the boiler station responds to changes without any risk to plant or personnel.

Use of the simulator will improve the skill level of operators and increase the effectiveness of operator training. There will be a reduced risk of damage to boilers and lost production. With improved operator performance the number of incidents should reduce. This will improve the financial performance of the industry, the public perception of the industry and in the long term, reduce insurance costs.

4. INDUSTRY COMMUNICATION AND ENGAGEMENT

4.1. Industry engagement during course of project

The key messages from the project have been:

- A boiler simulator with a generic interface and a training program has been developed that can be used for operator training.
- Some of the component models of the simulator back end can be incorporated into factory DCSs. These component models would be used by the factory DCSs when operating in simulate mode.

During the course of the project there has been significant industry engagement. The industry interaction was organised through an industry reference group that included representatives from all milling companies. Boiler operator and industry surveys were carried at the start of the project to identify critical situations that occur during boiler operation, issues relating to operators changing roles, the experience and age distribution of the existing operator workforce, any past simulator use and simulator preferences. Nearly all the milling companies responded to the surveys.

An industry workshop was held at Pleystowe Mill on the 24 February 2017. Boiler operators, engineering managers, training managers and instrumentation staff from Mackay Sugar, Tully Mill, Sunshine Sugar and Wilmar attended.

The initial demonstration visit took place at the Wilmar Townsville office on Friday 14 September, 2018. Staff from Wilmar, Tully Mill and Mackay Sugar attended. The attendees included boiler operators, boiler operator trainers, instrumentation staff and boiler engineers.

The second (follow up) demonstration of the simulator took place at Millaquin Mill on Tuesday 28 May, 2019. Staff from Millaquin Mill, Bingera Mill, Isis Mill and Maryborough Mill attended the demonstration.

The boiler simulator development process has been communicated to representatives of all Australian sugar milling companies through QUT and SRA's Regional Research Seminars in 2016 to 2019. In addition, presentations on the simulator development process were made to the Australian Society of Sugar Cane Technologists conferences in 2018 (Mann, 2018) and 2019 (Mann, 2019) and the Australian Sugar Milling Council (ASMC) safety conferences in 2017 and 2018.

4.2. Industry communication messages

A boiler simulator with a generic interface and a training program has been developed that can be used for operator training. Some of the component models of the simulator back end can be incorporated into factory DCSs. Use of the simulator will improve the skill level of operators and increase the effectiveness of operator training and operator refresher training. There will be a reduced risk of damage to boilers and lost production. With improved operator performance the number of incidents should be reduce. This will improve the financial performance of the industry, the public perception of the industry and in the long term, reduce insurance costs.

5. METHODOLOGY

5.1. Introduction

A training simulator consists of a front end, the interface that the user interacts with, and a back end that carries out the calculations. The front end receives inputs from the user that are sent to the back end and the calculated results are returned to the front end, which displays the results in a suitable format. This work involves the development of both back end and front end components of a boiler simulator and the interfacing of the two components into an integrated generic simulator for boiler operators. The development of the simulator was guided by the industry at all stages of the project.

5.2. Initial industry input

Boiler operator and industry surveys were carried at the start of the project to identify critical situations that occur during boiler operation, issues relating to operators changing roles, the experience and age distribution of the existing operator workforce, any past simulator use and simulator preferences. An industry workshop was held at Pleystowe Mill on the 24 February 2017. Boiler operators, engineering managers, training managers and instrumentation staff from Mackay Sugar, Tully Mill, Sunshine Sugar and Wilmar attended.

5.3. Back end development

This involves developing physically based sub-models (software code) of boiler station components that can predict the steam state and transient response of these components to different inputs and combining these sub-models into the simulator back end. The sub-models have adjustable parameters such as heat exchange surface areas to simulate the characteristics of specific boilers. The back end development was guided by input from respondents to boiler operator and industry surveys and participants in an industry workshop. DCS factory data was used in the development and evaluation of the back end.

5.4. Front end development

This involves the development of a generic user interface that has some features of a DCS used by boiler operators but will not represent all the graphical details of a DCS. In earlier feedback on this proposed work it was noted that having a generic interface too close to that of a mill DCS interface would cause confusion. Feedback on the generic user interface was received during an initial site visit at the Wilmar Townsville office on Friday 14 September, 2018. Staff from Wilmar, Tully Mill and Mackay Sugar attended. The attendees included boiler operators, boiler operator trainers, instrumentation staff and boiler engineers.

5.5. Deployment

The updated simulator with the training program was demonstrated during a second site visit and feedback was used to update the simulator and training program. The second (follow up) demonstration of the simulator took place at Millaquin Mill on Tuesday 28 May, 2019. Staff from Millaquin Mill, Bingera Mill, Isis Mill and Maryborough Mill attended the demonstration.

6. RESULTS AND DISCUSSION

6.1. Initial industry input

The operator and industry surveys provided useful input on the issues associated with boiler operation in the sugar industry. A large number of critical situations were identified, which include:

- Low and high drum water level;
- Load swings;
- Loss of fuel;
- Fuel quality (wet fuel, variable properties);

- Fuel overfeeding;
- Undergrate fires;
- Tube failure;
- Loss of boiler fans;
- Start-up during crushing;
- Loss of flame;
- Furnace explosions;
- Loss of feedwater;
- Poor feedwater quality;
- Insufficient air flow;
- Blackouts;
- Ash system chokes;
- Light up procedures; and
- Instrumentation issues (gauge glasses/trips).

Other important, but less critical issues related to boiler operation were also raised in the surveys:

- Control of the boiler station when factory low pressure steam demand is low;
- Cold start-ups;
- Wet weather stoppages;
- Load sharing between boilers of different sizes;
- Situations where the cause of a problem is unknown;
- Recalling start-up and operating procedures at the start of each season;
- Adjusting to shift work;
- Changing from a physical role during the maintenance season to a sedentary role during the crushing season; and
- Mental fatigue.

The discussions at the industry workshop, attended by representatives from Mackay Sugar, Tully Mill, Sunshine Sugar, Wilmar, Sugar Research Limited (SRL) and QUT, reinforced the findings of the operator and industry surveys. Other issues such as boiler purging requirements, the standardisation of trips and responses to trips and the number of alarms were also discussed. Participants talked about the simulator used by Wilmar for control system testing and training and the boiler simulator used at Tarong power station. There was a preference for any simulator to have an identical interface to the DCS screens currently used by operators but the high cost of site specific replicator simulator was identified as a major issue. There was much interest in using a simulator to evaluate and train operators.

A consistent message from the surveys and workshop was that any simulator should correctly predict the trends in a boiler's response to changes. Predicting the precise variation of process variables with time was not seen as necessary, especially for a boiler simulator with a generic interface that is being developed in this project. It was noted by some workshop participants that some commercially available boiler simulators do not predict the correct trends. Having the simulator correctly changes in the gas/air and water/steam flow paths of the boiler with variations in steam load, the response of a boiler to poor fuel and failures of boiler components were seen as most important.

6.2. Back end development

The back end consists of sub-models for the different boiler components (furnace, screen, superheater, convection bank, economiser, flue gas air heater, water air heater and steam drum).

The heat transfer calculations in the sub-models were in most cases simplified versions of calculations widely used for boiler design (Stultz and Kitto, 1992). The gas side pressure drops through the screen, superheater, convection bank, economiser and air heater, the air side pressure drop across the air heater, the steam side pressure drop through the superheater and the water side pressure drop through the economiser were calculated using correlations sourced primarily from Idelchik (1996). There are a number of models for boiler steam drum dynamics in natural circulation boilers in the open literature (Adam and Marchetti, 1999; Åström and Bell, 2000; Franke et al., 2003; Kim and Choi, 2005). The back end for the water/steam side of a boiler developed in this work was based mostly on the model of Kim and Choi (2005) that uses mass and energy balances for the steam drum and downcomer-riser loop. The mass and energy balances take into account the thermal properties of the steam, water, steam drum and boiler tubes to predict the transient response of the system to changes encountered during boiler operation. The approach used by Kim and Choi (2005) to estimate the flow through the downcomers appears to predict very high flows, so a more detailed approach based on a previously developed circulation model (Davy and Dixon, 2001), was used to estimate the downcomer and riser flows instead.

The back end sub-models were mostly written in VBA as part of a Microsoft Excel spreadsheet. It should also be possible transfer these sub-models, or at least elements of these sub-models, into the code used by factory DCSs when run in simulation mode. This could be completed later with the assistance of factory instrumentation staff.

The boiler simulator back end was evaluated by comparing the values of selected process variables predicted by the boiler simulator back end with DCS data (supplied by Mackay Sugar) from the Farleigh No. 4 boiler. This two drum natural circulation boiler has a furnace, superheater, convection bank, economiser and water air heaters to heat the undergrate and secondary air. The simulator back end calculations assumed constant fuel properties and used the logged steam flows as inputs.

The boiler simulator back end was used to predict a number of process variables using the steam flows from the factory DCS data as inputs. Fig. 1 shows the logged variation of steam flow and convection bank gas exit temperature and the convection bank exit temperature predicted by the boiler simulator back end, over a time period of 100 minutes. Fig. 2 shows the logged variation of steam flow and economiser gas exit temperature predicted by the boiler simulator back end, over the same time period. Over most of the time period the simulator back end correctly predicted the direction of the gas temperature changes in Fig. 1 and Fig. 2. The directions of the gas temperature changes were not correctly predicted between 30 and 40 minutes and between 90 and 100 minutes. This could be due to fuel variability, which could not be taken into account in the simulator back end, because fuel property data was not logged.

Fig. 3 compares the logged variation of induced draft (ID) fan speed with the variation of flue gas flow predicted by the simulator back end. For most of the time period the simulator back end predicted increases and decreases in flue gas flow corresponding to increases and decreases in ID fan speed.

