Lab Scale Boiler Setup for Process Control Research and Education

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Abstract: Natural circulation steam boilers are extensively used in process and power plant industries. Availability and performance of these boilers are critical for respective process/power plants and hence are typically designed and controlled conservatively. Currently with increased focus on flexibility and cost efficient performance, advance control and optimization methods and algorithms are explored both in academia and industrial research. However, majority of these studies are limited to simulation-based, with almost zero operational data to validate the improvement based on the advancement in controls technology. Goal of our work is to bridge this gap by providing a unique innovative laboratory scale boiler setup for controls research and education. This setup is designed in such a way to mimic real-world boiler dynamics from a system and controls perspective. This setup is also expected to improve overall process control education process because of the hands-on experience on modeling, system identification, control design and implementation on an equipment which is close to real world application.

Keywords: Boiler, Natural Recirculation, Educational Prototype.

1. INTRODUCTION

The steam boiler is an energy conversion equipment or device which transforms chemical energy of fuel such as coal, oil, gas or nuclear energy into steam which in turn is used for mechanical energy. Boilers are also commonly used in industry to generate a utility steam used for heating chemical compounds in a reactor. The primary function of a boiler is to maintain the steam energy in balance with the load demand while maintaining the internal variables such as pressure, level in a desired range. In systems and control application like control design, plant performance, operability and feasibility studies, mathematical model of the boiler plays an important role in system analysis process flow. It is very important to provide tight control of boiler drum parameters like pressure and drum level. Majority of research on boiler controls are limited to simulation-only-study based on first principle models. This limits students and academician to learn the real-world problem in depth, explore controls solutions and implement etc. Conducting experiments are the best way to get insight of these process dynamics and to calibrate first principle physics based model. However, in general, research engineers do not get much freedom to perform design of experiments on real life boilers, because of the cost and time involved. More over researching on real world boiler is not a viable solution because of the potential risk on availability of boiler. Goal of this work is to bridge this gap by developing a laboratory scale boiler which can mimic dynamics of real world boiler. In addition, any new control structure or method developed should be validated and compared with running plant control structure beyond simulation studies to understand performance improvement versus implementation cost. This scale down lab boiler is designed and developed to concur a realistic control studies on boiler to harvest mutual benefit for industry and academia. Developed Lab boiler is a scale down version of a nuclear steam generator [2 3].

This setup can also be used to teach boiler control to students and its challenges involved from systems and control perspective. Behaviour like swell and shrink can be easily demonstrated in this system which pose a right half zero (non-minimum phase) problem to students and research scholar. Current boiler controls schemes like three element control [4] can be designed and implemented on this setup from an education stand point. Various boiler control modes like turbine follow boiler and boiler follow turbine from a grid event can be mimicked in this set up with additional bypass control scheme. Another advantage with this setup is to educate various steps involved in process control to design a real-world control application, like (1) modelling (2) Control Design and (3) Implementation and testing etc. In addition to PLC, this set up is equipped with the capability to interface with Labview, this enables research engineers to design advance process control algorithms, estimation and soft sensing to validate the notion. In addition, this setup is having a unique feature to vary the process dynamics with variable bubble distribution in evaporator and can also mimic uncertainty in total heat transfer. These features can be used to study robust control algorithm and its application to process control equipment. This paper is presented in three sections;

first section introduces overall design method used to develop this setup. Second section elaborates features of this setup and the last section briefly provides some useful examples with results from a control education standpoint.

2. LAB BOILER DESIGN

2.1 Overview

Steam generation is a complex process having complicated phase-change and nonlinear behaviour which is modelled with different levels of fidelity based on requirement. Design of these equipment needs rigorous analysis and step by step procedure, more over natural circulation loops are vulnerable to instabilities; these instabilities are primarily because of the non-linear nature of two phase flows. The design process of lab scale boiler uses the procedure mentioned in HTFS HANDBOOK [15]. There is a lot of literature focusing on mathematical treatments of these instabilities and classification of these instabilities [8 10 13]. For practical design purpose, there are stability maps with respect to various conditions like pressure drop ratio, exit quality and degree of sub cool. Important instabilities are

a) Ledinegg: This instability is observed in the negative slopping region of the pressure drop vs. flow curve (S shape curve).
b) Density Wave Oscillation: This instability is because of the oscillation of density induced pumping force and exit velocity.
c) Boiler Crisis: If the heat flux is greater than critical heat flux this will create film boiling in the tube which will reduce the heat transfer. This reduced htc will create tube break down.

