

People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
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Institute of Electrical and Electronic Engineering
Department of Power and Control

Final Year Project Report Presented in Partial Fulfilment of
the Requirements for the Degree of

MASTER

In Electrical and Electronic Engineering
Option: Control Engineering

Title:

Virtual Boiler Simulation and Control
Using LabVIEW

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Abstract

Worldwide, most electric power is produced by steam-electric power plants, which produce about 86% of all electric generation, enough reason to make it one of the most important challenges to nowadays engineers to develop more accurate models and virtual simulators, which is the main objective of our work.

In this project, a boiler simulator is built based on physical (mass and energy) conservation laws, we first used MATLAB/SIMULINK to construct each subsystem model alone, and then the subsystems were integrated to get the full boiler system implemented. To enhance the performance of the boiler a Drum level control loop is implemented and simulated based on two main methods, one-element control and three element control.

For interfacing we used LabVIEW to create a user accessible front panel, we then made use of the DAQ-USB6009 to communicate data between the boiler simulator and the control which was implemented in a different computer.

ACKNOWLEDGEMENT

We would first like to thank my thesis advisor Dr.Ouadi. The door to his office was always open whenever we ran into a trouble spot or had a question about my research or writing. He consistently allowed this paper to be my own work, but steered me in the right direction whenever he thought I needed it.

We must also express our very profound gratitude to our parents and to all the loved ones for providing us with unfailing support and continuous encouragement throughout our years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Once again, we especially thank Dr.Ouadi, it was a great pleasure for us to work on this project under his supervision.

Dedications

First, I'd like to dedicate this work to my beloved parents, for always being there for me and always encouraging and pushing me forward throughout not only the project, but the whole long journey in this university.

I shall also add a special thank you to my brother and sister for their non-stop support and multiple advices for me to successfully finish this work.

Finally, I'd like dedicate this work to whomever I crossed roads with, influenced or got influenced by during this experience, without them I wouldn't have made it until this point.

L.Yazid.

I dedicate this projet to my loved parents, my brother from the eldest to the youngest: Saleh, Seyf Eddine, Choayb and Abderrahmane for their much appreciated support and encouragement.

I would thank all my friends and all the staff of teacher who encouraged me to do this work.

B.Abdelhamid.

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Nomenclature:

g	- Acceleration due to gravity
F_a	- Air flow
AI	- Analog Input
AO	- Analog Output
F_{spa}	- Attemperator spray flow
η	- Attenuation coefficient for riser
η^1	- Attenuation coefficient for super heater
θ	- Burner tilt angle
C_f	- Calorific value of coal
η_f	- Chimney friction coefficient
V_{bf}	- Combustion chamber volume of boiler furnace
O_a	- content of fresh air in the recirculation
V_s	- Control volume of SSH
$A(h)$	- cross sectional area of the tank at any level h
DAQ	- Data acquisition
ρ_{eg}	- Density of furnace gas
ρ_{dw}	- Density of water in drum
l_d	- Drum level
V_{dw}	- Drum water volume
h_D	- enthalpy of circulating flow in the riser
h_{ew}	- Enthalpy of feedwater
h_{sp}	- Enthalpy of PSH steam

h_{spa}	- Enthalpy of spray water
h_{si}	- Enthalpy of SSH inlet steam
η_{ps}	- Experimental coefficient of the furnace gas model
F_{ew}	- Feedwater flow
F_f	- Fuel flow
P_g	- Furnace gas pressure
η_g	- furnace suction coefficient
T_{gp}	- Gas temperature at PSH
α_{gmp}	- Gas to metal heat transfer coefficient
α_{gm}	- Gas to metal heat transfer coefficient
δp_{dw}	- Gradient of drum steam density
δh_d	- Gradient of drum steam enthalpy
δh_{dw}	- Gradient of water enthalpy at drum conditions
a_r	- Heat transfer surface area for furnace
q_r	- Heat transferred by radiation to riser
q_s	- Heat transferred to secondary super heater
μ	- Ideal gas constant for combination gases
IO	- Input-Output
a_{ip}	- Inside heat transfer area
a_i	- Inside heat transfer area of SSH
K_i	- Integral gain
τ_i	- integral time
u_{sp}	- Internal energy of steam in PSH

IMC	- Internal Model Control
LabVIEW	- Laboratory Virtual Instrument Engineering Workbench
l	- Length of drum
LPV	- Linear Parameter Varying
LTI	- Linear Time Invariant
$y_1(t), y_2(t),$ $y_3(t), y_4(t)$	- Linear transfer function model outputs for the four operating regions
p_s	- Main steam pressure
T_s	- Main steam temperature
F_{eg}	- Mass flow of furnace gas through the boiler
F_{sp}	- Mass flow rate of steam in PSH
F_s	- Mass flow rate of steam in SSH
M_{mp}	- Mass of PSH section
M_m	- Mass of SSH metal
MATLAB	- MATrix LABoratory
α_{msp}	- Metal to steam heat transfer coefficient
α_{ms}	- Metal to steam heat transfer coefficient
MISO	- Multi-Input Single-Output
MIMO	- Multiple-Input Multiple-output
NI-ELVIS	-National Instruments Educational Laboratory Virtual Instrumentation Suite
a_{op}	- Outside heat transfer surface area
a_o	- Outside heat transfer surface area
e_x	- percentage excess air level

PC	- Personal Computer
PSH	- Primary Super Heater
Kp	- process gain
PLC	- Programmable Logic Controller
P	- Proportional
Kp	- Proportional gain
PI	- Proportional Integral
PID	- Proportional Integral Derivative
Tmp	- PSH metal temperature
R	- Radius of drum
Fr	- Recirculation gas flow
Td	- Saturated steam temperature
h(t)	- scheduling parameter
SSH	- Secondary Super Heater
Tm	- secondary superheater metal temperature
SISO	- single input single output
ha	- Specific enthalpy of air
heg	- Specific enthalpy of furnace gas
hr	- Specific enthalpy of Recirculation gas
Cpg	- Specific heat of exhaust gas at constant pressure
Cpg	- Specific heat of exhaust gases
Cs	- Specific heat of main steam
Cmp	- Specific heat of PSH metal

C_{vp}	- Specific heat of PSH steam at constant volume
C_m	- Specific heat of SSH metal
C_v	- Specific heat of steam at constant volume in SSH
C_{sp}	- Specific heat of steam at PSH outlet
C_{si}	- Specific heat of steam at SSH inlet
γ_{sp}	- Specific weight of steam in PSH
γ_s	- Specific weight of steam in SSH
T_{si}	- SSH inlet steam temperature
T_m	- SSH inlet temperature
F_d	- Steam flow from drum
p_d	- Steam pressure in the drum
X_q	- Steam quality
σ	- Stefan-Boltzmann constant
ϵ	- Stoichiometric air/fuel volume ratio
T_g	- Temperature of furnace gas
T_{sp}	- Temperature of PSH steam
τ_p	- time constant
V_2	- volume of a cylindrical portion shaded
V_1	- volume of a spherical segment
V_d	- Volume of drum
V_{sp}	- Volume of PSH
T_w	- water wall temperature
$w(h)$	- weights which are the function of the scheduling variable

CHAPTER ONE

Introduction to Boilers

1.1 Introduction

Boilers are mainly used for steam production for a wide range of industrial purposes: electricity generation, chemical process and heating. During this chapter, we will see the main descriptions of Boilers and focus and its working principles.

1.2 General Boiler Description

1.2.1 Boiler Definition

A Boiler is basically a closed vessel into which water is heated until the water is converted into steam at required pressure. The boiler is essentially a closed vessel inside which water is stored. Fuel (generally hydrocarbon and coal) is burnt in a furnace and hot gases are produced. The heat energy from these hot gases comes in contact with water vessel thus producing the necessary steam.

Boilers are classified into different types based on their capacity, fuel type, materials, working pressure and temperature and whether they are condensing or non-condensing. Hot Water boilers- are generally available in standard sizes from 10 kW to over 30 MW. In commercial buildings, natural gas is the most common boiler fuel, because it is usually readily available, burns cleanly, and is typically less expensive than oil or electricity [1].

1.2.2 Applications of Boilers

Boilers have several, various applications whether industrial or in daily life applications; the mains one are stated below:

- ✓ To drive steam turbines, marines, Locomotives etc.
- ✓ In industries like textile, paper, sugar, tire, chemical, breweries etc...
- ✓ Heating systems for cement production.
- ✓ Stationary applications to provide heat, hot water and steam for domestic use.

1.2.3 Boiler Types

Boilers can be categorized according to the method used to transfer the thermal energy.

1.2.3.1 Fire-Tube Boilers

Fire tube boiler is one of the most basic types of boilers and the design is also very old. It was popular in 18th century. It was mainly used for steam locomotive engines.

Figure 1.1 shows the basic design of a fire-tube boiler.

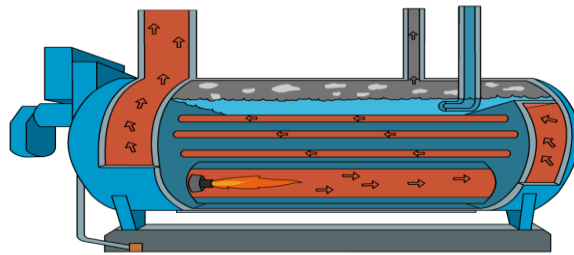


Figure1.1 Fire-Tube Boilers Scheme

Operation of fire tube boiler is as simple as its construction. In fire tube boiler, the fuel is burnt inside a furnace. The hot gases produced in the furnace then passes through the fire tubes. The fire tubes are immersed in water inside the main vessel of the boiler. As the hot gases are passed through these tubes, the heat energy of the gases is transferred to the water that surrounds them.

As a result steam is generated in the water and naturally comes up and is stored upon the water in the same vessel of fire tube boiler. This steam is then taken out from the steam outlet for utilizing for required purpose. The water is fed into the boiler through the feed water inlet.

As the steam and water is stored in the same vessel, it is quite difficult to produce very high pressure steam. General maximum capacity of this type of boiler is 17.5 kg/cm^2 and with a capacity of 9 Metric Ton of steam per hour. In a fire tube boiler, the main boiler vessel is under pressure, so if this vessel is burst there will be a possibility of major accident due to this explosion.

1.2.3.2 Water-Tube Boilers

A water tube boiler is such kind of boiler where the water is heated inside tubes and the hot gasses surround them. Actually this boiler is just opposite of fire tube boiler where hot gasses are passed through tubes which are surrounded by water.

