Modelling of Boiler Drum Level Control using Flownex Software Environment

MR LOUIS VAN DER WESTHUIZEN, PROF IGOR A. GORLACH
Mechatronics Department
Nelson Mandela University
Gardham Avenue, Summerstrand, Port Elizabeth, South Africa
SOUTH AFRICA
s214009246@mandela.ac.za , Igor.Gorlach@mandela.ac.za

Abstract: - Power plants are critical in producing the electricity required by modern society. In the majority of countries in the world, including South Africa, the primary sources of electricity are fossil fuel power generation plants. A rapidly increase share of renewable generation places huge demands on conventional coal-fired power plants. The inherent variability of renewable energy sources implies that coal-fired plants designed for continuous base load production must now be used for variable load. This can have negative effect on the overall efficiency and life expectancy of these plants. The challenge is, therefore, to balance the network demands with the power station operation, its thermal efficiency, availability and extended plant life expectancy. Hence, the main focus of the current research is on the efficiency of the boiler operation and control through modelling of the boiler subsystems, the processes and simulating various operating conditions, which include fluctuation loads, trips and other important scenarios. In this paper, a model of the boiler drum is presented. The model was developed using Flownex simulation environment software, consisting of the thermo-fluid model as well as the control system model, which are seamlessly integrated providing an efficient tool for design and analysis. The developed model allows to predict behaviour of the boiler and its subsystems and observer fluctuations of the critical process parameters, as well, as to perform a sensitivity analysis and to assist control engineers to improve the plant efficiency.

Key-Words: - Power generation, boiler control, boiler modelling

1 Introduction

A power generation plant consists of two main sub-systems: the boiler and the steam turbine-generator. The boiler (or steam generator) is responsible for burning the fuel in a controlled manner and capturing the heat energy using a system of circulating water and steam. The turbine then converts the energy captured by the steam into mechanical rotation, and finally into electrical energy by means of the generator. The fuel and air/flue gas circuit is an open circuit that is concentrated around the boiler, while the steam and water circuit is a closed circuit between the boiler and turbine and acts as the working fluid within the Rankine cycle. The evaporation of water takes place in two types of boiler arrangements: once-through boilers and steam-drum boilers, Fig. 1. In steam-drum boilers, the boiler drum is used as the point at which water and steam are separated. Water at the bottom of the boiler drum passes through tubes along the walls of the furnace. The convection currents in the feed-water caused from heat expelled due to the combustion of coal allows steam to rise from the bottom of the tubes through the top of the furnace and back into the boiler steam drum.

The efficiency of the boiler and its control system has been the subject of research for decades and reported in [1-9]. The efficiency of a boiler depends, among other factors, on the control strategy. There are a number of critical process parameters that influence the boiler performance, which include the boiler drum level, the steam pressure, temperature and flow rate, the furnace pressure, the residual oxygen in flue gas, the MW load, etc. These parameters are constantly monitored in order to assess the health of and efficiency of the boiler and auxiliary systems. The parameters in the boiler are categorised within hierarchical control, which establishes various high or low levels of control between the interrelating systems. For example, the boiler drum level parameter provides an input for the boiler control system, and, hence, determines the combustion process parameters as well as the feed-water flow rate.

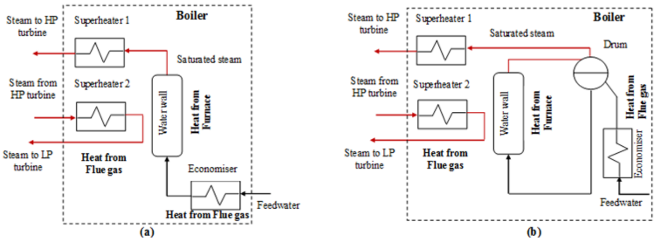

Fig.1 - Diagrams of a) once-through boiler, b) steam-drum boiler with natural circulation

The feed-water control system provides the appropriate amount of feed-water to the boiler to match the evaporation rate, essentially ensuring that the mass flow of feed-water into the boiler is equal to the mass flow of steam leaving the boiler. However, the control task is complex and the main focus of the control is rather to maintain the boiler drum level within a small operating range about its set point through actuation of the feed-water control valves and variable speed pumps, and to initiate a boiler trip if the drum level goes above or below its safe operating levels.