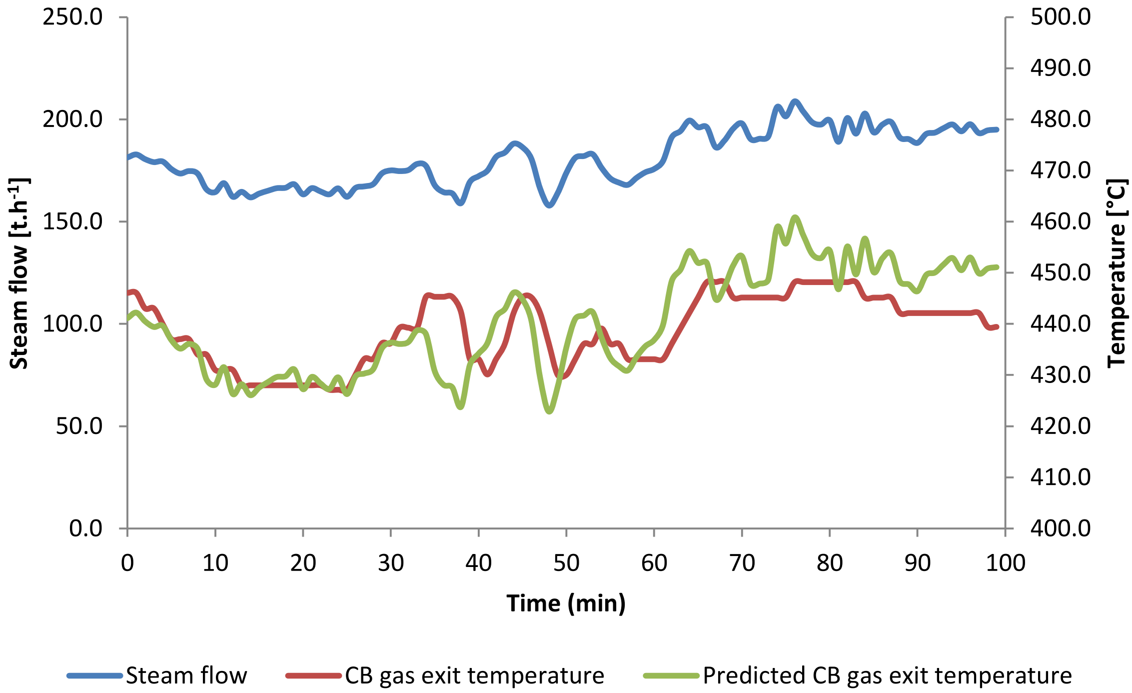

Figure 1 **Logged variations of steam flow and convection bank (CB) gas exit temperatures and the convection bank gas exit temperature predicted by the boiler simulator back end.**

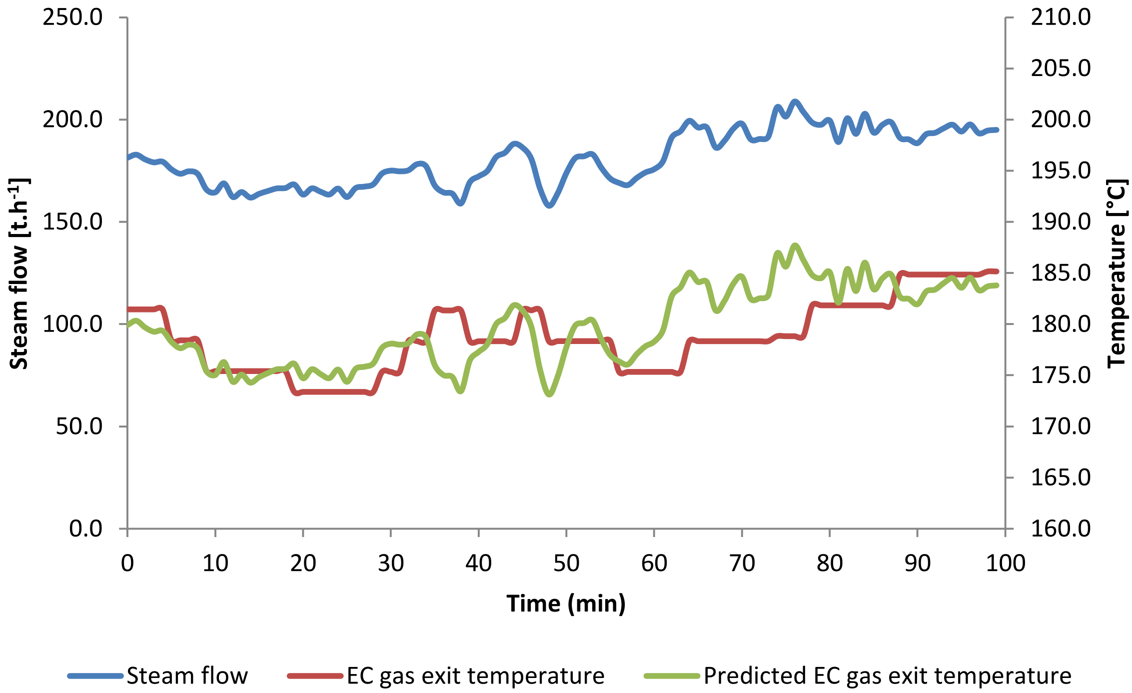

Figure 2 **Logged variations of steam flow and economiser (EC) gas exit temperatures and the economiser gas exit temperature predicted by the boiler simulator back end.**

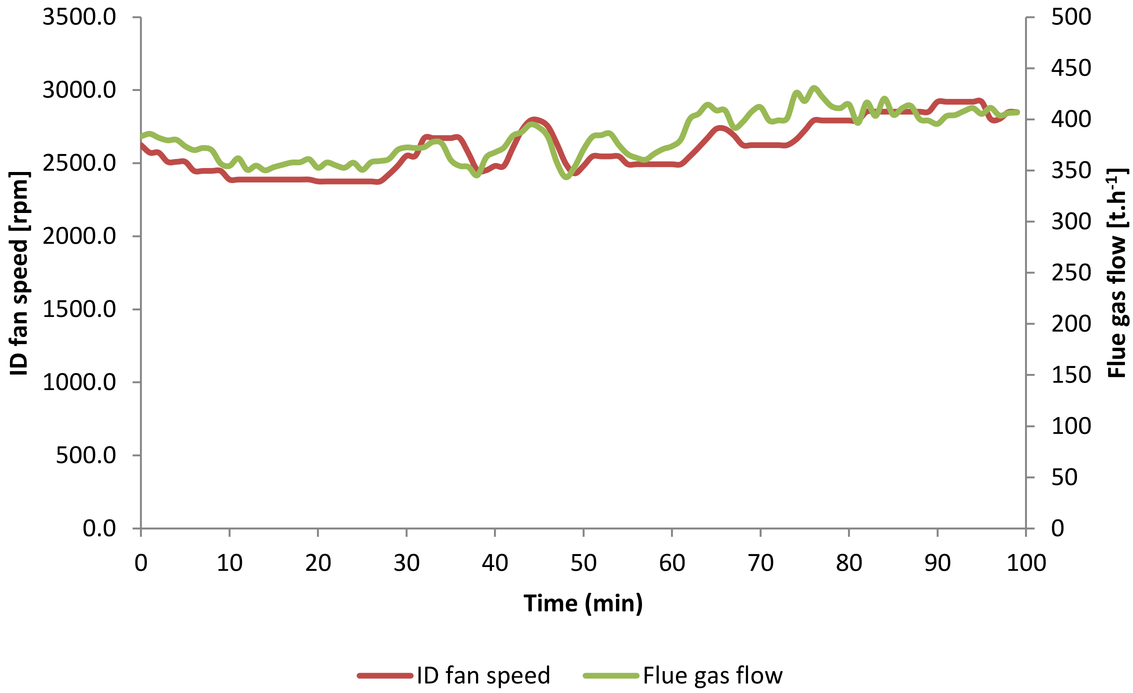

Figure 3 Logged variations of induced draft (ID) fan speed and the flue gas flow predicted by the boiler simulator back end.

There were problems getting the model of Kim and Choi (2005) to correctly predict how the drum pressure and drum level respond to changes in factory steam demand and steam generation in the boiler risers. It is essential for a boiler simulator to be able to predict this shrink-swell behaviour. A simpler alternative approach was used that is based on the geometry of the boiler tubes and steam drum and quality (steam mass fraction) of the steam-water mixture. Fig. 4 shows a simplified representation of the flows associated with a boiler steam drum.

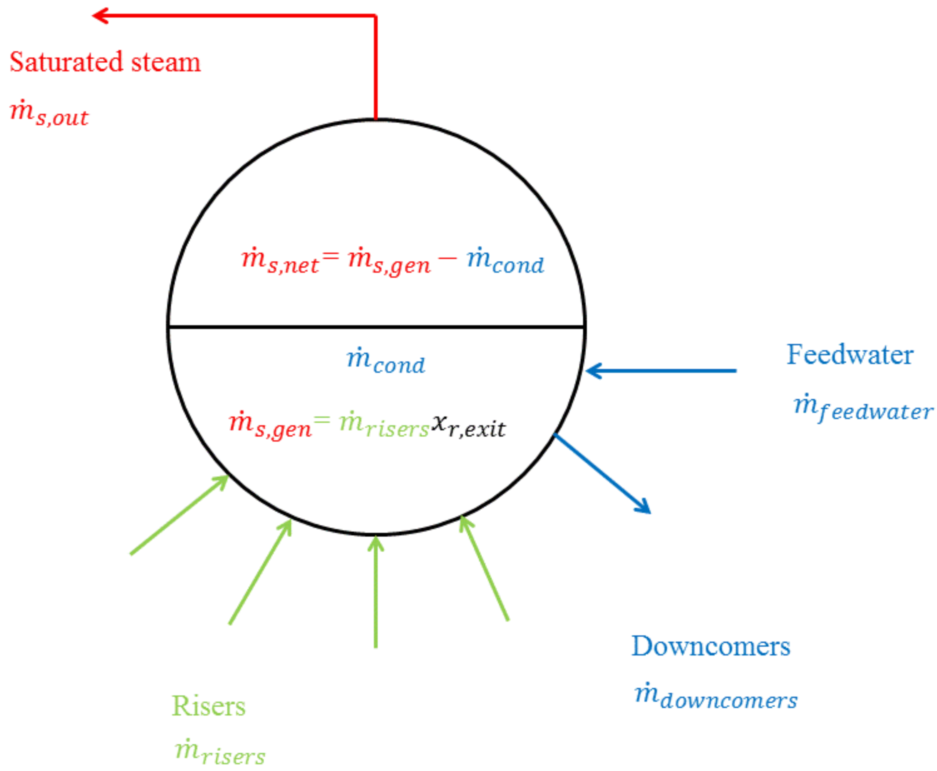

Figure 4 Simplified representation of the flows associated with a boiler steam drum. Steam separation equipment not shown.