The working principle of water tube boiler is very interesting and simple. A very basic diagram of water tube boiler is shown in Figure 1.2.

It consists of mainly two drums, one is upper drum called steam drum other is lower drum called mud drum. These upper drum and lower drum are connected with two tubes namely down-comer and riser tubes as shown in the Figure, Water in the lower drum and in the riser connected to it, is heated and steam is produced in them which

comes to the upper drums naturally. In the upper drum the steam is separated from water naturally and stored above the water surface. The colder water is fed from feed water inlet at upper drum and as this water is heavier than the hotter water of lower drum and that in the riser, the colder water push the hotter water upwards through the riser. So there is one convectional flow of water in the boiler system [2].

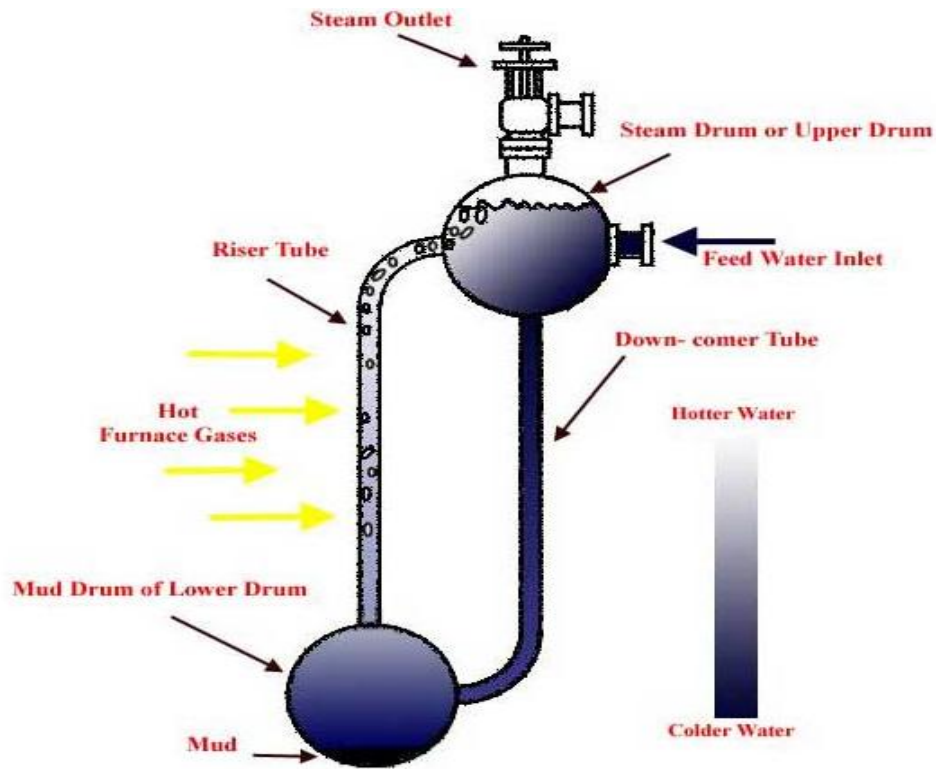


Figure1.2 Water-Tube Boilers Diagram

1.3 Case Study

1.3.1 Definition

In this work, we will be implementing a 210 MW power plant boiler, based on a model that captures the key dynamical properties of the boiler. The model is based on physical principles and has a number of parameters; most of which are determined from construction data and few of them from field test data.

The Boiler is divided into five subsystems, each subsystem is modeled individually and then an integrated system is built, and dynamics are observed.

The main five boiler subsystem models are:

- ✓ Boiler furnace model.

- ✓ Boiler drum model.
- ✓ Primary Super-Heater model.
- ✓ Attenuator model.
- ✓ Secondary super-Heater model.

Following sections describe the design and development aspects of the boiler subsystem models as well as the integrated boiler model.

1.3.2 Boiler Furnace

An industrial Boiler furnace is equipment used to provide heat for a process, or can serve as a reactor which provides the heat of reaction. The following sections describe the process and first principle model.

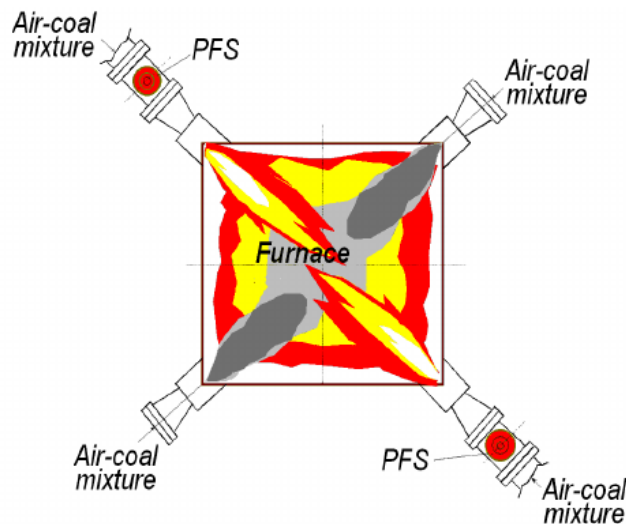


Figure1.3 Boiler Furnace Scheme

1.3.2.1 Boiler Furnace Process

In the Boiler furnace, fuel flows into the burner and is burnt with the air provided by an air blower. The flames heat up the tubes, which in turn heat the fluid inside the first part of the furnace, known as the radiant section or firebox. In this chamber combustion takes place, and the heat is transferred mainly by radiation to the tubes around the fire in the chamber. The heating fluid passes through the tubes, and is thus heated to the desired temperature. This heated fluid is then circulated round the whole plant to the heat exchangers to be used wherever heat is needed, instead of directly heating the product line, as the product or material may be volatile or prone to cracking at the furnace temperature.

1.3.2.2 Boiler Furnace Mathematical Model

The behavior of the boiler furnace is captured by the following mass and energy balance equations [3].

The mass balance for combustion is given by:

Rate of change of furnace gas flow = Fuel flow + Air flow + Recirculation gas flow
- Gas flow through boiler.

This equation is mathematically represented as:

$$\frac{d}{dt} \rho_{eg}(t) = \frac{1}{V_{bf}} \{F_f(t) + F_a(t) + F_r(t) - F_{eg}(t)\} \quad (1.1)$$

Where:

Ff(t) - Fuel flow

Fa(t) - Air flow

Fr(t) - Recirculation gas flow

Feg(t) - Mass flow of the furnace gas through the boiler

$\rho_{eg}(t)$ - Density of the furnace gas

Vbf- Combustion chamber volume of the boiler furnace

The energy balance for combustion is given by:

Rate of change of energy of hot gas = Energy from the fuel input + Energy from the air input + Energy from the recirculation gas - Heat energy transferred to the riser - Heat energy transferred to the secondary super heater - Heat energy carried by the furnace gas.

This equation is mathematically represented as:

$$V_{bf} \rho_{eg}(t) \frac{d}{dt} h_{eg}(t) = \{C_f F_f(t) + h_a F_a(t) + h_r(t) F_r(t) - q_s(t) - q_r(t) - F_{eg}(t) \varepsilon (1 - 1100 \text{exheg}(t))\} \quad (1.2)$$

Where:

$h_{eg}(t)$ - Specific enthalpy of the furnace gas

Cf - Calorific value of coal

ha- Specific enthalpy of air

hr(t) - Specific enthalpy of the Recirculation gas

qr(t) - Heat transferred by radiation to the riser

qs (t)- Heat transferred to the secondary super heater

ε - Stoichiometric air/fuel volume ratio

e_x - percentage of excess air level

$q_r(t)$ and $q_s(t)$ are modeled using the Stefan Boltzmann law for radiation which is the following:

$$q_r(t) = \{\eta\theta(t)a_r\sigma(T_g^4(t) - T_w^4(t))\} \quad T_g^4(t) \ll T_w^4(t) \quad (1.3)$$

$$q_s = \{\eta_1(1 - \theta(t))a_r\sigma(T_g^4(t) - T_m^4(t))\} \quad (1.4)$$

Where:

$\theta(t)$ - Burner tilt angle

η - Attenuation coefficient of the riser

η_1 - Attenuation coefficient of the super heater

$T_m(t)$ - secondary super heater metal temperature

$T_g(t)$ - Temperature of the furnace gas

a_r - Heat transfer surface area of the furnace

$T_w(t)$ - water wall temperature

σ - Stefan-Boltzmann constant

1.3.3 Boiler Drum

Boiler drum is the crucial part of the boiler system and there are many modeling efforts on it. It is a reservoir of water/steam at the top end of the water tubes. The drum stores the steam generated in the water tubes and acts as a phase-mixture. This section will discuss the process description and the mathematical modeling of a boiler steam drum of our boiler.



Figure 1.4 An Industrial Boiler Drum

1.3.3.1 Boiler Steam Drum Process

The burning gases from the furnace pass around a group of vertical tubes. These tubes, called risers, carry a mixture of water and steam. At the top of the risers is the drum, which is a horizontal cylinder, kept about half full of water. The upper part of the drum contains steam. The tubes that leave the bottom of the drum (the down comers) are insulated from the combustion chamber and carry the water down to a mud drum, where mud is separated from the water. Heating the riser tubes with hot flue gas causes the water to circulate and steam to be released in the steam drum.

In this work, the design approach of McDonald et al (1971) is followed, for writing down the mass and energy balance equations for the drum [4].

1.3.3.2 Boiler Steam Drum Mathematical Model

Mass and Energy balance equations of the boiler drum are stated below [3]. Starting by the mass balance equation:

Rate of change of the mass of steam and water in the drum = Feed water flow to the drum - steam flow from the drum.

Then it is described by the differential equation:

$$\frac{d}{dt} [(V_d - V_{dw}(t))\rho_d + V_{dw}(t)\rho_{dw}] = \{F_{ew}(t) - F_d(t)\} \quad (1.5)$$

Where:

V_d - Volume of the boiler drum

$\rho_d(t)$ - Density of steam in the drum

$\rho_{dw}(t)$ - Density of water in the drum

$V_{dw}(t)$ - Drum water volume

$F_{ew}(t)$ – Feed water flow

$F_d(t)$ - Steam flow from the drum

The energy balance equation of the boiler drum is given by:

Rate of change of the energy of steam and water in the drum = Total energy of steam and water mixture after leaving the water walls - Energy of drum water - Energy of drum steam.