Stability maps developed by J C Freidly [5] for natural recirculation as shown in figure for Ledinegg and Density wave types is used. The maps are based on pressure drop ratios between raiser and down comer to exit quality with respect to various degree of sub cooling (based on Jacob number). For lab boiler design, instead of investigating rigorous mathematical approach, just used stability maps to ensure boiler stability. For boiler crisis, we used correlations for critical heat flux based on operation pressure which ensured lab boiler operating conditions are way below these limits. Design steps are followed like a typical industrial boiler for steady state. The only difference is having a provision for varying void fraction to emulate wide range of operation.

2.1 Reference Boiler and Steady State Calculations

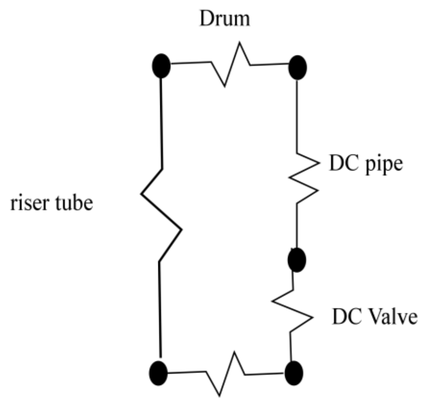
Reference boiler used for this design is from a nuclear steam generator. Detail design data of reference boiler is provided in [2,3]. Data of reference boiler is provided as below. A scaling philosophy is followed as described by Ishii [6]. Here pressure and thermal flux are used as scale down variable, remaining variable are computed as per this variable and available material constraint.

Reference Boiler/Steam Generator Key Design Data

a. Heat input 540 x 10^3 KW
b. Operation Pressure = 45 bar(a) and 270 kg/sec
c. Feed Water Temperature 180C
d. Thermal Flux =162.66 KW/m^2
e. Area ratio is 2.8

Area ratio is approximated close to the reference boiler. Seven heaters of 19 mm inside riser is considered as heating element for boiler, similar to 19 mm of reference boiler. From energy balance and target thermal flux, heating power is approximated as 7KW. Steam generation is computed using steady state steam tables as shown below, 95C feed water inlet is assumed for feed water temperature. Solving energy balance equation for a pressure 4 bar and inlet temp 95C with 7 KW heat yields a steam generation of 10.5 kg/h. Next item is riser-down comer effective height, for convenience 1 meter is taken in this design iteration. This will reduce design problem to match pumping head of boiler to losses by iteratively choosing recirculation ratio CR. Figure 1 below shows the simplified natural recirculation circuit used for calculation. A steady state lumped model is used for down comer a 10 node riser model and standard pipe losses, and valve drops are used for calculation. Some examples of these steps are given in detail with example in V Ganapathy [14]. Boiler design uses following steps iteratively solve equation below.

$$\oint \rho g l sin\theta = \frac{\rho_l f l v^2}{2d} + \Phi^2 \frac{\rho_l f l v^2}{2d} + \delta P_{valve} + \delta P_{blends} + \delta P_{drum}$$



Re-Circulation Path of Proposed Lab Boiler Used for Design

Figure 1 Re-circulation Circuit of Lab Boiler

Lab boiler design is verified for thermos syphon stability from natural recirculation perspective. For this stability maps provided by J. F Freidly [5]is used. Figure 2 below shows the boiler operation range and stability regime.