In a natural circulation boiler virtually all the steam is generated in the tubes where the steam-water mixture flows upwards which are known as risers. The riser tubes are usually all the furnace wall tubes and most of the convection bank tubes. In the remaining convection bank tubes (the tubes furthest from the furnace) very little steam is generated and water flows downwards. These tubes are known as downcomers. Note that some boilers also have external downcomers that are not heated by the boiler flue gas. In Fig. 4 the total flow in the riser tubes is $\dot{m}_{risers}$(t/h) and the total flow in the downcomer tubes is $\dot{m}_{downcomers}$ (t/h). The feed water flow is $\dot{m}_{feedwater}$ (t/h) and the flow of saturated steam leaving the drum is $\dot{m}_{s,out}$ (t/h). The total steam generation in the boiler risers $\dot{m}_{s,gen}$(t/h) is the product of $\dot{m}_{risers}$ and the average quality of the mixture at the exit of the boiler risers $x_{r,exit}$ which is approximately equal to the reciprocal of a boiler's circulation ratio (C).

$$x_{r,exit} = \frac{1}{C}. \quad (1)$$

If the assumed quality of the mixture at the bottom of the boiler risers is 0 and it is assumed that the quality increases linearly with length along the tubes then the mean quality in the risers and in the steam drum below the water level ($x_{r,mean}$) can be approximated by:

$$x_{r,mean} = \frac{x_{r,exit}}{2}. \quad (2)$$

The average void fraction in the boiler riser and in the drum below the water levels, $\alpha_{r,mean}$, can then be calculated using:

$$\alpha_{r,mean} = \frac{x_{r,mean}}{x_{r,mean} + (1 - x_{r,mean})\frac{\rho_g}{\rho_f}} \quad (3)$$

where ρ_g (kg/m^3) is the steam density at steam drum conditions and ρ_f (kg/m^3) is the water density at steam drum conditions; both calculated using steam properties functions. The void fraction is used to calculate the total volume of steam below the drum water level, $Vol_{steam\ below}$(m^3), from the total internal volume of the riser tubes, $Vol_{r,int}$(m^3), and the volume of the steam drum below the water level $Vol_{drum,below}$(m^3):

$$Vol_{steam\ below} = \left(Vol_{r,int} + Vol_{drum,below}\right)\alpha_{r,mean}. \qquad \mathbf{4}$$

$Vol_{r,int}$ (m^3) is calculated from the geometry of the riser tubes and $Vol_{drum,below}$ (m^3) is calculated from the geometry of the steam drum and the drum level.

Shrink and swell occur when there is a difference between the net steam generation rate, $\dot{m}_{s,net}$(t/h), and the steam flow leaving the steam drum, $\dot{m}_{s,out}$ (t/h). The net steam generation rate is the difference between the steam generation in the boiler risers, $\dot{m}_{s,gen}$(t/h), and the condensation rate that occurs in the steam drum due to the heating of feedwater to steam drum conditions, $\dot{m}_{s,cond}$:

$$\dot{m}_{s,net} = \dot{m}_{s,gen} - \dot{m}_{s,cond}. \qquad \mathbf{5}$$

The change in steam mass, Δm (kg), in the steam drum (above and below the water level) and in the boiler risers is given by:

$$\Delta m = \frac{(\dot{m}_{s,net} - \dot{m}_{s,out})\Delta t}{3.6}. \qquad \mathbf{6}$$

This change in steam mass will cause a change in steam density which can be estimated using

$$\rho_{s,new} = \frac{\left(Vol_{steam\ below} + Vol_{drum,above}\right)\rho_{s,old} + \Delta m}{Vol_{steam\ below} + Vol_{drum,above}} \qquad \mathbf{7}$$

where $\rho_{s,new}$ (kg/m^3) and $\rho_{s,old}$ (kg/m^3) are the new and old steam densities respectively and $Vol_{drum,above}$ (m^3) is the volume of the steam drum above the water level. The new boiler pressure P_{new}can be determined $\rho_{s,new}$ using steam properties functions. After the change in steam density the new steam drum volume below the water level $Vol_{drum,below,new}$ (m^3) can be calculated from the old steam drum volume below the water level $Vol_{drum,below,old}$ (m^3) using:

$$Vol_{drum,below,new} = Vol_{steam\ below}\left(\frac{\rho_{s,old}}{\rho_{s,new}} - 1\right) + Vol_{drum,below,old}. \qquad \mathbf{8}$$

The new drum level can be calculated from the geometry of the drum and $Vol_{drum,below,new}$.

When the net rate of steam generation ($\dot{m}_{s,net}$) exceeds the steam flow leaving the steam drum ($\dot{m}_{s,out}$), then the mass of steam in the system (steam drum and boiler risers) will increase, Δm will be positive from equation 6 and the steam density will increase according to equation 7. This increases the steam pressure and reduces the steam volume below the drum water level according to equation 8, which then in turn lowers the drum level. This behaviour is known as 'shrink'. Conversely, when the steam flow leaving the steam drum exceeds the net rate of steam generation, the change of steam mass in the system will be negative and the steam density and pressure will reduce. This increases the volume of steam below the steam drum water level, which in turn raises the drum level. This behaviour is known as 'swell'. Both shrink and swell can cause serious problems. If shrink causes the drum level to get too low, there can be catastrophic failure of the boiler tubes due to overheating. If swell causes the drum level to get too high, there can be carryover of water droplets into and subsequent failure of the superheater tubes and downstream turbines.

This new model for predicting the steam pressure and drum level response to changes in steam generation and steam demand was incorporated into the visual basic for applications (VBA) section of the Microsoft Excel spreadsheet where the other sub-models of the back end were developed.

6.3. Front end development

6.3.1. Initial development

The front end of the simulator uses the SysCAD package as the generic interface. The SysCAD package has trending and history capabilities similar to those of the distributed control system (DCS) interfaces that boiler operators are familiar with. The back end sub-models (written in VBA) were converted to the programmable module (PGM) language used by SysCAD. The SysCAD package has water/steam properties functions and controllers that are used to carry out the iterative calculations. Geometry information and model parameters for the different components of the boiler are input using access windows like the one shown in Fig. 5.

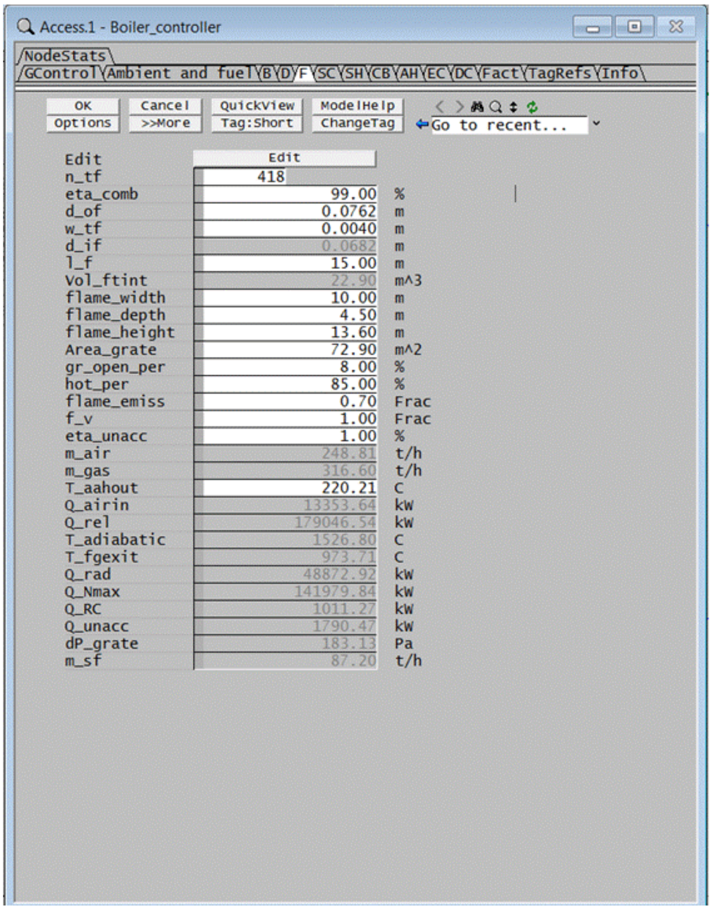

Figure 5 A typical access screen for the boiler simulator front end. User input values have a white background, calculated values have a grey background.

While the SysCAD interface is not as detailed as the DCS interfaces used in boiler stations it is available at much lower cost and it should be possible to transfer many of the sub-models in the back end to a factory DCS interface at a later date.

Fig. 6 shows a screen shot of the initial version of the generic interface. It shows a schematic of the boiler with the feedwater input, superheated steam output and a simplified version of factory steam users (turbine A and turbine B). Selected process variables are shown in the annotation table near the top left of the layout screen and selected trend variables are shown in the trend window at the bottom left of the layout screen. The simulator has a boiler controller which includes the code used for the calculations and a flow controller that adjusts the positions of dampers and control valves.

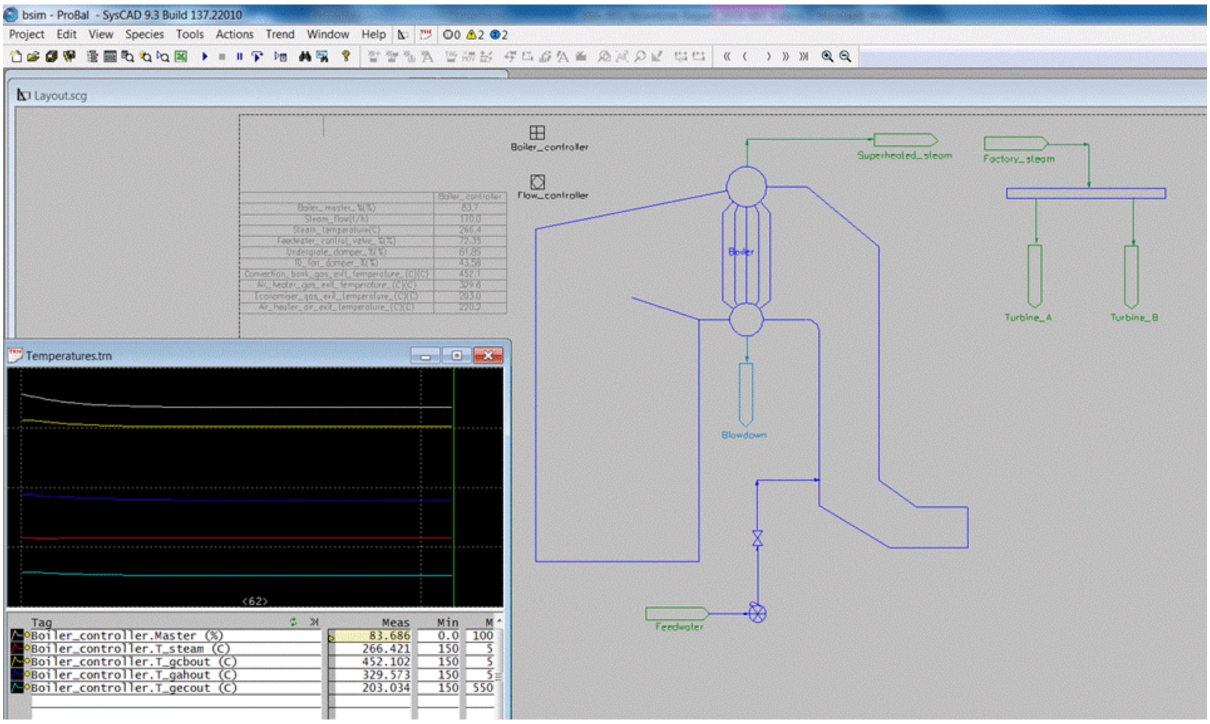

Figure 6 Screen shot of the initial version of the boiler simulator generic interface.