This is described by the differential Equation:

$$\frac{d}{dt} [(V_d - V_{dw}(t))\sigma_d h_d(t) + V_{dw}(t)\rho_{dw}(t)h_{dw}(t)] = \{F_d(t)h_w(t) - (F_D(t) - F_{ew}(t)h_{dw}(t) - F_D(t)h_d(t))\} \quad (1.6)$$

Where:

$F_D(t)$ - Total circulating flow through the riser

$h_w(t)$ - Enthalpy of the steam water mixture leaving the water walls

$h_{dw}(t)$ - Enthalpy of water in the drum conditions

$h_d(t)$ - Enthalpy of drum steam

The temperature of steam and water in the drum are both assumed to be equal to the Saturation temperature T_d , corresponding to the drum pressure P_d . The following linear relations are derived for use in the drum using steam tables.

$$T_d(t) = 968192.556\rho_d(t) + 274.40489 \text{ }^\circ\text{C} \quad (1.7)$$

$$P_d(t) = 1701297.8956\rho_d(t) + 36.9363 \text{ Kg/cm}^2 \quad (1.8)$$

$$\rho_{dw}(t) = -2.0132\rho_d(t) + 79.6473 \times 10^{-5} \text{ kg/cm}^3 \quad (1.9)$$

$$h_d(t) = -657929.084\rho_d(t) + 688.738 \text{ kcal/Kg} \quad (1.10)$$

$$h_{dw}(t) = 1128501.642\rho_d(t) + 277.057 \text{ kcal/Kg} \quad (1.11)$$

The boiler drum level l_d responds in an integrating manner to the steam flow F_d and feed water flow $F_{ew}(t)$. Basically, the drum model describes the dynamics of the drum water volume $V_{dw}(t)$ in terms of the mass and energy conversion equations. A separate relationship between $V_{dw}(t)$ and $l_d(t)$ is derived from the geometry of the drum, and this equation is solved using the Newton-Raphson method to obtain $l_d(t)$.

1.3.4 Primary Super Heater

The Super heater is a heat exchanger, in which heat is transferred to the saturated steam to increase its temperature. The boiler super heater is a secondary heat exchanger that accepts saturated steam from the boiler drum and adds sensible heat to the steam. Super heaters in large steam generator systems are frequently split into two parts: the Primary Super Heater (PSH) and the secondary super heater (SSH) in this part we'll be discussing the first part: the primary super heater (PSH).

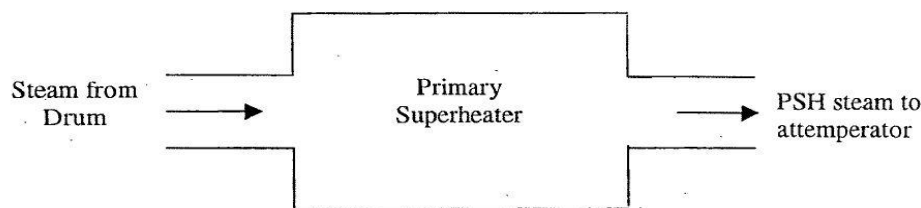


Figure 1.5 Primary super heater block

In this context, it was felt necessary to have a versatile model for the PSH that could be used for the building of boiler simulators as well as implementation of integrated control systems for the optimization of boiler operation.

1.3.4.1 Primary Super Heater Mathematical Model

Applying the law of conservation of energy for the PSH steam line and the PSH tube separately, the energy balance equations are written as follows [3].

Change in internal energy of PSH steam = Heat transferred from the metal to steam + Energy of the boiler drum - steam Energy of the PSH outlet steam

This is described by the differential Equation:

$$\gamma_{sp} V_{sp} \left(\frac{\partial u_{sp}}{\partial T_{sp}} \right) \frac{dT_{sp}(t)}{dt} = \{ a_{ip} \alpha_{msp} (T_{mp}(t) - T_{sp}(t)) + F_d(t) h_d(t) - F_{sp}(t) h_{sp}(t) \} \quad (1.12)$$

Where:

$T_{sp}(t)$ PSH outlet steam temperature

$T_{mp}(t)$ PSH metal temperature

V_{sp} Volume of PSH

γ_{sp} Specific weight of steam in PSH

u_{sp} Internal energy of steam in PSH

a_{ip} Inside heat transfer area of PSH

α_{msp} Metal to steam heat transfer coefficient

$F_{sp}(t)$ Mass flow rate of steam in PSH

$h_{sp}(t)$ Enthalpy of steam in PSH

The energy balance of the primary super heater tube is given by:

Heat energy stored in the PSH tube = Heat energy received from the hot gas - Heat energy transferred to the steam.

This is described by the differential Equation:

$$M_{mp} C_{mp} \frac{dT_{mp}(t)}{dt} = \{ a_{op} \alpha_{gmp} (T_{gp}(t) - T_{mp}(t)) - a_{ip} \alpha_{msp} (T_{mp}(t) - T_{sp}(t)) \} \quad (1.13)$$

Where:

M_{mp} Mass of PSH section

C_{mp} Specific heat of PSH metal

a_{op} Outside heat transfer surface area of PSH

α_{gmp} Gas to metal heat transfer coefficient

$T_{gp}(t)$ Gas temperature at PSH

The developed primary super heater model is used for developing the integrated boiler model. The nominal values of the primary super heater variables are given the appendix.

1.3.5 Attemperator Model

In an Attemperator, desuperheated spray water is mixed with the superheated steam at the outlet of the PSH, in order to maintain the main steam temperature at a desired value. The water spray is modulated by a suitable control valve. Since the Attemperator has a very small volume, the storage in it is negligible. The steady state mass and energy balance equations are given by [5].

The mass balance equation of the Attemperator is given by:

Steam flow through SSH = Steam flow through PSH + Attemperator spray flow

$$\text{Or: } F_s(t) = F_{sp}(t) + F_{spa}(t) \quad (1.14)$$

Where:

$F_s(t)$: Steam flow through SSH

$F_{spa}(t)$: Attemperator spray flow

The energy balance equation of the Attemperator is given by:

Energy of SSH inlet steam = Energy of PSH outlet steam + Energy of Attemperator spray water

The developed Attemperator model is used for the development of an integrated boiler model.

1.3.6 Secondary Super Heater

Secondary Super heaters are one of the most important accessories of a boiler; their job is to improve the thermal efficiency. The choice of the material that constitutes the super heater is really important, as we have to choose a material that is high temperature and corrosion resistant. There are three types of super heaters: radiant, convection, and separately fired. A super heater can vary in size from a few tens of feet to several hundred feet.

1.3.6.1 Secondary Super Heater Mathematical Model

The design procedure for the steam temperature optimal control system normally makes use of a model for the SSH in the state-space form. In this section, the analytical

modeling approach is used for developing a state-space model for the SSH. Applying the law of conservation of energy for the main steam line and the SSH tube separately and based on the works of Sato et al in 1984, the energy balance equations are written as follows [5]:

Rate of change in the internal energy of SSH steam = Heat transferred from SSH metal steam + Heat obtained from the PSH steam reduction due to the application of spray
Heat energy of SSH steam.+ Heat

Mathematically written as follows:

$$V_s \frac{d}{dt} (\rho_s(t)h_s(t)) = \{a \alpha_{ms}(T_m(t) - T_s(t)) + F_{sp}(t)h_{sp}(t) + (h_{spa}(t) - h_f(t))F_{spa} - F_s(t)h_s(t)\} \quad (1.15)$$

Where:

- V_s - Control volume of SSH
- $\rho_s(t)$ - Density of SSH steam
- $h_s(t)$ - Enthalpy of SSH steam
- a_i - Inside heat transfer area of SSH
- α_{ms} - Metal to steam heat transfer coefficient
- $h_f(t)$ - Specific enthalpy of evaporation

1.3.7 The Integrated Model

Integrating all of the above subsystems together to implement a full system as follows:

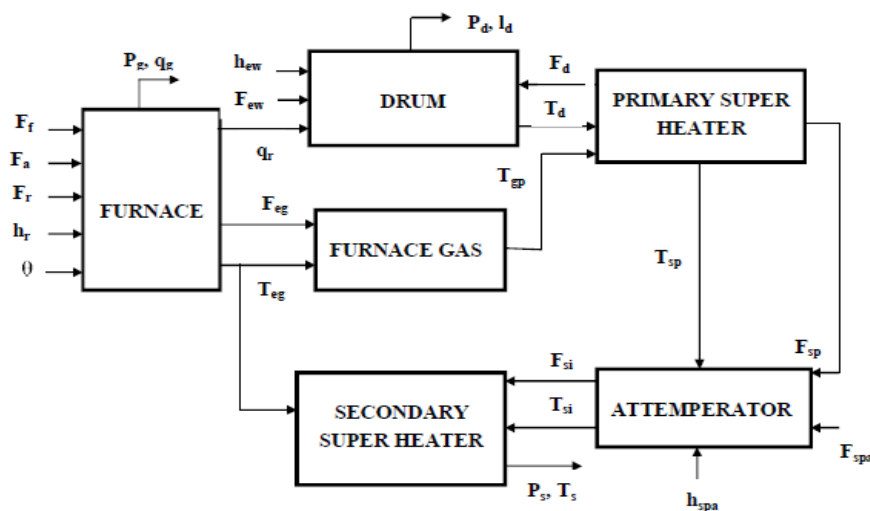


Figure 1.6 Integrated Boiler model diagram

1.4 Conclusion

After this introduction to the world of boilers, and specifically our 210MW boiler, it is clearly seen that the steam generation is a complex and potentially dangerous process, thus the need for Boiler simulators has become a must.

One way to build a boiler simulator is to use the equations described earlier in MATLAB/SIMULINK, and this is what will be discussed in the next chapter.

Chapter Two

Boiler modeling using

MATLAB

2.1 Introduction

In this Chapter we will be implementing the mathematical models described in chapter one, and simulating for different changes in the input variables to see the dynamics of our Boiler using the SIMULINK/MATLAB toolbox.

