BOILER SIMULATION TOOL DEVELOPMENT

By

AP MANN
Queensland University of Technology
a.mann@qut.edu.au

KEYWORDS: Boiler simulation, Combustion, Safety, Training

Abstract
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. In some other industries simulation packages are an integral part of operator training, maintenance of skill levels and assessment of competence. Most of the training for sugar factory operators is on the job under the direction of a mentor and with assistance from peers. A simulation package that allows a trainee to test how changes in settings affect operations and for trainers to test how trainees respond to specific events without any risk is an ideal way to augment the usual on the job training.

This paper summarises the progress towards the development of a boiler simulator for the sugar industry.

Introduction
A highly skilled workforce is critical for the sugar industry to make the most of the opportunities and deal with the challenges posed by a changing world. Recent boiler 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.

Background
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 that 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 have 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 parameters (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 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 this is not possible for a new plant. 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 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 Queensland University of Technology (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 have to maintain production while doing their utmost to avoid catastrophic damage to boiler plant (Rodman and Banweg, 2013).

For boiler simulators or any other type of process simulators to work effectively, they 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 and users of these models need to be familiar with the heat transfer processes that occur in a boiler as detailed geometric information about all the heat transfer components is required for accurate predictions.

Computational fluid dynamics (CFD) is becoming 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, quite
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.

**Boiler simulator development process**

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. After performing the calculations, results are sent from the back end 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.

**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 simulator back ends. 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. Distributed control system (DCS) factory data was used in the development and evaluation of the back ends.

**Front end development**

A generic user interface will be developed 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. The plan is to include a training program as part of the simulator front end. Industry input will be sought to determine the scenarios to be included in the training program.

**Deployment**

In this final stage of the work the simulator with the generic interface and training program will be demonstrated to some boiler operators at a workshop and any feedback received will be used to improve the model and interface.

**Progress to date**

The work up until this point has focussed in identifying industry priorities and developing the boiler simulator back ends.

**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.

**Model development**

In this work sub-models for the different boiler components (furnace, screen, superheater, convection bank, economiser, flue gas air heater, water air heater and steam drum) were combined into back ends for the gas/air and water/steam sides of a boiler.

The heat transfer calculations used by the back ends were in most cases simplified versions of widely used boiler design models (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 ends are mostly written in VBA as part of a Microsoft Excel spreadsheet. These models can be transferred to SysCAD when the generic interface is developed in the next stage of the project. It should also be possible transfer these back ends, or at least elements of these back ends, 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 ends were evaluated by comparing the values of selected process variables predicted by the boiler simulator back ends 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.

**Comparisons with factory DCS data**

The boiler simulator back ends were used to predict a number of process variables using the steam flows from the factory DCS data as inputs. Figure 1 shows the logged variation of steam flow and convection bank gas exit temperature and the convection bank exit temperature predicted by a boiler simulator back end, over a time period of 100 minutes. Figure 2 shows the logged variation of steam flow and economiser gas exit temperature predicted by a 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 Figure 1 and Figure 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.

Figure 3 compares the logged variation of induced draft (ID) fan speed with the variation of flue gas flow predicted by a 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.
Fig 1—Logged variations of steam flow and convection bank (CB) gas exit temperatures and the convection bank gas exit temperature predicted by a boiler simulator back end.

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

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

Unfortunately, at the time of writing of this paper, the water/steam side back end was not predicting the drum pressure and level trends in the DCS data, and the approach based on the Kim and Choi (2005) needs further refinement for better prediction of steam drum variations. It is likely
that elements of other models (Äström and Bell, 2000; O'Kelly, 2012) will need to be incorporated into the water/steam side back end for improved predictions.

**Conclusions**

Sugar factories depend on boiler operators for reliable crushing operations and simulators can make an important contribution to improving and maintaining their skill levels. The simulator development process described in the paper is an important part of the investment the industry can make in its only long term sustainable competitive advantage – its people.

**Acknowledgements**

The input from the respondents to the boiler operator and industry surveys and the industry workshop participants is greatly appreciated. Peter Mitchell from Mackay Sugar is acknowledged for supplying the DCS data used to evaluate the simulator back ends and Mackay Sugar is acknowledged for allowing publication of some of that data. The support for this work from the People and Safety Committee of the Australian Sugar Milling Council and the funding support of Sugar Research Australia are gratefully acknowledged.

**REFERENCES**