Lab Boiler Design Boundary data

a) Heat Input= 7 KW
b) Operating Pressure =4 bar
c) Feed Water Temperature 95C

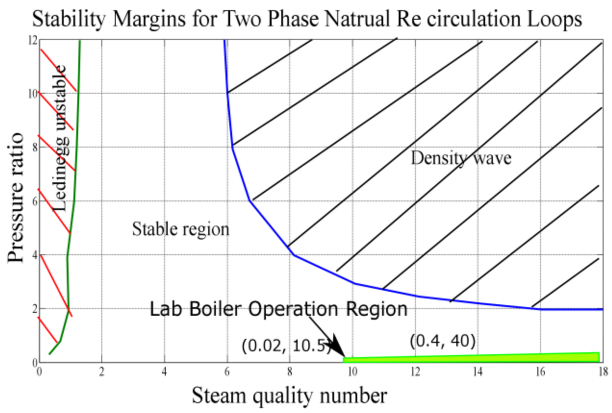


Figure 2 Lab Scale Boiler Operation Region on J C Friedly's Stability Maps

To enable this concept of having variation in bubbles across rise an innovative approach to change circulation ratio and hence steam distribution. Green space in figure 2 shows the possible operation region for proposed boiler. A detail simulation analysis of design, drawings, components used, system P and ID, photos and videos etc. are restricted currently in this article because of patent application under review stage for this setup [12].

2.2 Lab Boiler Setup

The Lab boiler setup is designed to mimic real world recirculation type drum boilers. To incorporate wide range dynamics in this small set up a unique feature to vary dynamics at same operation point is also included in the design. Figure 3 shown below is boiler setup and block diagram of system with process and manipulative variables. The process variable of interest to be controlled are drum pressure and drum level where as the manipulative variables are (a) Heat input (b) Steam Flow (c) Feed water flow and (d) Feed water heat input respectively. The lab scale boiler operation range is shown in table 1.

Functionally this setup is having two process variables, that is, pressure and level which is to be maintained. There are four manipulative variables, (1) Main Heat input (2) Feedwater heat input (3) Steam flow and (4) Feed water flow to achieve this. This set up is instrumented with industrial standard instruments and are interfaced with computer and controlled based on algorithm written in LabVIEW

Table 1. Lab Boiler Operation Point

Operation Parameter	Operation range	Units
Drum Pressure	4	bar
Drum Level	100	mm
Main Heater input	7	KW
Feed water temperature	90 to 110	$^{\circ}$C
Feed water flow rate	8 to 12	LPH
Steam Flow rate	8 to 12	Kg/hr

Figure 3 Lab Scale Boiler Setup

2.3 Lab Boiler Features

(a) Uncertainty and Robustness

This lab-scale boiler set-up also possesses special features to apply user-defined perturbations in the boiler-drum process operational behaviour, through changing suitable process manipulated/disturbances variables, and system parameter variations. This helps to use this set-up in experimental study and analysis of boiler-drum operational behaviour that mimics such scenario observed in real-life industrial boilers, and investigate performance of various control schemes/algorithms for such scenario. With this feature, boiler can be operated at three different modes (Mode A, B and C). The steam distribution in three modes is as shown in figure 4. As the swell and shrink are primarily because of the re distribution of bubbles in the riser [1], the effect is visible on the step test of steam valve at same operation condition at three modes. Figure 5 shows response of level for a steam perturbation at three modes of boiler configuration. It is very clear that this small lab boiler exhibits dynamic swell similar like an industrial boiler, more over there is a visible variation is the zero crossing for different modes. This feature enables control research and education on robust control theory and application.

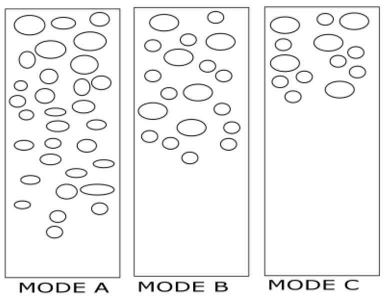


Figure 4 Expected Steam distribution at three modes of operation

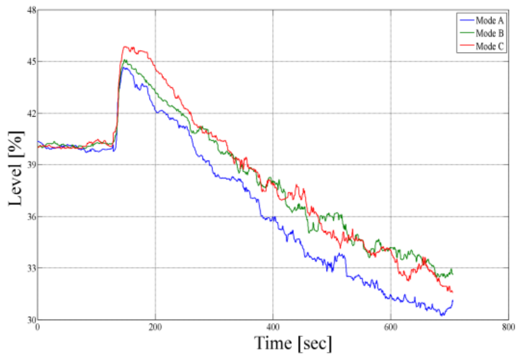


Figure 5 Drum Level Swell test at three modes

(b) Industrial Control Schemes

This setup can be used to educate industrial boiler control schemes like, please refer Dukelow [4] for details of boiler control.