2.2 Simulation of the Boiler Furnace

2.2.1 State space model

Rearranging the mathematical model discussed in the first chapter we get the following differential equations:

$$V_{bf}\rho_{eg}(t)\frac{d}{dt}h_{eg}(t) = \left\{C_f F_f(t) + h_a F_a(t) + h_r(t)F_r(t) - q_s(t) - q_r(t) - F_{eg}(t)\varepsilon\left(1 - \frac{1}{100}e_x\right)h_{eg}(t)\right\} \quad (2.1)$$

$$\frac{d}{dt}\rho_{eg}(t) = \frac{1}{V_{bf}}\{F_f(t) + F_a(t) + F_r(t) - F_{eg}(t)\} \quad (2.2)$$

In order to obtain a state-space model for the system, we define a 2x1 state vector $X(t)$, a 5x1 input vector $U(t)$, a 5x1 output vector $Y(t)$ for the boiler furnace as follows:

$$X(t) = \begin{bmatrix} h_{eg}(t) \\ \rho_{eg}(t) \end{bmatrix} ; \quad U(t) = \begin{bmatrix} F_f(t) \\ F_a(t) \\ F_r(t) \\ h_r(t) \\ \theta(t) \end{bmatrix} ; \quad Y(t) = \begin{bmatrix} q_r(t) \\ q_s(t) \\ q_g(t) \\ T_g(t) \\ P_g(t) \end{bmatrix}$$

Using the above notations, a nonlinear state-space model for the furnace is derived in the form:

$$\dot{X}_1 = f_1(X, U)$$

$$\dot{X}_2 = f_2(X, U)$$

Then the model is linearized around the operating point: $X_0 = \begin{bmatrix} 289.896 \\ 0.45052 \end{bmatrix}$ to obtain the

following model:

$$A = \begin{bmatrix} -2.00135 & -244.111282 \\ -0.000236 & -0.192285 \end{bmatrix}$$

$$B = \begin{bmatrix} 7.0959 & -1.7085 & -0.7815 & 0.0130 & 37.0643 \\ 0.000192 & 0.000192 & 0.000192 & 0.0000 & 0.0228 \end{bmatrix}$$

$$U_0 = [119.3 \cdot 10^3 \quad 715.8 \cdot 10^3 \quad 109.9 \cdot 10^3 \quad 169.92 \quad 0.8804]^T$$

2.2.2 SIMULINK model and Simulation results

Based on the state space equation presented above, we build the following SIMULINK model:

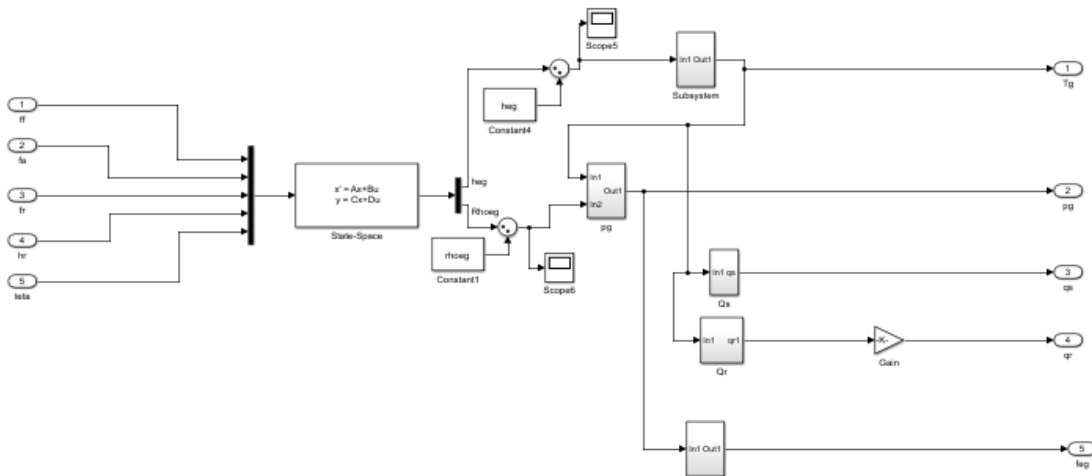
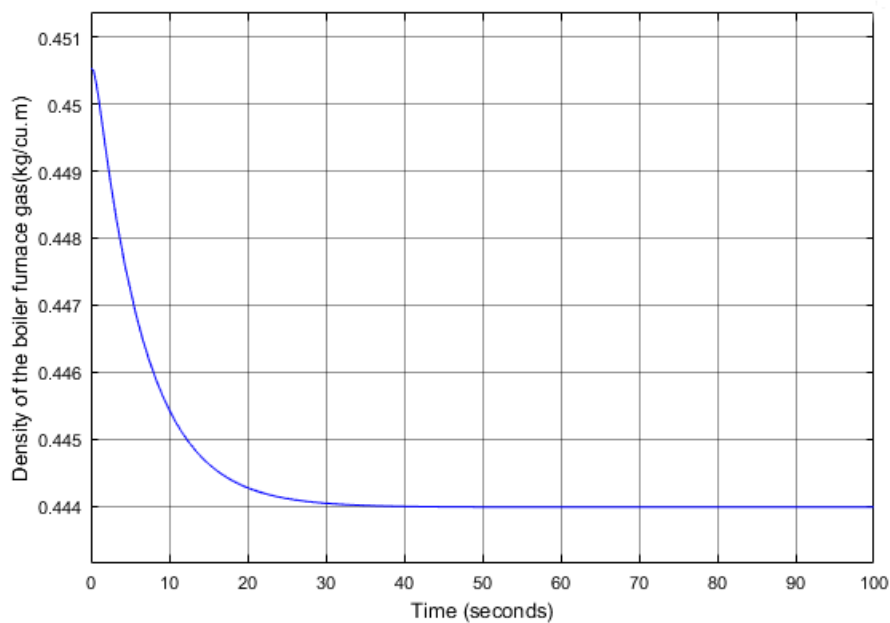
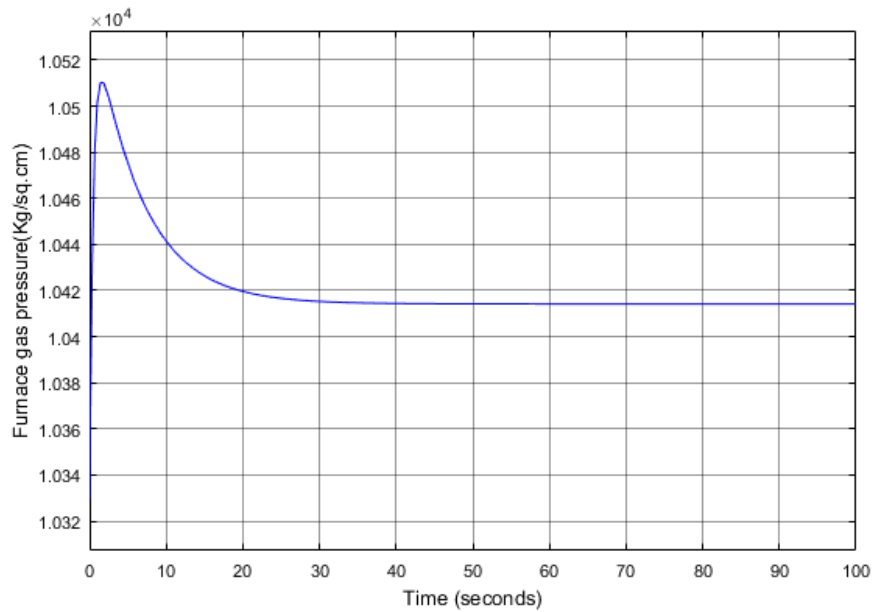


Figure2.1 boiler Furnace SIMULINK model

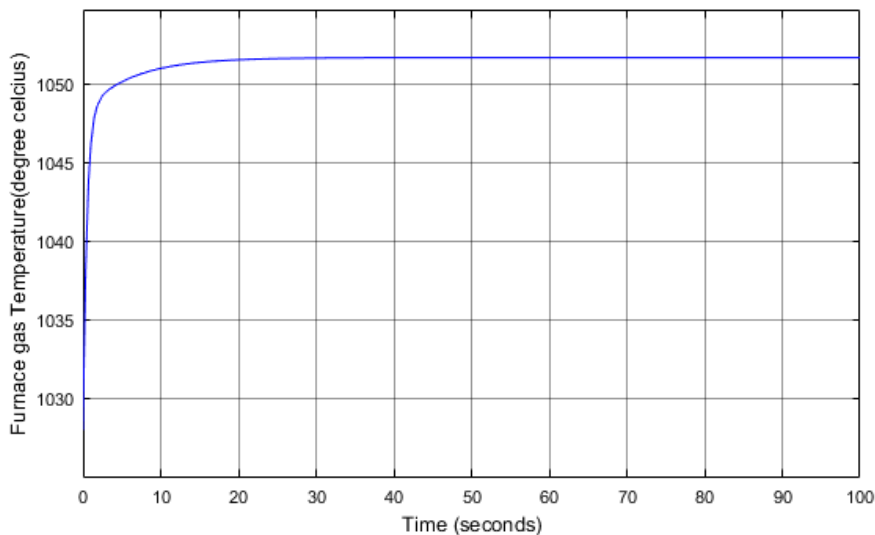
Simulating for a +5% change in the Fuel flow entering the Furnace, we get the following results:



(a)



(b)

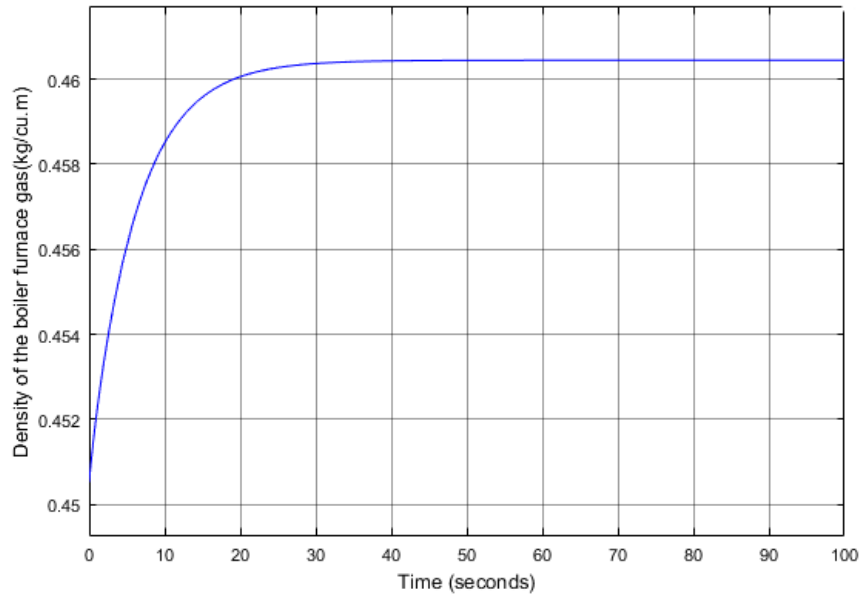


(c)