The control of the boiler drum level is challenging because of the many interactions that occur within the boiler system, and that the effects of these interactions are greater or smaller at various points in the boiler's load range. The level measurement itself is complicated by the inverse response transients to rapid changes in the steam rate (load demand), known as shrink and swell. During a rapid load increase, the governor valves increase the flow of steam into the turbine, which uses stored energy from the boiler and causes the drum pressure to drop. At the same time, the firing rate is increased in order to meet the load demand and additional radiant heat energy is absorbed in the water walls.

As a result, the water density in the drum is lowered and there are more steam bubbles present, each of which occupies a larger volume than before the load change. Consequently, the volume of water in the drum increases or 'swells', which implies a reduction in feed-water flow is required while in fact the opposite is true. Similarly, with a rapid decrease in load, the drum pressure increases while the firing rate decreases, resulting in fewer bubbles that each occupy a smaller volume. The boiler drum level then drops or 'shrinks', implying a requirement for increased feed-water flow while the opposite is true. These effects are particularly significant in boiler drum that operate at lower pressures, as well as being influenced by the design of the internal drum layout. The actual controller for the boiler drum level control can be of several configurations, of which a three-element controller with a cascaded-feedforward control loop is the most common, Fig. 2.

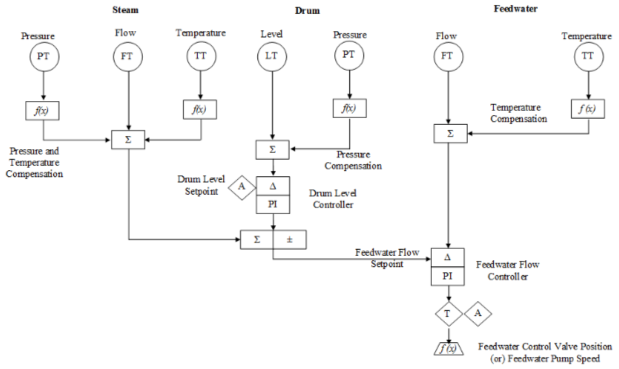

Fig. 2 - Control of a boiler drum level

The control applies either proportional or proportional-plus-integral action to the drum level (where the use of the integral action may not be necessary owing to the inherent integrating action of the drum itself). The steam flow rate measurement is used as a feedforward signal and summed with the drum level error. This output is cascaded into the inner control loop as the demand set point for the feed-water flow rate. The error between the feed-water demand signal and actual flow is processed by a controller. The manipulated variable (output) is the feed-water correction signal – either a signal for control valve position regulation or for pump speed control. This three-element control logic was used in modelling of the boiler drum level control as describe in the following section.

2 Modelling

The boiler drum model, consisting of a thermo-fluid and control models, was developed using Flownex®, which is a one-dimensional simulation software package. The boiler drum dimensions and the process parameters were modelled based on a real boiler drum, Table 1.

The thermo-fluid model of a boiler drum with a natural water circulation is shown in Fig. 3. The heat generated from the combustion of pulverized coal in the furnace is transferred to the riser tubes which evaporates the water. The evaporated water results in a change of density with that of the water in the boiler drum, thus causing a natural circulating flow. Accordingly, the evaporated water-steam mixture re-enters the lower part of the boiler drum. Depending on the load demand required, steam flows from the top of the boiler drum accordingly. Consequently, due to change of steam flow leaving the boiler drum, the water level in the drum changes. The feed-water is then altered in order to maintain a steady water level. Flow resistance components are used to represent the streams flowing into and out of the drum. Boundary condition components are connected to the two phase drum which are used to specify mass flow, temperature and pressure. An important input parameter of the two-phase tank is the connection specification of the streams to and from the drum. A specific height fraction is used to specify the height of the inflow and outflow components of the boiler drum.

Design Parameters and Operating Conditions	
Drum Pressure	8500 kPa
Drum Volume	40 m^3
Drum Diameter	2 m
Steam Mass Flow	50 kg/s
Steam Temperature	299.78 □C
Feed-water Mass Flow	50 kg/s
Feed-water Temperature	35 □C
Down comer Volume	11 m^3
Down comer Mass Flow	100 kg/s
Riser Volume	37 m^3
Riser Mass Flow	100kg/s
Drum Water Level	1.067
Drum Steam Quality	0.051

Table 1 - Model design parameters

Furthermore, the initial conditions of feed-water and steam flow are specified as 50 kg/s with a feed-water temperature of 35^{0}C. A fixed mass flow of the down comer is specified as 100 kg/s. A heat input of 130 MW is specified inside the riser flow resistance component to simulate the heat transfer from the combustion of pulverized coal.