(1) Single element control

This controller uses simple PI loop to track and reduce disturbance in level. This control action activates when only level deviates from its set point and perform poor during steam load disturbance impact on level. More over feed pump disturbance also impact the controller performance hence another one element is added that is explained in next section.

(2) Three element control

This structure uses a feedback control of level in cascade with feed water flow control. In addition, a feed forward action on flow set point is added based on the flow difference between steam and feedwater.

In addition, this setup can also mimic both turbine follow boiler mode by controlling steam flow using a bypass valve and boiler follow turbine mode by controlling heat input.

(c) Basic to Advance Process Control

This setup could be used to design basic SISO control using classical control design. Since these system dynamics includes time delay, right half zero and nonlinearities, all advancement to classical controller like smith predictor, IMC based design etc. could be deployed and experimented. A 2X2 MIMO structure using two modes (1) controlling pressure using bypass (turbine follow boiler mode) and (2) controlling pressure using heat input (boiler follow turbine mode) could be demonstrated. In addition, advance process control using model based optimization approaches can be experimented for graduate students.

3. EXPERIMENT RESULTS

This section gives some experimental results of assignment and project performed by students on this setup from a process control research and education perspective. Currently only a limited number of cases (1) modelling (2) control design are presented here. However, students and research scholars are performing experiments on advance topics like robust control, model based control etc. Advance control experiments and results are out of scoped with respect to goal and aim of this article.

3.1 Modelling and Identification

Mathematic modelling is an important step for process control design. Mathematical models could be based on physics or from experiments. This set up can be used to develop physic based models or fine tune existing physics based model to validate models

(a) Physics Based Model

This set up is also used to validate and develop physics based boiler model. As an example, a five state Astrom and Bell's [1] model is used to develop a nonlinear model of this lab boiler. The model is tuned to match steady state response and results are compared as shown in figure. The results of the response from model and its comparison with actual measurement is shown in figure 6. The result of step response to steam flow is shown in the figure 6. Lab boiler exhibits swell on level which is closely captured by the non-linear model.

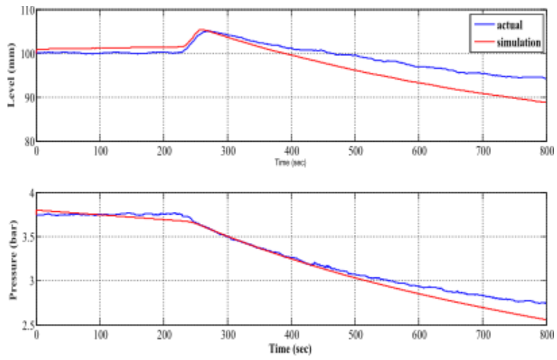


Figure 6 Astrom and Bells Model [1] Tuning Results

(b) System Identification

This setup is used to perform system identification experiments to derive control oriented models for design purpose. Test input signals like 'step' and 'PRBS' is injected to each manipulative variables and outputs are collected. Using this data, input/output linear/non-linear models are identified. A set of such experimental results are shown in figure 7 and 8. A detailed set of these results is published [6].

These test inputs are used to identify control oriented models like transfer function or simple time series models. This is a good example to showcase and train system identification techniques on process control applications. The figure above shows step change to feedwater flow to identify transfer function of flow to level of system. Identified transfer function is shown below.

$$\frac{Level(s)}{feed\ flow(s)} = \frac{0.0046944}{s(10.51s+1)(0.30536s+1)} * e^{-6s}$$