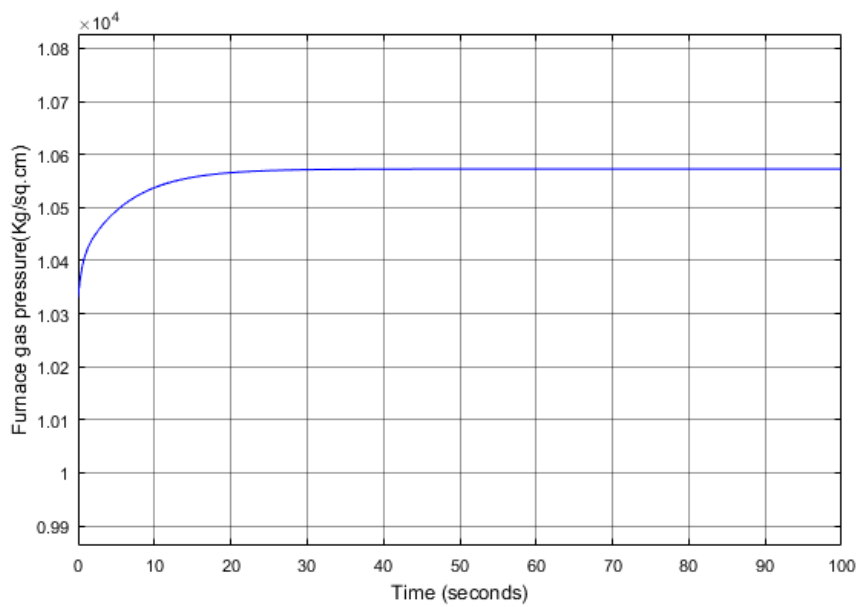
Figure 2.2 Response of (a) Density (b) pressure (c) Temperature of Furnace gas to 5% increase in fuel flow

It is observed that the specific enthalpy of gas, furnace gas temperature, heat transferred to the riser and heat transferred to the SSH, increase gradually and reach the steady state values. Due to the increase in fuel flow, the furnace gas pressure and mass flow of furnace gas through the boiler reaches the peak value initially, and decreased to steady state values. The density of the exhaust gas decreases slowly due to the increase in fuel flow.

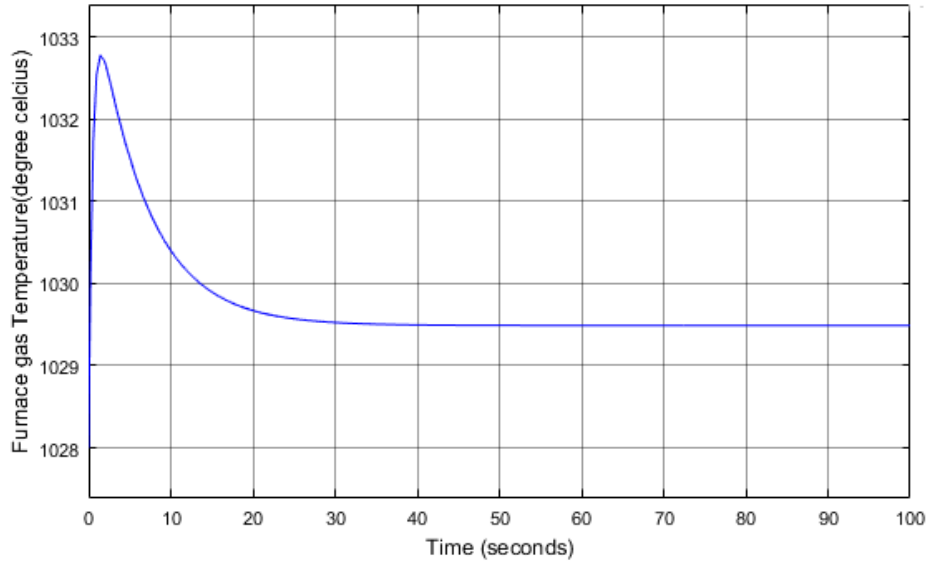
Simulating again for 10% increase in Burner tilt, we get the following results:



(a)



(b)



(c)

Figure 2.3 Response of (a) Density (b) Pressure (c) Temperature of the Furnace gas to 10% increase in Burner tilt

We see that the specific enthalpy of gas, furnace gas temperature, heat transferred to the riser, increase to reach a peak value initially then decrease to steady state values. Due to the increase in burner tilt angle, the furnace gas pressure and mass flow of furnace gas through the boiler increase gradually to reach steady state values along with the density of the exhaust gas.

2.3 Boiler Drum Model Simulation

2.3.1 State Space Model

Using the equations stated in the first chapter, we derive the following differential equations first:

$$\frac{d}{dt} \rho_{eg}(t) = \frac{1}{q_2(t)q_4(t)\rho_{dw}(t)} \left\{ \rho_{d(t)} F_{ew}(t) - \rho_{dw}(t) F_d(t) + X_{q(t)} F_D(t) (\rho_{dw}(t) - \rho_d(t)) \right\} \quad (2.3)$$

$$\frac{d}{dt} V_{dw}(t) = \frac{1}{q_4(t)\rho_{dw}(t)} \left\{ (1 + q_3(t)) F_{ew}(t) - q_3(t) F_d(t) + X_q(t) F_D(t) \right\} \quad (2.4)$$

Then we proceed to calculate the water level in the drum as follows:

$$f(l_d) = \frac{1}{3} \pi l_d^2 (3r - l_d) + l \left\{ \frac{\pi r^2}{2} + r^2 \sin^{-1} \left(\frac{l_d - r}{r} \right) + (l_d - r) \sqrt{2rl_d - l_d^2} \right\} - V_{dw} \quad (2.5)$$

Using Newton-Raphson method we finally obtain the exact value of the drum level. Let us first define a 2x1 State vector $X_d(t)$, 4x1 Input vector $U_d(t)$ and a 3x1 Output vector $Y_d(t)$ for the boiler drum and then formulate a state space model.

$$X_d(t) = \begin{bmatrix} \rho d(t) \\ V_{dw}(t) \end{bmatrix}; \quad U_d(t) = \begin{bmatrix} F_{ew}(t) \\ q_r(t) \\ F_d(t) \\ h_{ew}(t) \end{bmatrix}; \quad Y_d(t) = \begin{bmatrix} L_d(t) \\ P_d(t) \\ T_d(t) \end{bmatrix}$$

With the above notations, the differential equations and the output equations are presented in the form of a nonlinear state space model of the form:

$$\dot{X}_d = f(X_d, U_d)$$

$$Y_d = g(X_d)$$

2.3.2 SIMULINK model and Simulation results

The simulation studies are carried out with the help of the nominal values of the boiler drum variables and parameters as shown in the figure:

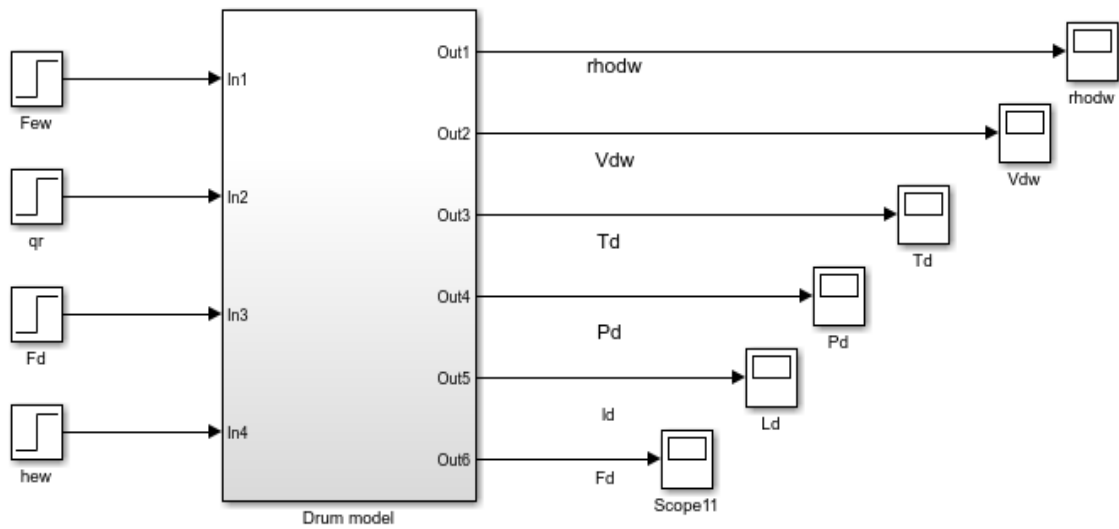
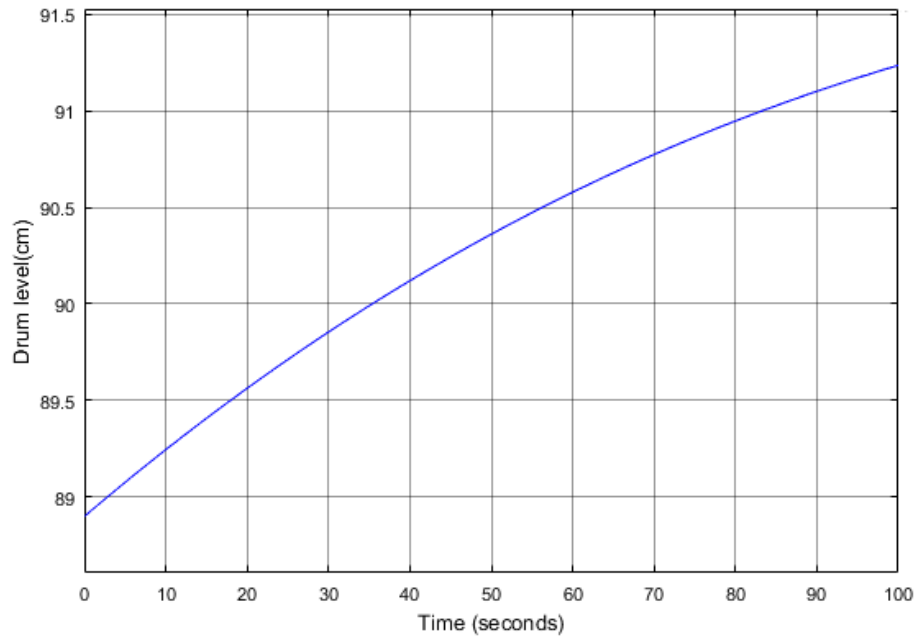
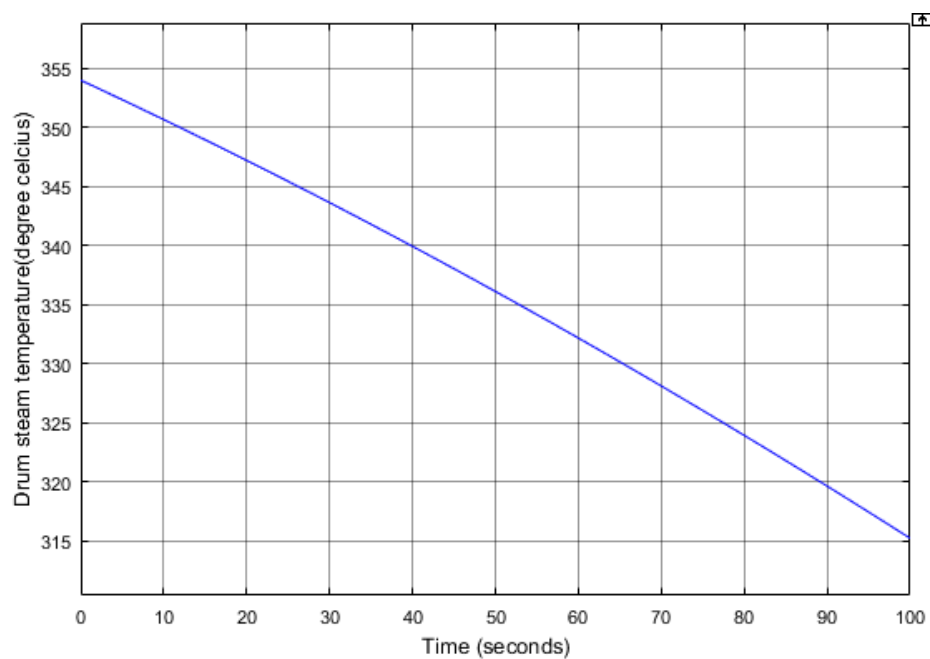