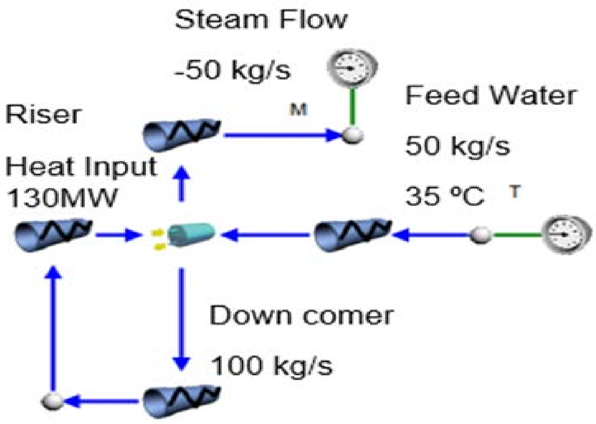

Fig. 3 - Thermo-fluid boiler drum model

3 Control

Three control models of the boiler drum level control were developed. Certain boiler systems incorporate single-element control when steady load or low load conditions are utilised. Single-element control is used in boilers during startup however single element proves unsatisfactory as newer boilers have a minimum water storage in the boiler drum compared to that of the steam flow rate. Larger sized boilers with significant load fluctuations required higher level control methods. Two-element control, which uses the measure of steam flow and drum level to control the feed-water valve is able to handle boiler systems with slightly greater load fluctuations. Larger units with small storage capacity related to throughput, and units experiencing severe, rapid load swings, usually require three-element controls, whereby water flow is matched with steam flow and reset from the drum level signal.

3.1 Single Element Control

Single-element control is the simplest form of control method in which the method only uses boiler drum level measurement for control and consists of a simple feedback loop, Fig. 4. This control method controls the feed-water control valve, altering the amount of feed-water depending on the variation of the drum level from the set point. The control output can also include the feed-water pump speed or a combination of both pump speed and feed-water valve fraction opening.

The implementation of single-element control receives a signal from the level transmitter specifying the boiler drum water level this forms as the process variable. Using proportional-plus-integral-plus-derivative control, the drum level is compared with that of the drum level set point. The control output is then modified to either increase or decrease the mass flow of feed-water to the boiler drum accordingly.

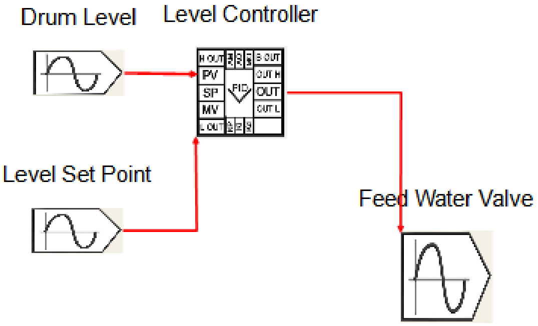

Fig. 4 - Single-element feedback control logic

3.2 Two-Element Control

Two-element control uses the addition of steam flow with that of drum level measurement. Two-element control uses a feedback loop by incorporating a proportional controller, Fig. 5. This control method uses the steam mass flow as a feedforward control measure. The measurement of steam mass flow is summed with that of the output from the proportional level controller. The steam flow adjusts the feed-water control valve based on steam flow signal and the drum level controller signal. The output of the summed signal from the level controller and that of the steam flow measurement is used to regulate the control output accordingly. In ideal conditions, the feed-water flow is equal to that of the steam flow, thus ensuring a steady drum level.

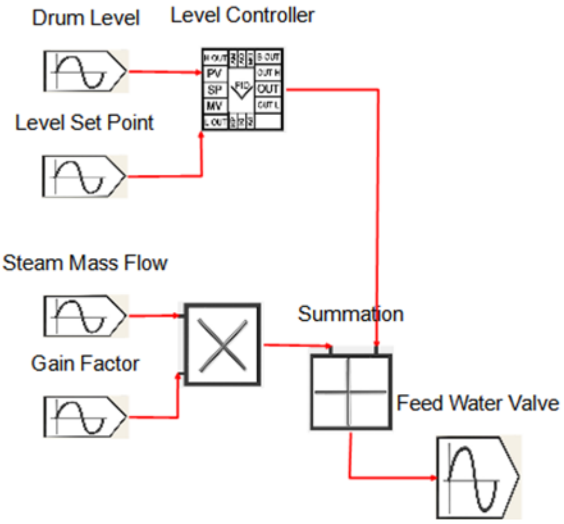

Fig. 5 - Two element feedforward control logic

3.3 Three-Element Control

As described, the three-element control utilises the measurements of steam mass flow, feed-water mass flow as well as boiler drum level. The control method makes use of simplistic cascade feedforward control using proportional-plus-integral-plus-derivative controllers, Fig. 6. Three-element control typically consists of two controllers, namely a level controller and a feed-water controller. The level controller receives signals from the level transmitters specifying the boiler drum water level as well as the drum level set point. The output of the level controller is then summed with that of the rate of change of steam mass flow.