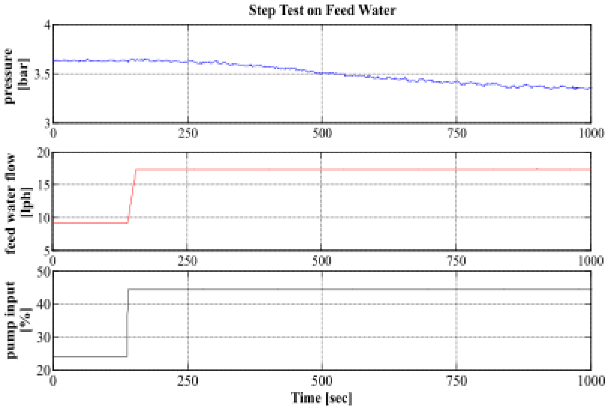


Figure 7 Step Input Test Signal for Identification

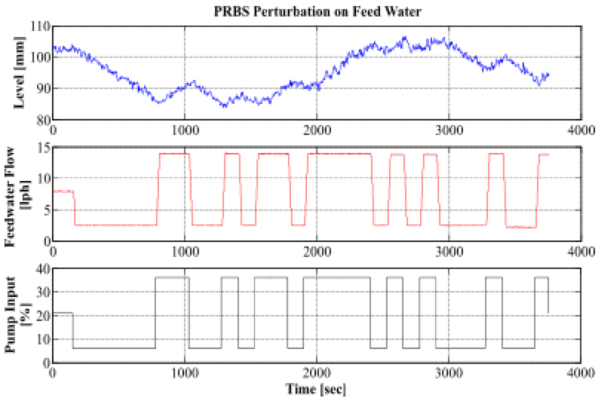


Figure 8 PRBS Input Test Signal for Identification

3.2 Control Design

A SISO control design and MIMO control design experiment results are presented in this section. Details of each design procedure is out of the scope for this papers goal and aim. A classical three element control and a classical MIMO design is performed in the setup.

(a) Three Element Control

A three-element control [4] is designed using classical control approach and fine-tuned using lambda tuning method. The block diagram of boiler setup in this configuration is as shown in figure 9. The control structure consists of a cascade loop with flow and level control as inner and outer loop respectively. A feed forward control based on flow difference between steam and feed water flow is augmented to flow set point. The result of this experiment is shown in figure 10. The controller is designed and implemented based on classical control design recipe and fine-tuned using Lambda tuning rules. The results show the response of drum level for a steam flow disturbance on the boiler steam load valve.

(a) MIMO Control

In real world boiler controls are seldom operated as multivariable controls. However, from an academic research perspective, this set up could be used as pilot boiler to experiment novel control. This section presents a classical inverted de-coupler [9] based MIMO experiment results. The block diagram of the boiler setup in MIMO configuration is as shown in figure 11. In this setup both pressure and level are controlled simultaneously in a MIMO structure. The results of this experiment are shown in Figure 12 and 13. In this control, pressure is controlled using a steam control valve at the outlet and level is controlled using feed pump. The steam load or disturbance valve is used to inject disturbance to the system. The control design is using inverted de-coupler MIMO design approach [9,11] and the results are fine-tuned after implementation.