Figure2.4. boiler Drum SIMULINK model

Simulating for +15% change in the feed water to the Drum: we get the following:



(a)

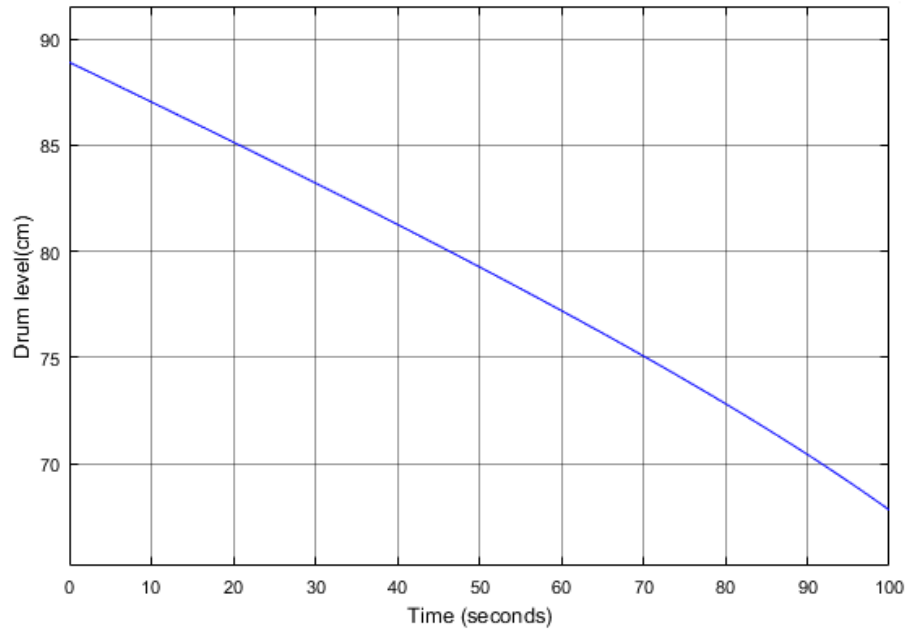


(b)

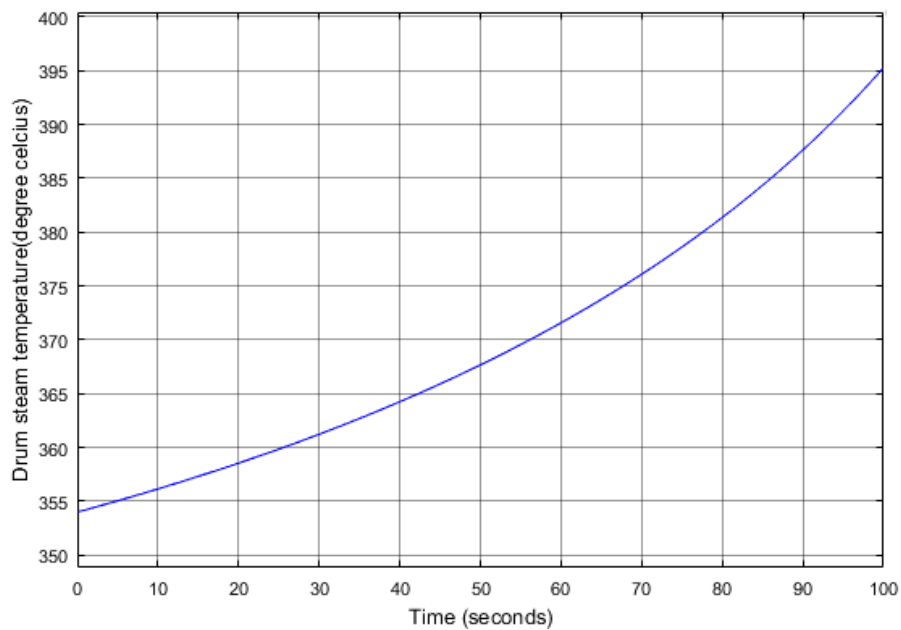
Figure 2.5 Response of (a) drum water level (b) drum steam temperature to 15% increase in Feed water

We see that the drum level (hence the Drum water Volume) increases, in the other hand the drum steam temperature (hence drum steam density) decreases.

We then simulate again for -15% change in the feed water and we get the simulation results shown in the figures:



(a)



(b)

Figure 2.6 Response of (a) Drum Water Level (b) Drum Steam Temperature to 15% Decrease in Feed water

For this case, we see the inverse happening, Drum level (hence the Drum water volume) is decreasing, while the drum steam temperature (hence the Drum steam density) is increasing.

2.4 Primary Super-Heater Model Simulation

2.4.1 State space model

Using differential Equations (1.12), (1.13) and (1.15) a linear second order state space model is derived for the PSH as given below:

$$\dot{X}_p = A_p * X_p + B_p * U_p$$

Where:

$$X_p(t) = \begin{bmatrix} T_{sp}(t) \\ T_{mp}(t) \end{bmatrix}$$

$$U_p(t) = \begin{bmatrix} T_d \\ T_{gp} \end{bmatrix}$$

A_p is the 2 x 2 System matrix and B_p is the 2 x 2 Input matrix.

Using these system variables and parameters, the system matrix A_p and Input matrix B_p

are computed around the operational point $X_0 = \begin{bmatrix} 420 \\ 430 \end{bmatrix}$ and given below:

$$A_p = \begin{bmatrix} -3.759262 & 3.594246 \\ 0.053294 & -0.054462 \end{bmatrix} ; B_p = \begin{bmatrix} 0.165017 & 0 \\ 0 & 0.001168 \end{bmatrix}$$

2.4.2 SIMULINK model and Simulation results

Based on the state space equation presented above, we build the SIMULINK model shown in the figure:

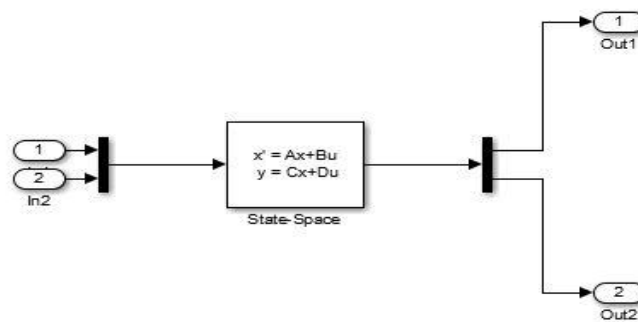
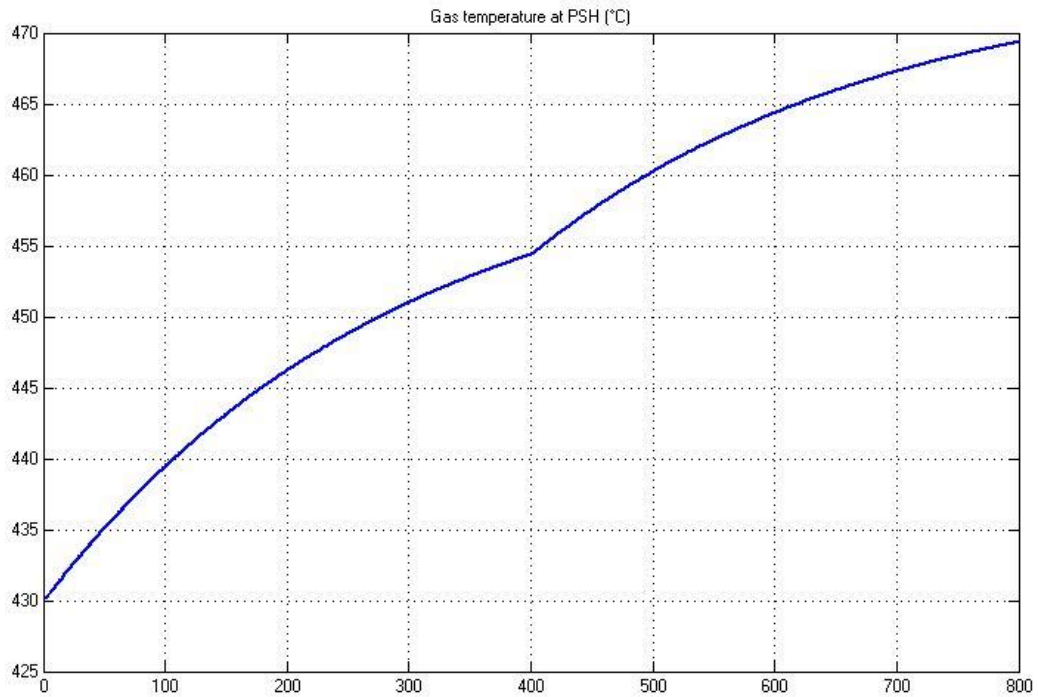
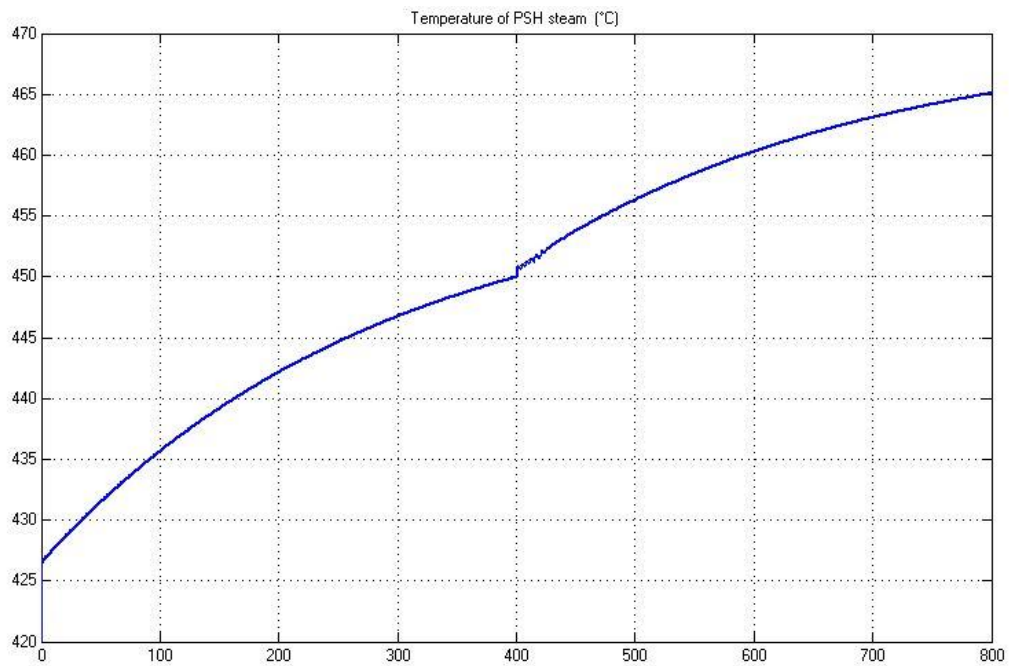