The rate of change of steam flow forms as an anticipation signal to increase the response time of the control output as well as the accuracy of the process variable. The summed signal of the level controller and rate of change of steam mass flow forms as the set point to that of the feed-water controller. The feed-water mass flow rate is passed to the feed-water controller as the process variable. Using proportional-plus-integral-plus-derivative control, the control output is adjusted accordingly to increase or decrease the required feed-water mass flow for maintaining a steady drum level.

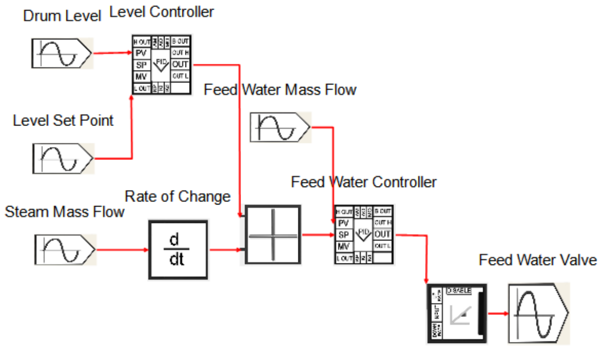

Fig. 6 – Three-element cascade feedforward control logic

3.4 Controller Tuning

The Ziegler-Nichols method is used to fine tune proportional-plus-integral-plus-derivative controllers used in both one element and three element control as well as a proportional controller used in two element control. The Ziegler-Nichols method is used to determine the parameters of controllers, namely the controller gain, Kp, integrator time constant, Ti, and the derivative time constant, Td. The Ziegler-Nichols method works by generating a process variable response curve due to a step change in the control output.

As illustrated in the Fig. 7, the control output is therefore increase by 10% from an initial condition of 50kg/s. The step change generates a response curve of the process variable (drum level) which allows for the tuning of controllers.

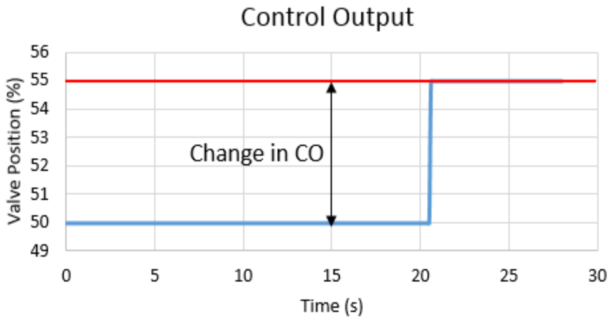

Fig. 7 – Change in control output for controller tuning

Fig. 8 illustrates that with a 10% step increase in the control output, a 0.1374% increase in the process variable is produced.

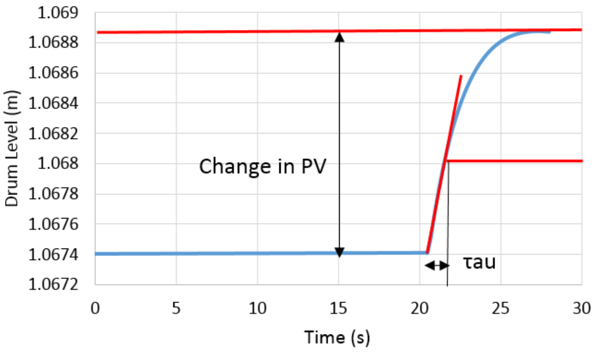

Fig. 8 – Process variable response curve

Furthermore, the response curve of the process variable can be used to determine both the dead time and time constant of the system in order to calculate controller parameters.

The dead time of the system is the measured time from which the change in the control output occurs until a tangent line on the response curve intersects the original level of the process variable. Similarly, the time constant is measured by calculating the difference from the time intercept to that of 63% of the process variable change. By performing the required measurements in order to determine the dead time and time constant provided by the response curve, it is found that the system has a dead time of 0.4 s and a time constant of 1.45 s. Using the information gathered from the response curve, the process gain can be calculated as:

$$gp = \frac{change\ \ in\ process\ \ variable\ \ \%}{change\ \ in\ control\ \ output\ \ \%} \qquad (1)$$

With the use of Equation 1, it was found that the process gain measured 0.01374.