The simulated boiler has a furnace, screen, superheater, convection bank, economiser, air heater and dust collector in that order along the gas flow path. It is relatively easy to change the simulator to the other common boiler arrangements (boiler component listed according to order along the gas flow path)

- Furnace, screen, superheater, convection bank, air heater, economiser, dust collector;
- Furnace, screen, superheater, convection bank, air heater, dust collector; and
- Furnace, screen, superheater, convection bank, economiser, dust collector.

The SysCAD software has scripting capability which makes it possible to set up scenarios for the simulator to solve. These scripts are saved as text files for use in the training program.

The trends in Fig. 7 show the predicted effects of a step increase in bagasse moisture content on the boiler master and the air heater gas exit temperature. The air heater gas exit temperature initially reduces due to the lower heating value of the wetter bagasse, but as the boiler master and therefore fuel flow into the furnace increases, the air heater gas exit temperature increases and stabilises at a value slightly higher than the air heater gas exit temperature before the bagasse moisture content increase.

Figure 7 Predicted response of the boiler master (white line) and air heater gas outlet temperature (red line) to a step change in bagasse moisture content from 50% to 52% (green line).

The predicted initial changes to the drum pressure and drum level after a step reduction in factory steam demand are shown in Fig. 8. The drum pressure increases and the drum level reduces. This is an example of shrink. Note that eventually the drum pressure and drum will return to their normal values when the steam generation (controlled by the boiler master) reduces to match the factory steam demand (not shown in Fig. 8).

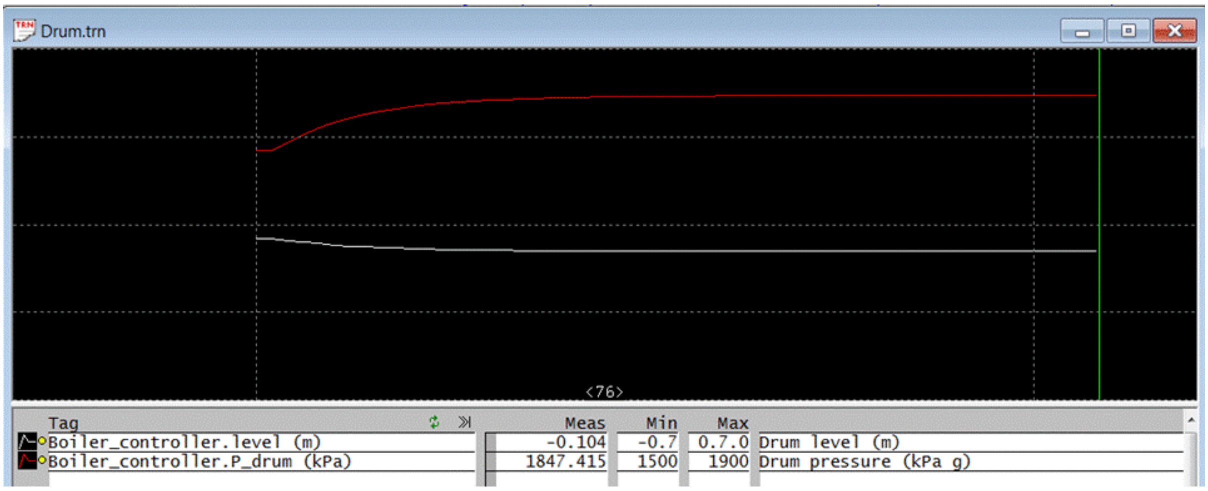

Figure 8 Predicted initial response of the boiler drum level (white line) and drum pressure (red line) to a step change reduction in factory steam demand from 170 t/h to 160 t/h.

6.3.2. Initial demonstration

The initial demonstration visit took place at the Wilmar Townsville office on Friday 14 September, 2018. Staff from Wilmar, Tully Mill and Mackay Sugar attended. The attendees included boiler operators, boiler operator trainers, instrumentation staff and boiler engineers.

The simulator components which include the inputs to the sub-models for the different boiler components were explained at the start of the session. This was followed by demonstrations of how the simulator predicted the response of the boiler to changes in fuel properties and factory steam demand.

There was robust discussion about the role of simulators in the training of operators. Some expressed the opinion that the only simulator that could be useful would be a site specific simulator that exactly replicates the screens seen by the boiler operators. Others expressed the view that a generic simulator would be useful for making operators and trainee operators familiar with the important processes associated with boiler operation in a sugar factory. It was pointed out that there is a big difference in competence level between someone who has just completed a boiler ticket (obtained a licence to operate a boiler) and an experienced boiler operator. In many cases it can take decades to go from one to the other and simulators are one way to accelerate that learning process. It was also pointed out that younger people often prefer and learn more quickly using computer simulation instead of reading the textbooks used in the theory component of boiler tickets. There was general agreement that a generic simulator will be of more use to novice operators or to people returning to a boiler operator role. A more expensive site specific simulator with identical screens to the factory DCS would be of more use to experienced operators.

The generic interface presented at the initial demonstration was intended as a starting point for discussions rather than an attempt to replicate the DCS screens at any particular factory. Several suggestions were made at the demonstration for improving the interface. These included:

- Having process variables (temperatures, pressures, damper and control valve openings) and set points on the screen near the relevant part of the sketch;
- Including a time scale on the trends;
- Showing the settings of each individual bagasse feeder;
- Having the simulator run continuously; and
- Including more detail in the representation of the factory.

6.3.3. Updates based on initial demonstration feedback

All the suggestions listed above were incorporated into the updated interface which is shown in Fig. 9.

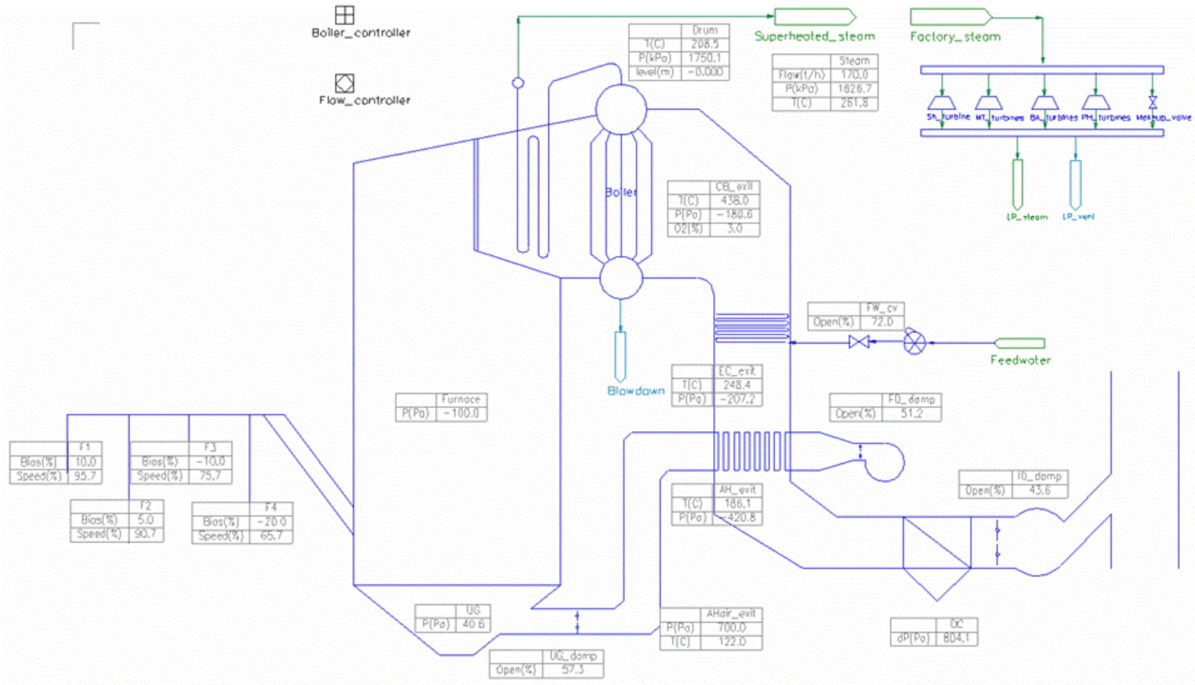

Figure 9 Updated boiler simulator interface based on suggestions from the initial demonstration.

The sketch of the boiler now shows a more detailed representation of the boiler components. Process variables are now shown in the relevant part of the display and the settings of each individual feeder are shown. A more detailed representation of a sugar factory that includes all the main high pressure steam users was also incorporated into the interface.

At the time of the initial demonstration the simulator could only solve in steady state mode which mean it was more of a boiler design tool than a simulator. The simulator is a lot more useful in dynamic mode. A dynamic licence for SysCAD was activated and changes were made to the back and front ends of the simulator to accommodate dynamic simulations. The sub-models used for the gas and air flow calculations were not changed because the gas and air flows through boiler in a matter of seconds so the gas and air flow paths can be approximated as steady state. However the transient behaviour occurring on the water/steam side of a boiler occurs over longer time scales and modifications had to be made to the PGM code and controllers that are used to predict the steam drum level and steam pressure. The dynamic simulations were set up to solve in real time – i.e. one second of simulation time corresponds to one second of real time.

6.3.4. Final demonstration

The second (follow up) demonstration of the simulator took place at Millaquin Mill on Tuesday 28 May. Staff from Millaquin Mill, Bingera Mill, Isis Mill and Maryborough Mill attended the demonstration. The demonstration started with a presentation that summarised the boiler simulator development process to date followed by explanations of how data is input to the simulator, how scenarios are set up and how outputs from the simulator are displayed. There was a lot of interest from attendees in using the simulator for operator training and how factory control systems could send data to and receive data from the simulator so that so that the usual distributed control system DCS screens could still be used.

The feedback on the simulator was very positive. Most of the suggestions for improvement related to future integration with DCS screens at factories. One suggestion that could be implemented prior to factory implementation was the inclusion of dynamic bars in the graphics screen to indicate drum level and feeder speeds. The dynamic bar is a visual representation of process variable that is similar to what many operators are familiar with. Dynamic bars have been added and the updated graphics screen is shown in Fig. 10.