Figure2.7 PSH SIMULINK model

For +5% change in T_d we get the following results for T_{gp} and T_{mp} Respectively



(a)

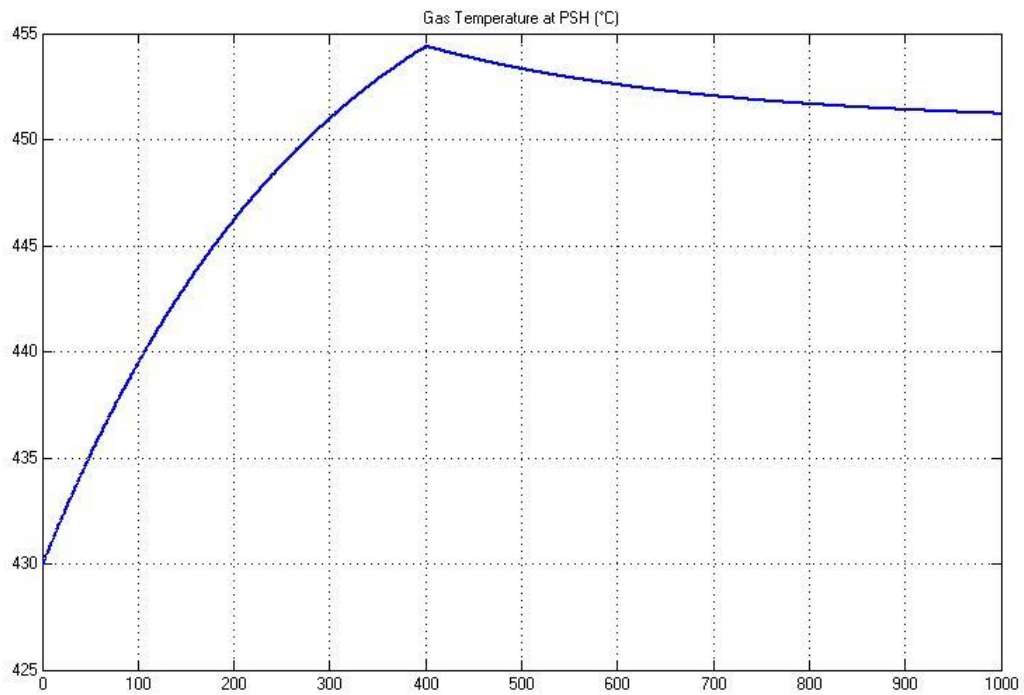


(b)

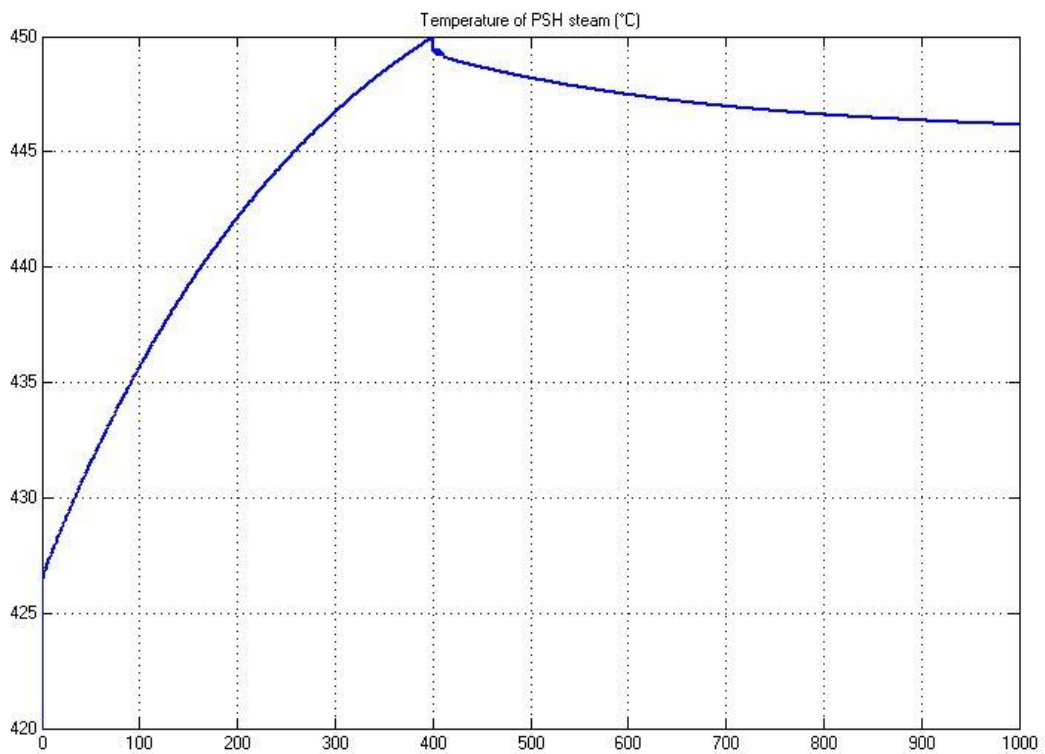
Figure 2.8 Response of (a) $T_{gp}(t)$ and (b) $T_{mp}(t)$ to 5% increase the drum steam temperature

the change is made at 400(s) we notice that for 5% increase in T_d , the output temperatures also increases to settle at a steady state value.

Now we try with -5% change in the input drum temperature we see that:



(a)



(b)

Figure 2.9 Response of (a) $T_{gp}(t)$ and (b) $T_{mp}(t)$ to 5% decrease in the drum steam temperature

T_{gp} and Temperature of PSH steam both decrease to reach a steady state value.

2.5 Attenuator Model Simulation

2.5.1 Output Equations for the Attenuator

Using the Equations of chapter one, the following variation equations are obtained:

$$\Delta F_s(t) = \Delta F_{sp}(t) + \Delta F_{spa}(t) \quad (2.6)$$

$$F_s(t)\Delta h_{si}(t) + \Delta F_s(t)h_{si} = F_{sp}(t)\Delta h_{sp}(t) + \Delta F_{sp}(t)h_{sp}(t) + F_{spa}(t)\Delta h_{spa}(t) + \Delta F_{spa}(t)h_{spa}(t) \quad (2.7)$$

Calculating and rearranging the above equations we get:

$$\Delta T_{spi}(t) = \frac{1}{F_s C_{si}} \left\{ (h_{sp}(t) - h_{si}(t)) \Delta F_s(t) + F_{sp} C_{sp} \Delta T_{sp}(t) - \Delta F_{spa}(t) (h_{sp}(t) - h_{spa}(t)) \right\} \quad (2.8)$$

2.6 Secondary Super Heater Model Simulation

2.6.1 State space model

Using differential Equations (1.12) and (1.13) and (1.15), a linear second order state space model is derived for the PSH as given below:

$$\dot{X}_s = A_s X_s + B_s U_s \quad \text{Where:}$$

$$X_s(t) = \begin{bmatrix} T_s \\ T_m \end{bmatrix}$$

$$U_s(t) = \begin{bmatrix} T_{si} \\ T_g \end{bmatrix}$$

A_s is the 2 x 2 System matrix and B_s is the 2 x 2 Input matrix.