Since the process gain, dead time and time constant is known, Ko can be determine using the equation below in order to calculate controller parameters.

$$K_o = \frac{\tau au}{\tau_d \times gp} \qquad (2)$$

Using Equation 2, Ko is calculated to be 263.828. By calculating the value of Ko the table below can be used to determine the parameters of various controllers, which include P, PI and PID controllers.

	K_p	T_i	T_d
P	K_o		
PI	$0.9K_o$	$3.3\tau_d$	
PID	$1.2K_o$	$2\tau_d$	$0.5\tau_d$

Table 2 – Design Parameters

4 Control Set Point Monitoring

In order to analyse the performance of the control system, the control set points, for example, the boiler drum level, and the behaviour of the mechanical actuators (pumps and valves) are monitored.

The proposed condition monitoring algorithms include the behaviour of mechanical actuators and process variables. These parameters include the duty cycle of mechanical actuators, the total percentage movement of the process variable and mechanical actuators associated with the particular process variable as well as the set point of the system. Additionally, the accuracy of the process variable can be measured to that of the set point regardless of the set point fluctuation.

The plant condition monitoring algorithms give a better understanding of how various control systems operate in different transient states. The primary focus on control systems is to develop a form of control that can reduce process variable fluctuations, thus increasing accuracy as well as reducing the duty cycle of mechanical actuators associated with that of a specific process variable. By reducing the process variable fluctuations as well as the duty cycle of mechanical actuators, the efficiency of the plant can be drastically increased.

The algorithms used to measure the duty cycle of mechanical actuators, accuracy and total percentage movement of process variables are given in the equations below.

The equation below illustrates the calculation of the duty cycle of an actuator which is denoted as the fraction for which an actuator is active during a specific cycle time.

$$Duty\ Cycle\ (\%) = \frac{Active\ \ time}{Total\ \ cycle\ \ time} \times 100 \qquad (3)$$

The total percentage movement of the process variable is calculated using the equation below where Xi denotes a reading of the process variable over a number of iterations denoted as n.

$$Total\ Movement\ (\%) = \sum_{i=1}^{n} |X_i - X_{i+1}| \qquad (4)$$

The accuracy of the process variable to that of the set point is calculated using the equation below. The equation calculates the difference between the process variable and the set point such that Yi and Xi denote the reading of the set point and process variable values respectively. If the absolute difference between the process variable and set point fall within upper and lower specified control limits the value of the process variable holds true for a specific range, n.

$$Accuracy\ (\%) = \frac{n-(LCL<\sum_{i=1}^{n}|Y_i-X_i|<UCL)}{n} \times 100 \quad (5)$$

Equations 3-5 will be used to analyse the performance of one element, two element and three element boiler drum level control.

5 Results and discussion

For research and study purposes, the initial conditions specified in the model are not related to actual plant data measurements. This allows the user to study varying scenarios and execute the model and an engineering simulator in order to study various performances of control systems.

By running a simulation of the boiler drum, a transient scenario of each control method are tested. Each transient scenario includes a steady set point specifying a drum level of 1.1 m.

Each control system will be aimed at maintaining a steady drum level set point where by the relevant performance measures will be analyzed.

The performance of various drum level control systems are monitored using a steady drum level set point of 1.1m. An initial drum level of 1.067 m is obtained due to initial conditions implemented in the thermo-fluid model as previously mentioned. All three-control systems are tested against a noise disturbance of steam flow fluctuating around 5% of the initial condition specified as 50 kg/s.

Figs. 9-12 show that the simulation results of the drum level using the three types of control, which indicates that the control system model proves empirically correct as the trends follow relevant direction and magnitude. It is clear as to how each control system performs differently due to the addition of control measurements. Additionally, the actual plant data is provided to illustrate the performance of the various control systems to that of the plant.