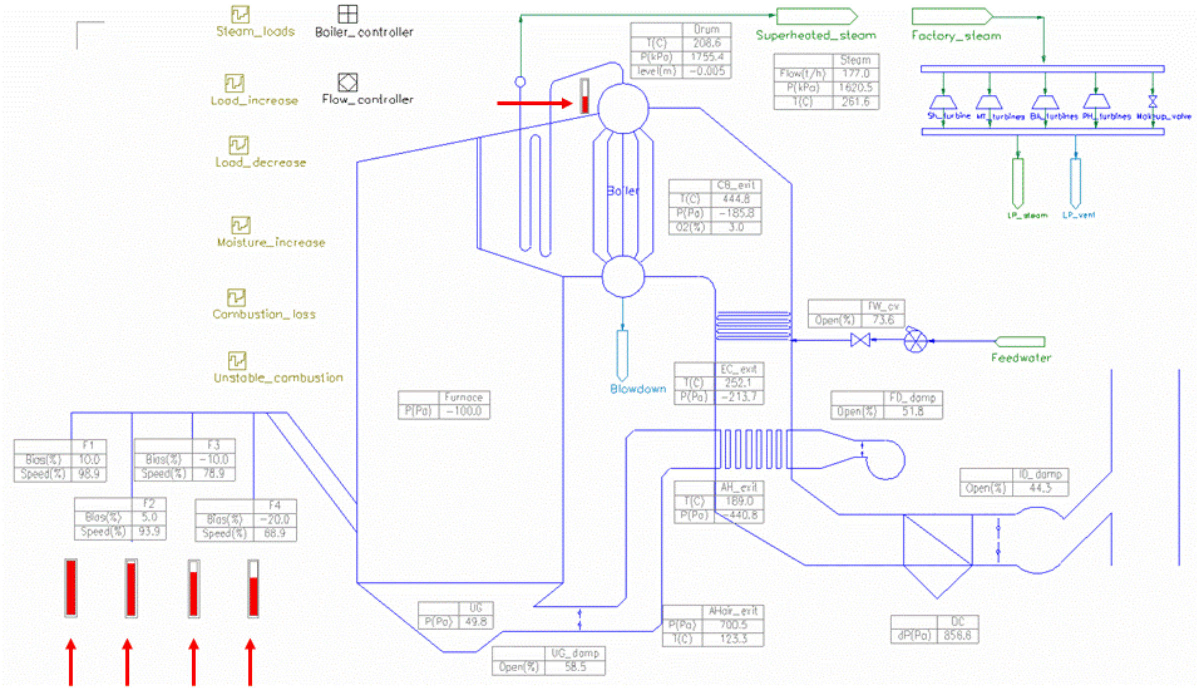

Figure 10 Updated graphics screen of the simulator with the red arrows indicating the location of the added dynamic bars.

6.4. Simulator training program

A training program in the simulator has developed and a training manual has been written. The attendees at the site visit noted that mill starts and stops and tube leaks were important situations that operators had to deal with so the training program scenarios include consequences of these situations. The scenarios included in the training program are:

- Steam load increase (consequence of a mill start);
- Steam load decrease (consequence of a mill stop);
- Fuel moisture increase (consequence of a mill restart after a stop);
- Combustion loss (consequence of a blown furnace tube or poor fuel quality); and
- Unstable combustion (consequence of poor fuel quality or operating the boiler at very high steam outputs).

The training program is based on getting the trainee to interpret the trends of process variables for the different scenarios. Fig. 11 shows some of the trends upon which the training program is based.

The training manual is included in the appendix.

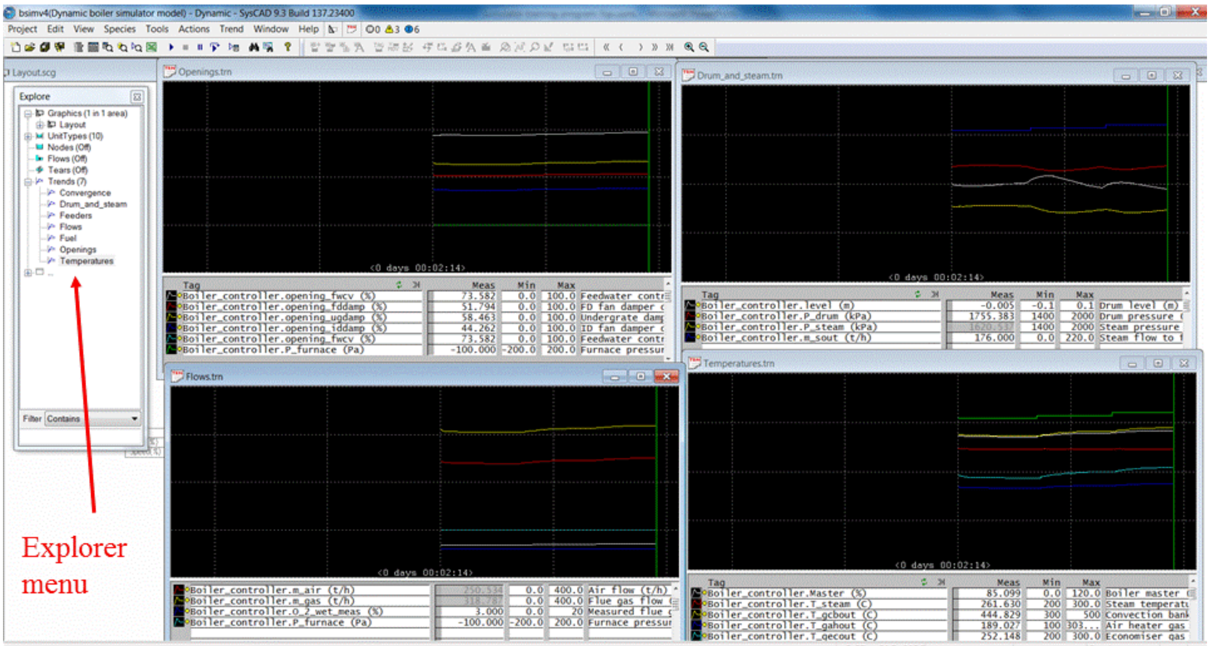

Figure 11 Updated graphics screen of the simulator showing some of the trends used in the training program.

7. CONCLUSIONS

This report summarises the development of a boiler training simulator for the sugar industry. A training simulator consists of a front end, the interface that the user interacts with, and a back end that carries out the calculations. The front end receives inputs from the user that are sent to the back end and the calculated results are returned to the front end, which displays the results in a suitable format. This work included the development of both back end and front end components of a boiler simulator and the interfacing of the two components into an integrated generic simulator for boiler operators. The development of the simulator was guided by the industry at all stages of the project.

Boiler operator and industry surveys were carried at the start of the project to identify critical situations that occur during boiler operation, issues relating to operators changing roles, the experience and age distribution of the existing operator workforce, any past simulator use and simulator preferences. An industry workshop was held at Pleystowe Mill on the 24 February 2017. Boiler operators, engineering managers, training managers and instrumentation staff from Mackay Sugar, Tully Mill, Sunshine Sugar and Wilmar attended.

The back end development involves developing physically based sub-models (software code) of boiler station components that can predict the steam state and transient response of these components to different inputs and combining these sub-models into the simulator back end. The sub-models have adjustable parameters such as heat exchange surface areas to simulate the characteristics of specific boilers. The back end development was guided by input from respondents to boiler operator and industry surveys and participants in an industry workshop. DCS factory data was used in the development and evaluation of the back end.

The front end development involves the development of a generic user interface that has some features of a DCS used by boiler operators but will not represent all the graphical details of a DCS. In earlier feedback on this proposed work it was noted that having a generic interface too close to that of a mill DCS interface would cause confusion. Feedback on the generic user interface was received during an initial site visit at the Wilmar Townsville office on Friday 14 September, 2018. Staff from Wilmar, Tully Mill and Mackay Sugar attended. The attendees included boiler operators, boiler operator trainers, instrumentation staff and boiler engineers.

The updated simulator with the training program was demonstrated during a second site visit and feedback was used to update the simulator and training program. The second (follow up) demonstration of the simulator took place at Millaquin Mill on Tuesday 28 May, 2019. Staff from Millaquin Mill, Bingera Mill, Isis Mill and Maryborough Mill attended the demonstration.

A boiler simulator with a generic interface and a training program has been developed in this project that can be used for operator training. Some of the component models of the simulator back end can be incorporated into factory DCSs. Use of the simulator will improve the skill level of operators and increase the effectiveness of operator training and operator refresher training. There will be a reduced risk of damage to boilers and lost production. With improved operator performance the number of incidents should be reduce. This will improve the financial performance of the industry, the public perception of the industry and in the long term, reduce insurance costs.

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8. RECOMMENDATIONS FOR FURTHER RD&A

While the feedback on the boiler simulator at the final demonstration was very positive it was noted that the boiler simulator would be even more useful for training if it could sit behind the control screens used by the operators at the different factories. This was also a recurring theme in the feedback received from the surveys, industry workshop and initial demonstration.

A way to address this would be to carry out a small extension project that would involve incorporating the simulator back end and solvers into the DCS at a particular factory. If this could be done successfully and the steps required to achieve this reported to the rest of the industry, it is likely there will be more widespread adoption of the boiler simulator.

9. PUBLICATIONS

Mann, A. P. (2018). "Boiler simulation tool development." Proceedings of the Australian Society of Sugar Cane Technologists, 40:482-489.

Mann, A. P. (2019). "Development of a boiler-simulation training tool." Proceedings of the Australian Society of Sugar Cane Technologists, 41:530–536.

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12. APPENDIX

12.1. Appendix 1 BOILER SIMULATOR TRAINING MANUAL

Boiler simulator training manual

Introduction

This boiler simulator helps the user become familiar with boiler operation by simulating scenarios that occur during the operation of a sugar factory boiler. This simulation based training will complement the information in boiler operating procedures and hands on training.

Brief description of the boiler simulator interface

The front end (interface) of the boiler simulator uses the SysCAD plant simulation package. The main screen of the boiler simulator (simulator front end) is shown in figure 1.

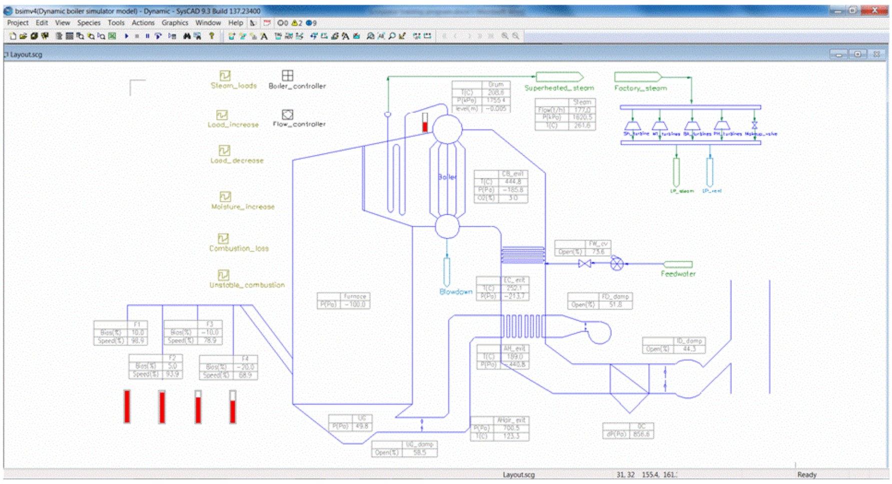

Figure 1 Boiler simulator main screen.