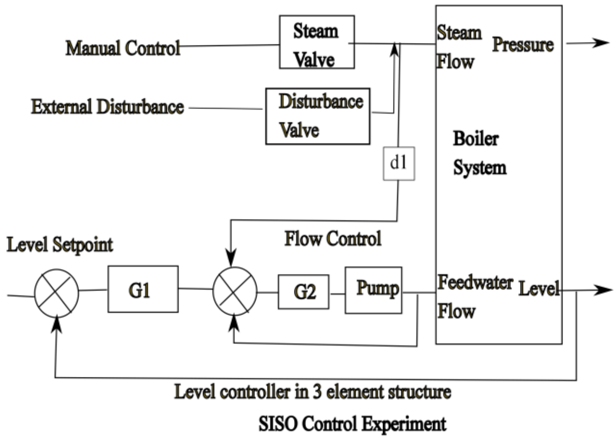


Figure 9 Three element control implementation

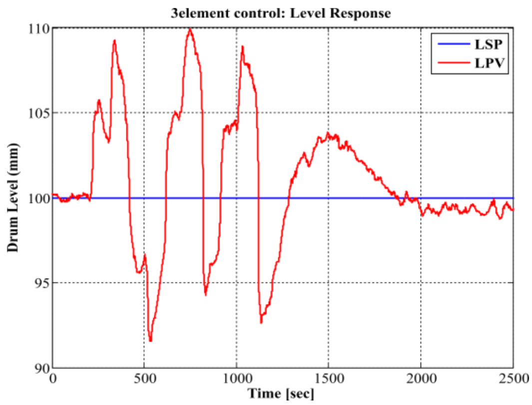


Figure 10- Drum level response for a steam disturbance

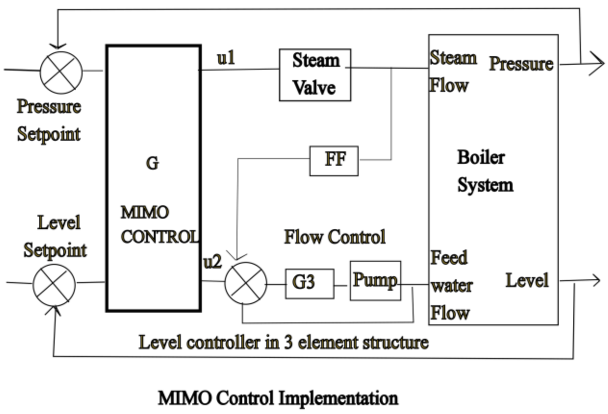


Figure 11 MIMO control implementation

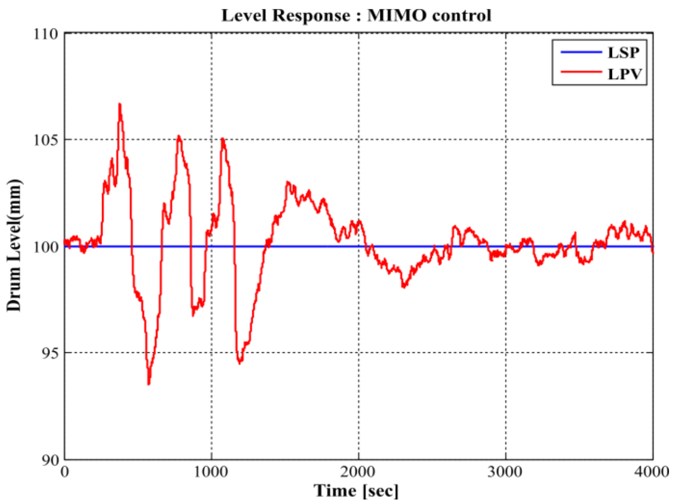


Figure 12 Level Response of MIMO Control

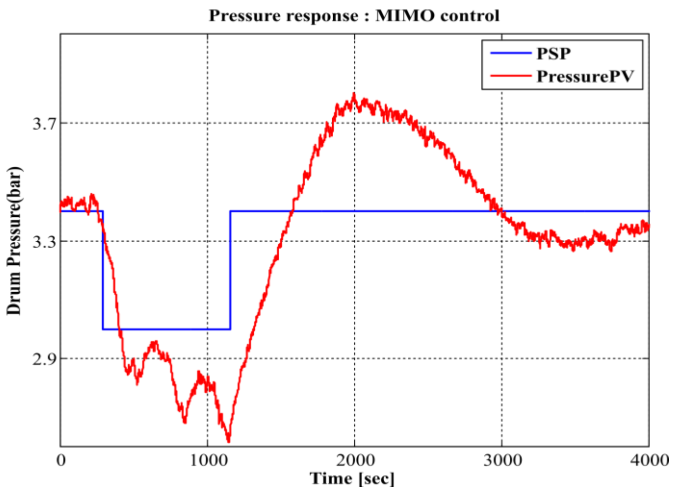


Figure 13 Pressure Response of MIMO Control

4. CONCLUSIONS

A lab scale boiler is designed for experimental process control research and education purpose. Initial tests, results and use case of this setup are highly impressive because of similar process dynamics with industrial boiler. Only a small set of experimental results are presented in this article, however future work is to explore advance control philosophy and methods on this setup for operational data to compare control performance with classical three element control. The setup is expected to bridge the gap on academic research on boiler/process control and improve the process control education. Moreover, boiler based power plants operations and control is passing through a set of challenges because of renewable integrations. Because of this could a new paradigm shift on operation and control of boiler power plant is expected in near future. Hence, research boiler setup is a useful tool for experimentation and validation of new methods and system

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