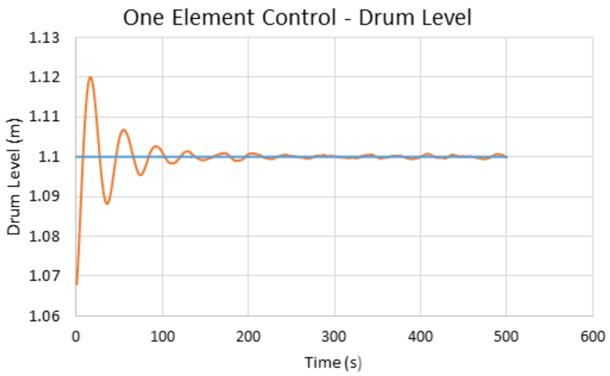

Fig. 9 – Drum level using single-element control

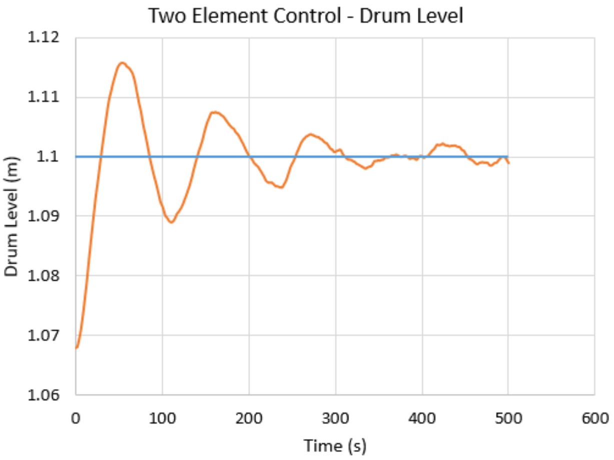

Fig. 10 – Drum level using two-element control

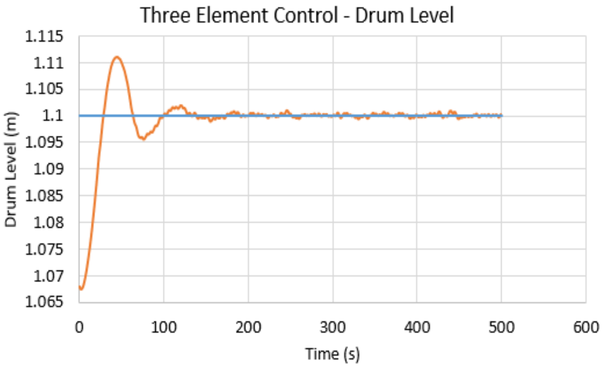

Fig. 11 – Drum level using three-element control

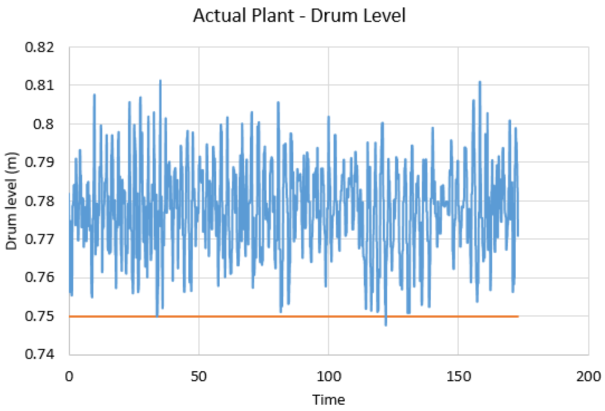

Fig. 12 – Drum level of actual plant data

Table 3 includes the relevant performance measures acquired by each control system. The results show that while one element control has a fast response time, a significant overshoot is present compared to that of three element control.

Additionally, it can be noticed that there are rapid changes in the process variable when using two-element as well as three-element control. This phenomenon can only be caused due to the addition of steam mass flow as feed forward control. Since the steam mass flow has a noise disturbance fluctuation of 5%, the disturbance is partly present in the process variable. Although present, three element control is able to maintain a minimal steady state error.

	Single-Element	Two - Element	Three-Element
Response Time (s)	5.6	20.1	17.7
Overshoot (%)	1.99	1.15	1.01
Settling Time	57.6	163	76.1
Undershoot (%)	0.88	1.1	0.56
Peak Time (s)	18.2	56.1	46.5

Table 3 – System performance parameters

In addition to analysing the various control systems from a controls perspective by measuring the response time and percentage overshoot. The performance of the control output is also studied to determine the reliability of each control system.

The reliability of a control system can be determined by studying the parameters of the control output associated with its direct control action. These parameters include the duty cycle and total percentage movement of the control output.

The reliability of a mechanical actuator is directly associated with that of its movement. Therefore, by decreasing the duty cycle and total movement of the actuator, the wear on the mechanism is decreased. By decreasing wear on mechanical components, downtime and maintenance is decreased which directly relates to cost saving and efficiency.