The main graphics screen (Layout.scg) shows a representation of a boiler with selected process variables from different parts of the boiler shown in tables. Pressing control-E opens up the explorer menu. Trends of selected process variables can be displayed by selecting the appropriate trend from this menu. Figure 2 shows the main graphics screen with the explorer menu open and the Openings, Drum and steam, Flows and Temperatures trends displayed.

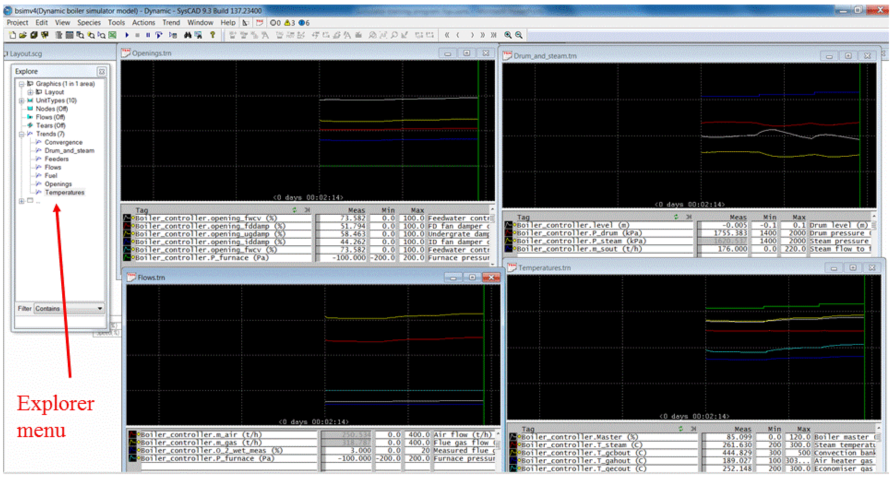

Figure 2 Boiler simulator main screen showing the explorer menu and the Openings, Drum and steam, Flows and Temperatures trends.

To clear the data from the trends, Project settings should be selected from the Edit pull down menu, the Historian tab selected from the resulting dialogue box and the Restart button as indicated in figure 3 selected.

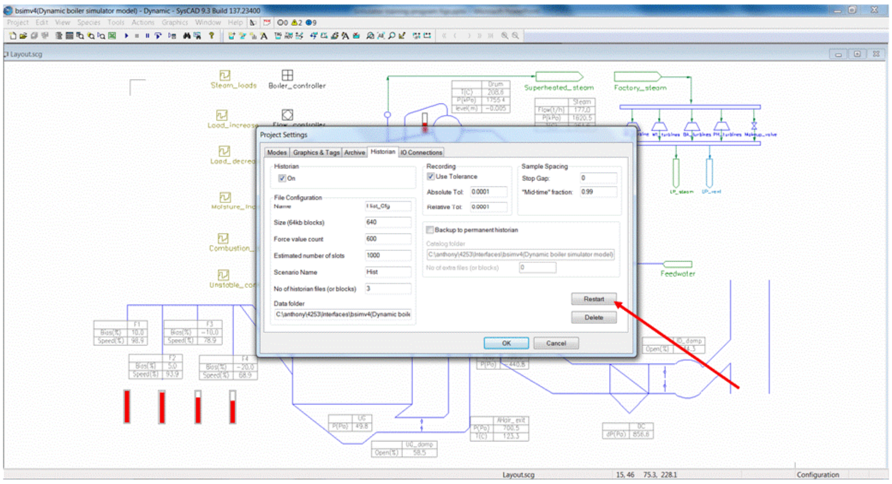

Figure 3 Boiler simulator main screen showing the explorer menu and the Project Settings dialogue box with the Historian tab selected. The location of the Restart button is indicated.

Boiler simulator scenarios

Sugar factory boilers are affected by a number of different factory operations such as changes in the steam flows to turbines and heating vessels, increases in bagasse moisture content, which often occurs when restarting the milling train after a stop, loss of combustion which can occur after a tube leak or poor fuel and unstable combustion which can occur with poor fuel and when the boiler steam output is very high. The training scenarios available in the simulator can be accessed by selecting

Command Scripts from the Tools menu to give the list of available scripts seen in figure 4.

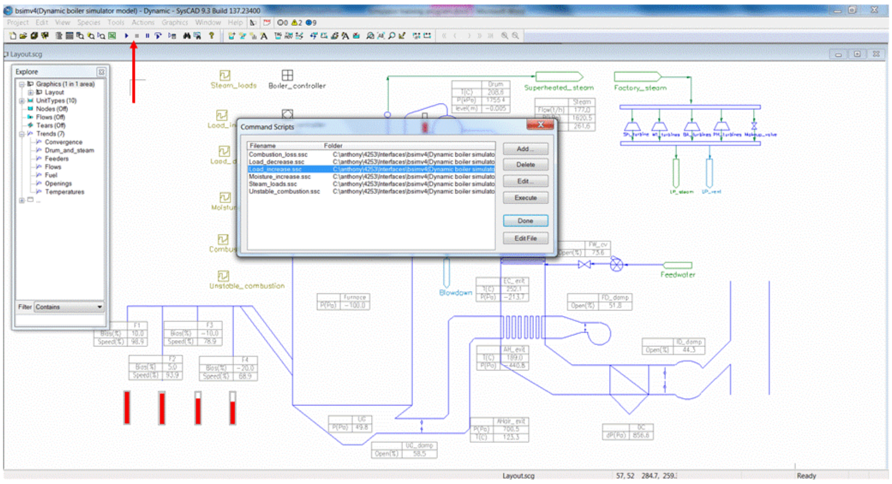

Figure 4 **Boiler simulator main screen showing the Command Scripts menu.**

Before executing any of the command scripts select the Drum_and_steam, Feeders and Temperatures trends from the explorer window. This will open the trend windows for Drum_and_steam, Feeders, and Temperatures. Clear any existing data from the trends by selecting the Restart button as shown in figure 3 and described in the text preceding figure 3. Note in figure 4 the small greyed out square that the red arrow points to. During a simulation this square becomes blue and a simulation can be stopped by clicking on this square.

Effect of steam load increase

Select the Load_increase.ssc file from the Command Scripts menu and then click on Execute. Allow the simulation to run for approximately 100 s. Note the simulations are in real time (the model takes 100 s to simulate 100 s of boiler operation time). Figure 5 shows the Drum_and_steam trend window, figure 6 shows the Temperatures trend window and figure 7 shows the Feeders trend window for the steam load increase scenario.

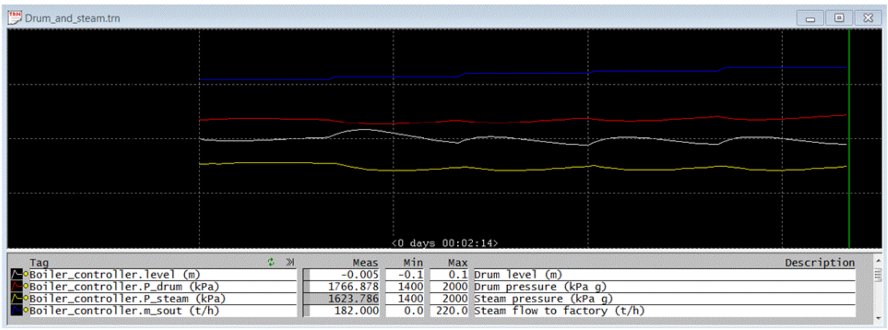

Figure 5 **Drum_and_steam trend window for the steam load increase scenario.**

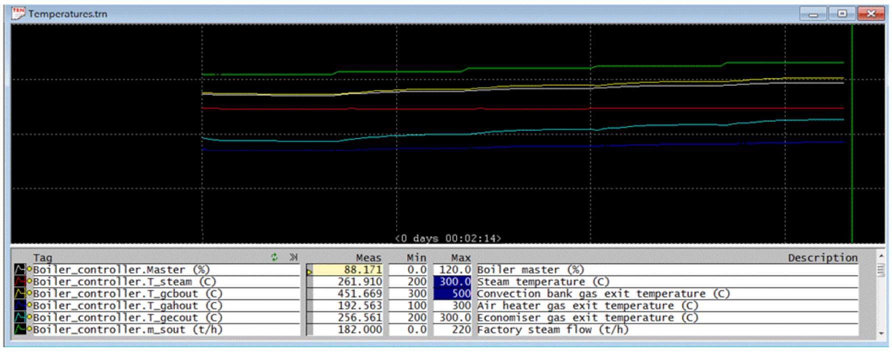

Figure 6 **Temperatures trend window for the steam load increase scenario.**

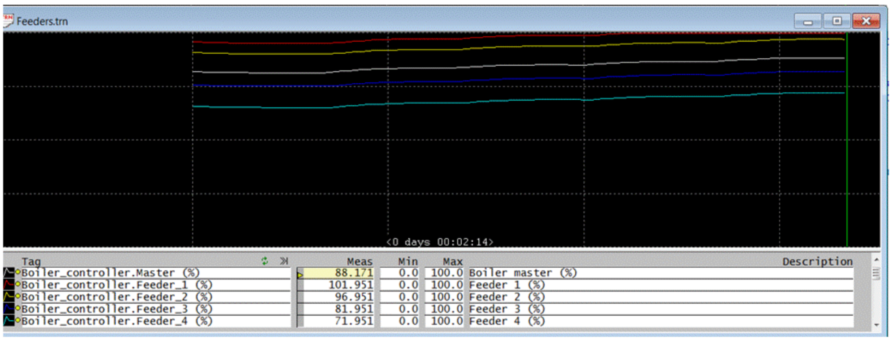

Figure 7 **Feeders trend window for the steam load increase scenario.**

The dark blue line in figure 5 shows the steam flow to the factory increasing at regular intervals. Note that as the steam flow to the factory increases, both the drum pressure (red line) and the steam pressure (yellow line) decrease and the drum level (white line) increases. The drum level increases because the lower drum pressure makes the bubbles under the water level (in the steam drum and in the boiler tubes) expand. This is known as 'swell'. Most boilers are set up to maintain a constant steam pressure so when the steam pressure reduces, the setting of the boiler master, which controls the speed of the feeders, increases. This increases the drum and steam pressure and reduces the drum level. This increase in the boiler master setting with increasing steam flow is shown by the green line in figure 6. Figure 6 also shows the convection bank gas exit temperature (yellow line) the air heater gas exit temperature (dark blue line) and economiser gas exit temperature (light blue line) increasing as the steam flow to the factory increases. The steam temperature (red line) stays relatively constant. Figure 7 shows the speeds of the four feeders increasing with the boiler master.

If the steam load increases very quickly it is possible the drum water level may get high enough to cause water droplet carryover into the superheater and factory turbines. Some boilers are set up to trip when the drum water level gets too high and some factories initiate emergency boiler blowdown.