The parameters that are studied include the duty cycle, total percentage movement of the control output, process variable accuracy to that of the set point and the total percentage movement of the process variable.

As mentioned previously, the duty cycle is a measure of the active time of the control output relative to the total cycle time. However, since the control output is constantly fluctuating, specified bounds are required in order to determine the difference between an active state and an inactive state of the process variable. Therefore, during each iteration of the drum model, the control output is regarded as active if the difference between the current and previous state is greater than 0.01 kg/s using a time interval of 0.1 s.

The various control systems show significant differences in the performance of the control output, evidently illustrated in Figs. 13-16.

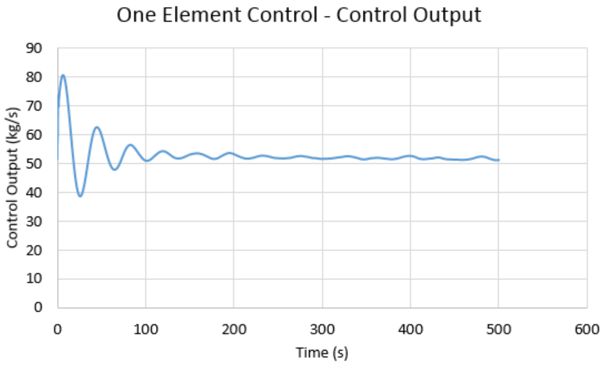

Fig. 13 - Control output using single-element control

Figs. 13-16 show that the various control methods have different trends in altering the control output in order to maintain a steady process variable. The performance parameters obtained from each control system are tabulated in the table below.

It is evident that the behavior of the control output associated with each control system is directly related to that of the performance of the process variable.

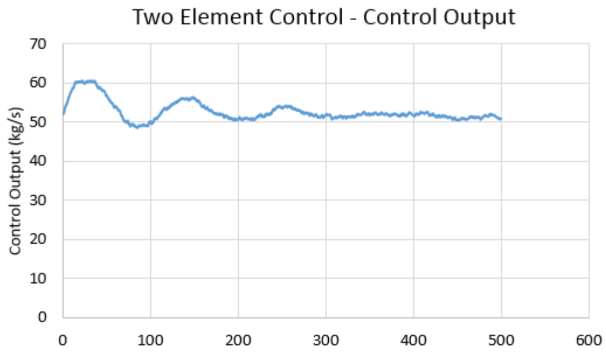

Fig. 14 - Control output using two-element control

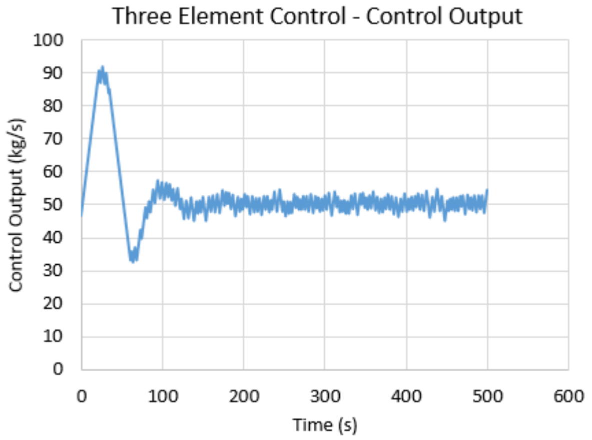

Fig. 15 - Control output using three-element control

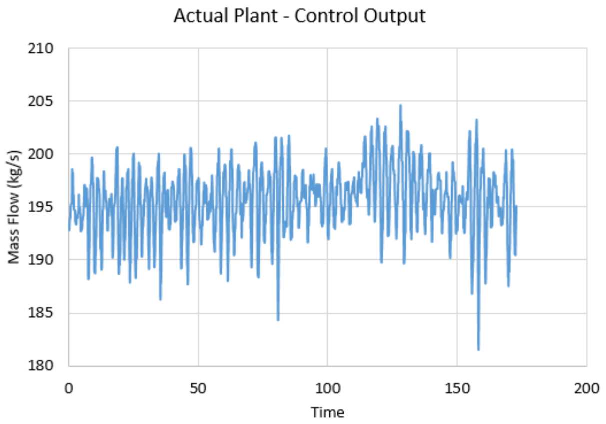

Fig. 16 - Control output of actual plant data

The use of single-element control produces large fluctuations in the control output during the response time of the system. Once the system reaches a steady state, the fluctuation of the control output is minimal since the control has a duty cycle of 35.17% and a total movement of 159.78% outperforming that of two-element and three-element control.