Effect of steam load decrease

Clear any existing data from the trends then select the Drum_and_steam, Feeders and Temperatures trends from the explorer window select the Load_decrease.ssc file from the Command Scripts menu and then click on Execute. Allow the simulation to run for approximately 100 s. Figure 8 shows the Drum_and_steam trend window, figure 9 shows the Temperatures trend window and figure 10 shows the Feeders trend window for the steam load decrease scenario.

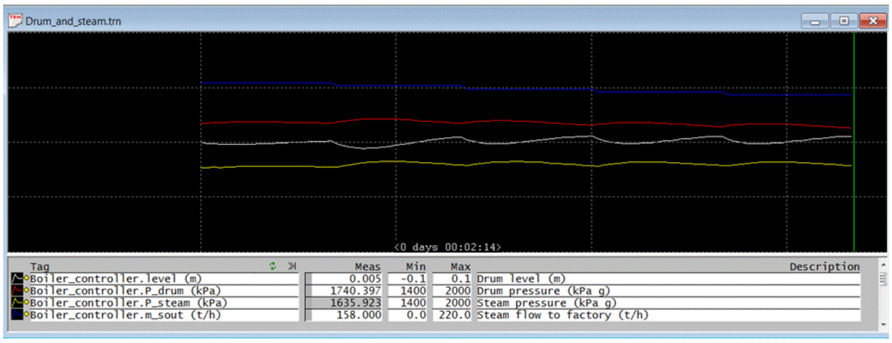

Figure 8 Drum_and_steam trend window for the steam load decrease scenario.

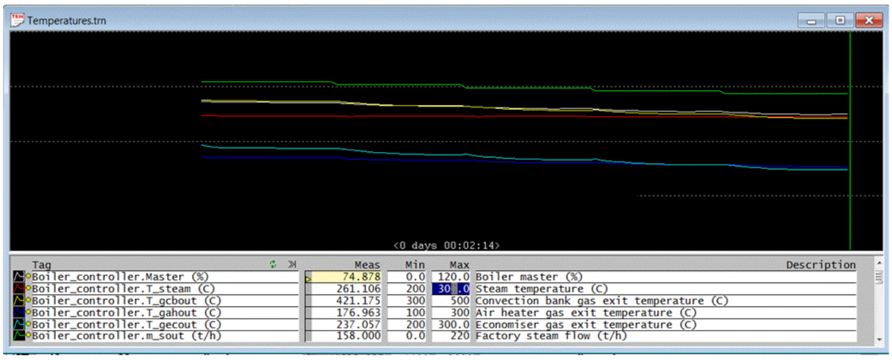

Figure 9 Temperatures trend window for the steam load decrease scenario.

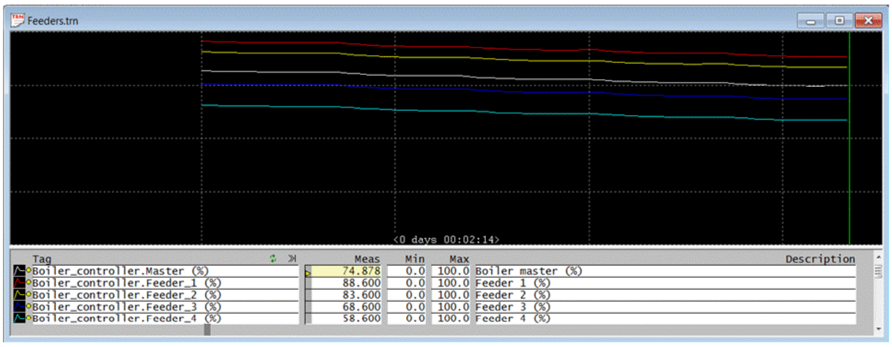

Figure 10 Feeders trend window for the steam load decrease scenario.

The dark blue line in figure 8 shows the steam flow to the factory reducing at regular intervals. Note that as the steam flow to the factory reduces, both the drum pressure (red line) and the steam pressure (yellow line) increase and the drum level (white line) reduces. The drum level reduces because the higher drum pressure makes the bubbles under the water level (in the steam drum and in the boiler tubes) contract. This is known as ‘shrink’. Most boilers are set up to maintain a constant steam pressure so when the steam pressure increases, the setting of the boiler master, which controls the speed of the feeders, reduces. This reduces the drum and steam pressures and increases the drum level. This reduction in the boiler master setting with reducing steam flow is shown by the green line in figure 9. Figure 9 also shows the convection bank gas exit temperature (yellow line) the air heater gas exit temperature (dark blue line) and economiser gas exit temperature (light blue line) reducing as the steam flow to the factory reduces. The steam temperature (red line) stays relatively constant. Figure 10 shows the speeds of the four feeders reducing with the boiler master.

If the steam load decreases very quickly it is possible the drum water level may get low enough to cause drying out of the top of boiler tubes and subsequent failure of these tubes. All boilers are set up to trip when the drum water level gets too low.

Effect of fuel moisture increase

Select the Fuel trend from the explorer window. Clear any existing data from the trends then select the Moisture_increase.ssc file from the Command Scripts menu and then click on Execute. Allow the simulation to run for approximately 120 s. Figure 11 shows the Drum_and_steam trend, figure 12 shows the Temperatures trend window, figure 13 shows the Feeders trend window and figure 14 shows the Fuel trend window for the fuel moisture increase scenario. Note that with this scenario it is assumed that the steam flow to the factory stays the same – see the dark blue line in figure 11.

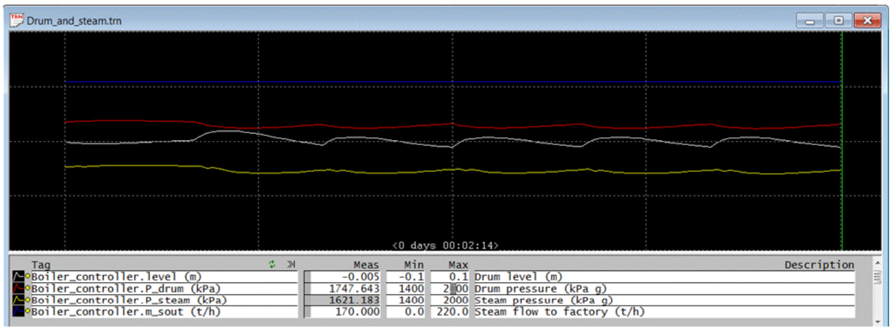

Figure 11 **Drum_and_steam trend window for the fuel moisture increase scenario.**

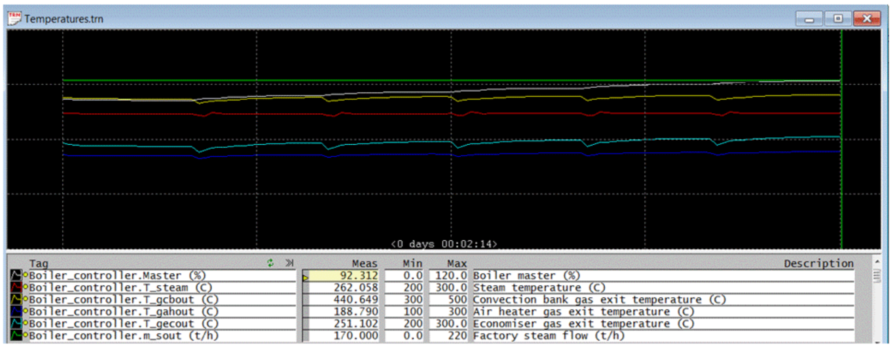

Figure 12 **Temperatures trend window for the fuel moisture increase scenario.**

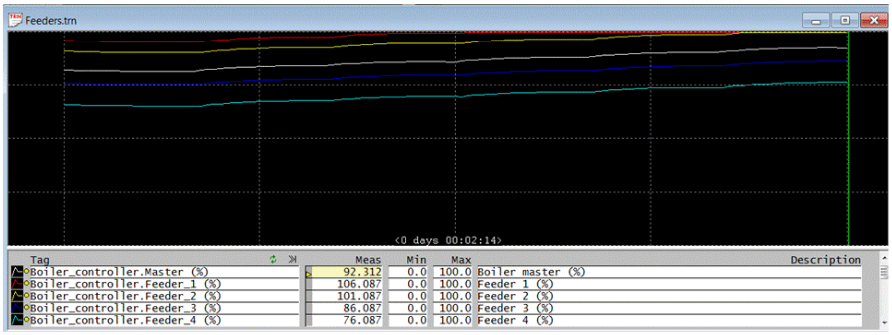

Figure 13 **Feeders trend window for the fuel moisture increase scenario.**

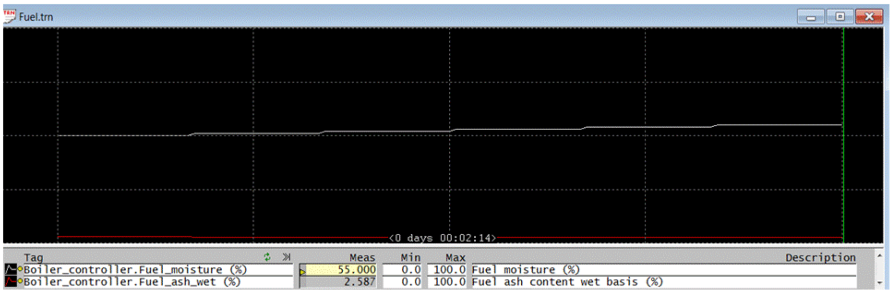

Figure 14 **Fuel trend window for the fuel moisture increase scenario.**

The fuel moisture increases from 50% to 55% are shown in figure 14 (white line). Corresponding to these fuel moisture increases are reductions in the drum (red line) and steam (yellow line) pressures seen in figure 11 and consequent increases in drum level (white line figure 11). Figure 12 shows that after each increase in fuel moisture, the boiler master increases to try to increase the steam pressure to its set point and there is a small dip in the steam temperature and all the gas temperatures. After the small dips in the gas temperatures the gas temperatures increase to temperatures slightly higher than the temperatures before the fuel moisture increase. After the small dips in steam temperature the steam temperature returns to the temperature it was before the fuel moisture increase. Figure 13 shows the feeders speeds increasing with the boiler master after each fuel moisture increase. When the fuel moisture content gets very high this increase in feeder speed will increase the amount of unburnt fuel on the grate. The boiler will often have to be put into manual so that the feeder speeds can be reduced and grate cleaning procedures initiated.

Effect of combustion loss

Select the Flows trend from the explorer window. Clear any existing data from the trends then select the Combustion_loss.ssc file from the Command Scripts menu and then click on Execute. Allow the simulation to run for approximately 100 s. Figure 15 shows the Drum_and_steam trend, figure 16 shows the Temperatures trend window, figure 17 shows the Feeders trend window and figure 18 shows the Flows trend window for the combustion loss scenario. Note that with this scenario it is assumed that the steam flow to the factory stays the same – see the dark blue line in figure 15.

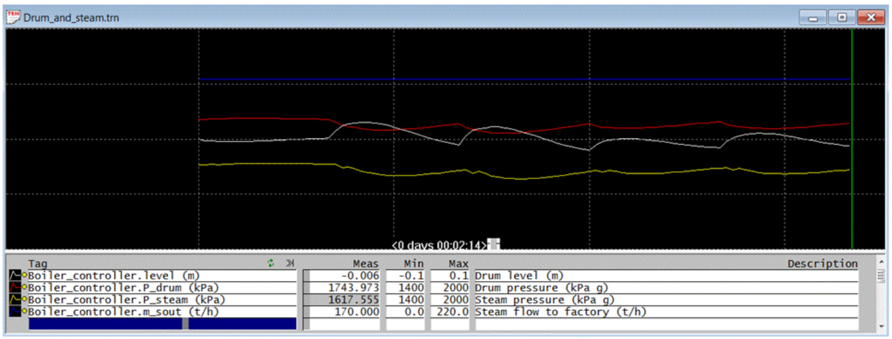

Figure 15 **Drum_and_steam trend window for the combustion loss scenario.**

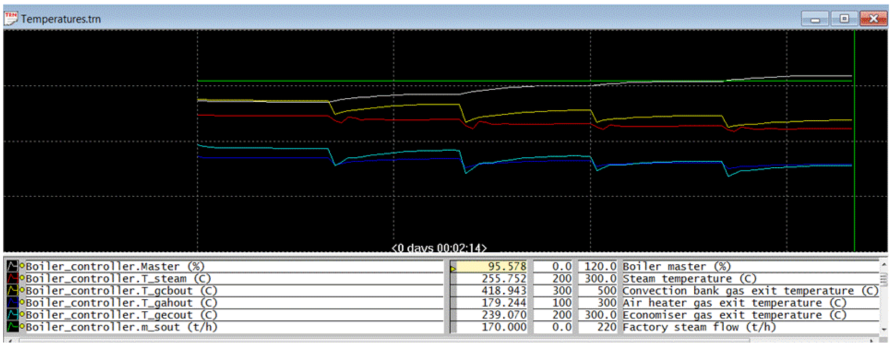

Figure 16 **Temperature trend window for the combustion loss scenario.**

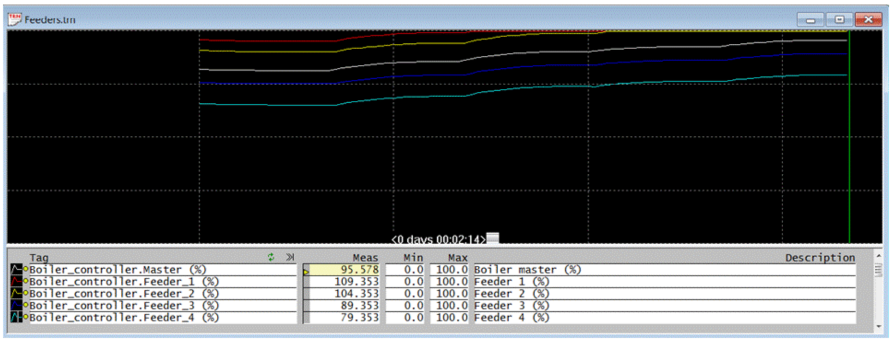

Figure 17 **Feeders trend window for the combustion loss scenario.**

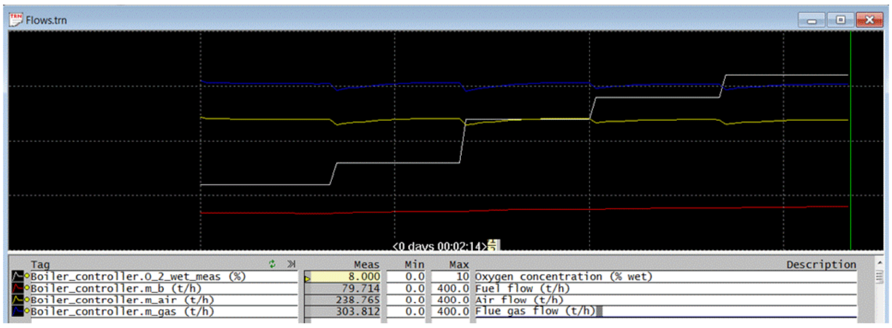

Figure 18 **Flows trend window for the combustion loss scenario.**

With a loss of combustion there is an increased build-up of unburnt fuel on the grate. Figure 15 shows that the drum pressure (red line) and steam pressure (yellow line) reduce and as a consequence the drum level (white line) increases. Figure 16 shows that the gas temperatures and steam temperatures reduce and the boiler master increases. This increases the speed of the feeders as seen in figure 17 which increases the amount of fuel entering the furnace. When there is a loss of combustion increasing the amount of fuel entering the furnace is usually counterproductive because there is often not enough heat to dry and initiate combustion of the fuel and the quantity of unburnt fuel increases. As seen in figure 18 the flue gas oxygen content increases because a lot of the fuel is not being burnt.

Usually the best response to a loss of combustion is to reduce the feeder speeds and initiate grate cleaning procedures.

Effect of unstable combustion

Select the Openings trend from the explorer window. Clear any existing data from the trends then select the Unstable_combustion.ssc file from the Command Scripts menu and then click on Execute. Allow the simulation to run for approximately 120 s. Figure 19 shows the Drum_and_steam trend, figure 20 shows the Temperatures trend window, figure 21 shows the Feeders trend window and figure 22 shows the Openings trend window for the combustion loss scenario. Note that with this scenario it is assumed that the steam flow to the factory stays the same – see the dark blue line in figure 19.

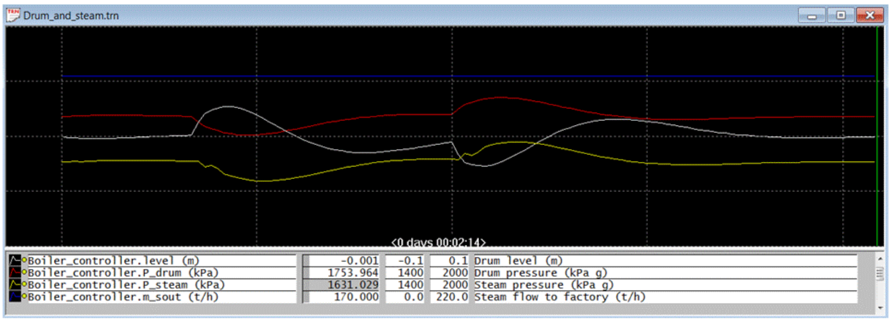

Figure 19 Drum_and_steam trend window for the unstable combustion scenario.

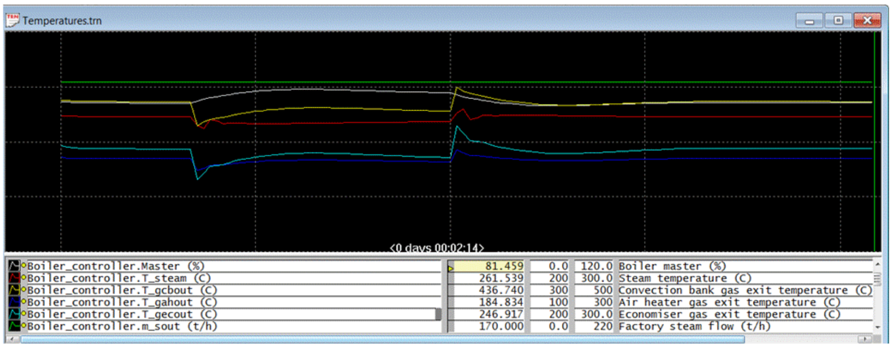

Figure 20 Temperatures trend window for the unstable combustion scenario.

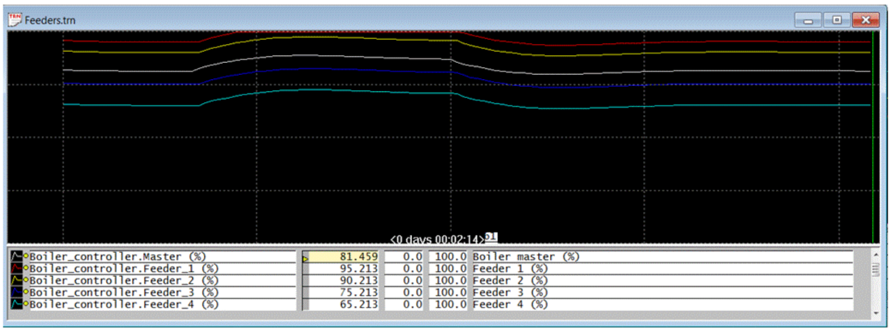

Figure 21 Feeders trend window for the unstable combustion scenario.

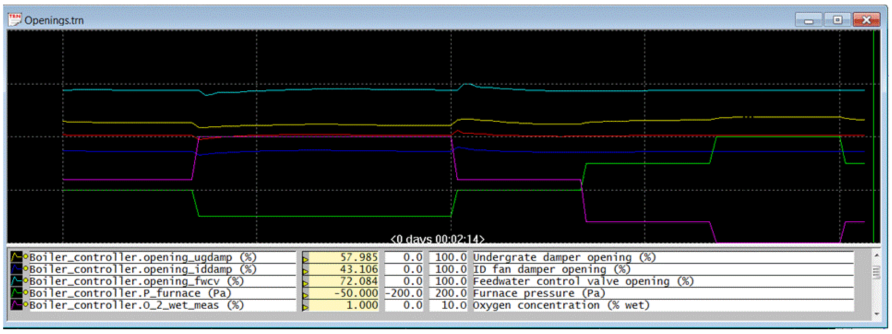

Figure 22 Openings trend window for the unstable combustion scenario.

With unstable combustion there is usually a cyclic build-up and subsequent burn off of fuel on the grate there is an increased build-up of unburnt fuel on the grate. When fuel is building up on the grate there is less heat generated in the furnace and therefore less steam generation – see the first dip in drum pressure (red line) and steam pressure (yellow line) and increase in drum level (white line) in figure 19. Around half way across the trend in figure 19 the drum and steam pressures increase and drum level reduces. This corresponds to the stage of combustion cycling where the fuel on the grate burns off.

The build-up and subsequent burn off of fuel on the grate correspond to reductions and subsequent increases in the gas and steam temperatures as seen in the trends in figure 20. Figure 21 shows that the boiler master and therefore the feeder speeds increase in the fuel build-up stage of the cycle and reduce in the burn off stage of the cycle. Figure 22 shows that in the grate build-up stage of the cycle the furnace pressure (green line) reduces and the flue gas oxygen concentration (purple line) increases. In the burn off stage of the cycle the furnace pressure increases and the flue gas oxygen concentration reduces.

Common responses to the onset of unstable combustion are to reduce the combustion air fraction to the grate and to reduce feeder speeds.