Again, the implementation of steam mass flow as a feed forward signal in the control system has a significant effect of the performance of the control output. This is evident as the duty cycle and total movement of the control output is significantly greater than that of one element control.

The performance parameters of each control system and that of the actual plant are obtained using condition monitoring algorithms. As previously discussed, these algorithms include the duty cycle of the control output, the total movement of the process variable (Total PV Move) and control output (Total CO Move) as well as the accuracy of the process variable (drum level) to that of the set point denoted as PV Accuracy. The above-mentioned parameters are illustrated in Table 4.

	Single-Element	Two-Element	Three-Element	Actual Plant
Duty Cycle (%)	35.17	99.46	99.7	66.94
Total PV Move (%)	7.66	6.85	8.26	296.4
PV Accuracy (0.5 %)	97.47	93.58	93.42	7.82
Total CO Move (%)	159.78	393.23	993.04	300.17

Table 4 – Condition performance parameters

Comparing the performance parameters of the Flownex model to that of the actual plant data it is found that the process variable has significantly less fluctuations in the model to that of the actual plant. Additionally, it is found that the actual plant performs significantly worse in terms of process variable accuracy to that of the set point. The results generated by the condition monitoring algorithms prove that the actual plant is only able to maintain the process variable to within 0.5% accuracy with a mere 7.82 % of the total cycle time.

4 Conclusion

In order to evaluate the performance of boiler sub-systems, in this research, a Flownex model of the boiler drum was created. The developed model includes thermo-fluid, control system elements and parameters of a real power plant boiler drum. Three control strategies, as well as control tuning were applied and analysed. The results of simulations of the boiler drum operating conditions were compared with the real power plant data and found to be in good correlation, especially with the three-element control logic of the boiler drum level.

As mentioned, the primary focus in developing control systems is to eliminate rapid fluctuations in the control output in order to increase plant efficiency. Three control structures for boiler drum level control were developed and tested against each other. The developed model clearly illustrates how changes in the control parameters affects the control behaviour. Using condition monitoring algorithms, the results for each control system are obtained in Table 4. Table 4 clearly illustrates that regardless of the extensive use of control measures, single-element control out performs the three-element controller in terms of the duty cycle of the control output, PV accuracy and the total % movement of the control output. Table 3 illustrates that although the three-element controller obtains little overshoot and a fast response time, the increased duty cycle and total movement of the control output causes increased wear on mechanical components such as the feed-water valves and pumps. Thus decreasing the plant life cycle.

The developed model allows to predict behaviour of the boiler and its subsystems. This allows control engineers to observe fluctuations of the critical process parameters, as well, as to perform a sensitivity analysis and to assist control engineers to improve the plant efficiency.

References:

[1] Dukelow, S. G. (1991). The Control of Boilers (2nd rev. ed.). USA: ISA - Instrumentation, Systems and Automation Society.

[2] Feltas, J. (2004). Boiler Effects on Steam Turbine Response. New York: Power Tech. Inc.

[3] Gilman, G. J. (2005). Boiler Control Systems Engineering. USA: ISA - Instrumentation, Systems and Automation Society.

[4] Ruano, A.E. (2005). Intelligent Control Systems using Computational Intelligent Techniques, UK: Lightning Source UK Ltd.

[5] Wang, L. (2013). The Application of Fuzzy Neural Network to Boiler Steam, IJCSI International Journal of Computer Science, 10(1), 3.

[6] Tanwar, P. (2010). Boiler Furnace Pressure Excursion and Set Points, International Journal of Computer Applications, 1(12), 15.

[7] Kristinsson, H. and Lang, S. (2010). Boiler Control - Improving Efficiency of Boiler Systems, Lund University, Lund.

[8] Morilla, F. (2012). Benchmark for PID control based on the Boiler Control Problem, Escuela Técnica Superior de Ingeniería Informática. UNED, Madrid.

[9] Archay, H. (2015). Condition Monitoring and Performance Optimisation of Vertical Spindle Type Mills, University of the Witwatersrand, Johannesburg.

[10] Rajkumar, T. (2013). Boiler Drum Level Control by Using Wide Open Control with Three Element Control System, International Journal of Scientific & Engineering Research, 4(5), 207.

[11] Lindsley, D. (2008). Power Plant Control and Instrumentation. UK: Lightning Source UK