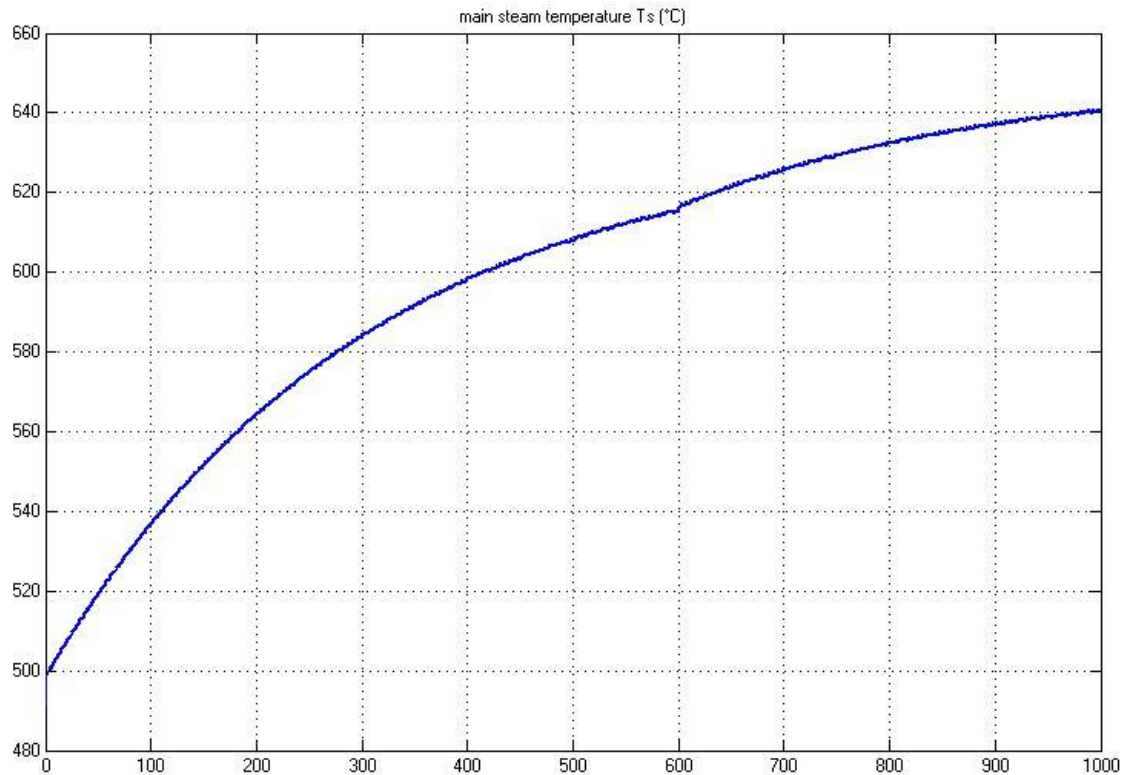
Using these system variables and parameters, the system matrix A_s , and the Input

matrix B_s are computed around the operational point $X_0 = \begin{bmatrix} 491 \\ 501 \end{bmatrix}$ and given below:

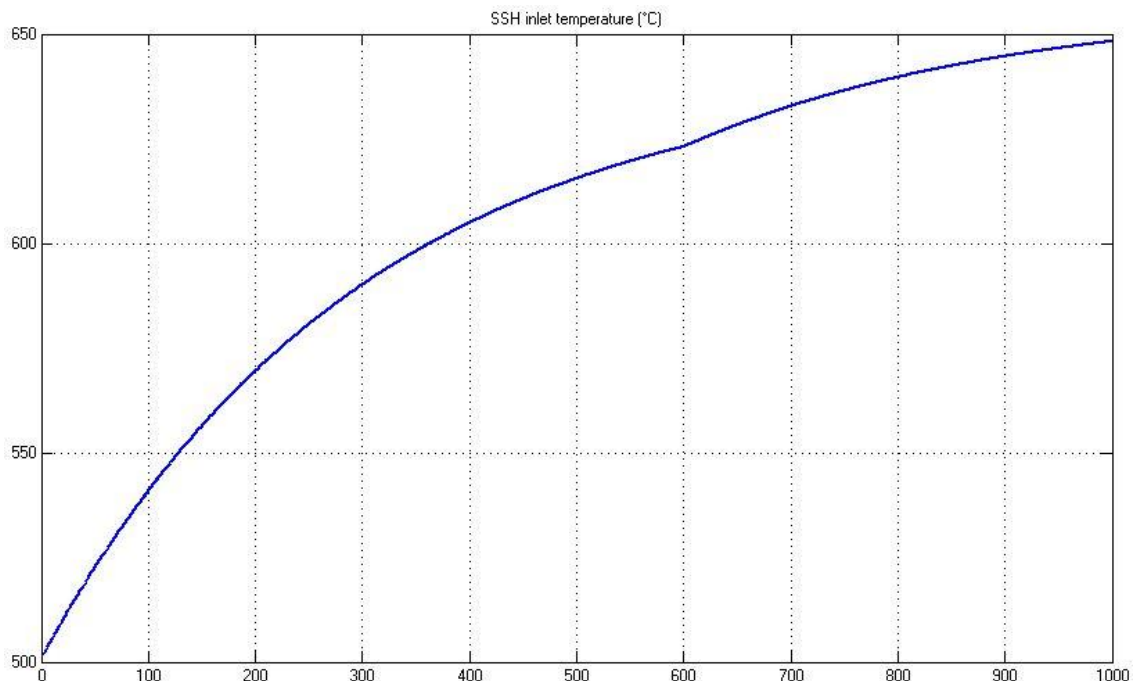
$$A_s = \begin{bmatrix} -3.94751 & 3.782493 \\ 0.053859 & -0.054981 \end{bmatrix} ; \quad B_p = \begin{bmatrix} 0.165017 & 0 \\ 0 & 0.001122 \end{bmatrix}$$

2.6.2 Simulation Results

For +5% and then -5% in inlet steam temperature we get the results shown in the figures:

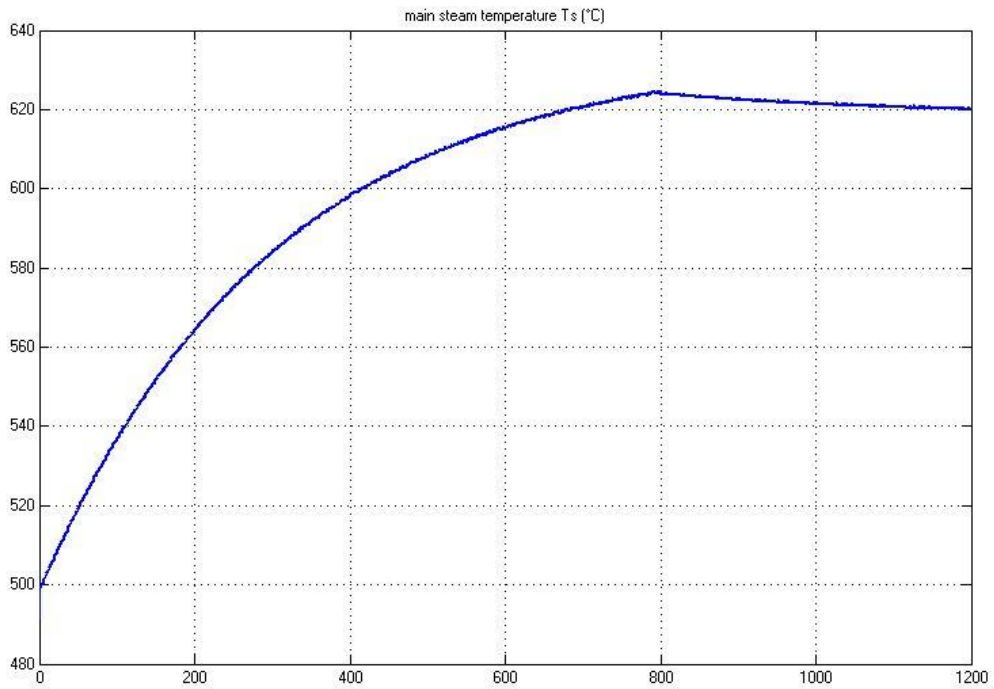


(a)

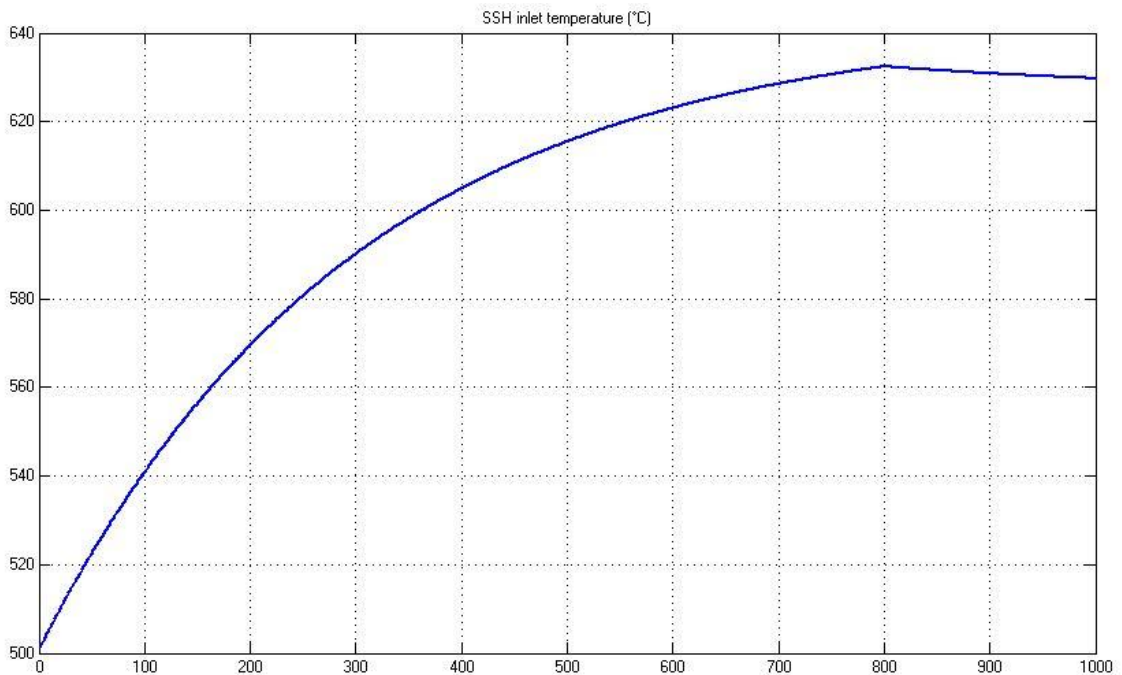


(b)

Figure 2.10 Response of (a) $T_{gp}(t)$ and (b) $T_{mp}(t)$ to 5% increase in inlet steam temperature



(a)



(b)

Figure 2.11 Response of (a) $T_{gp}(t)$ and (b) $T_{mp}(t)$ to 5% decrease in inlet steam temperature

We see that Both Inlet and main steam temperature increase for +5% change of the input temperature, also both decrease when applying a -5% change.

2.7 The integrated Model

Linking all the subsystems and building our system as shown in the figure:

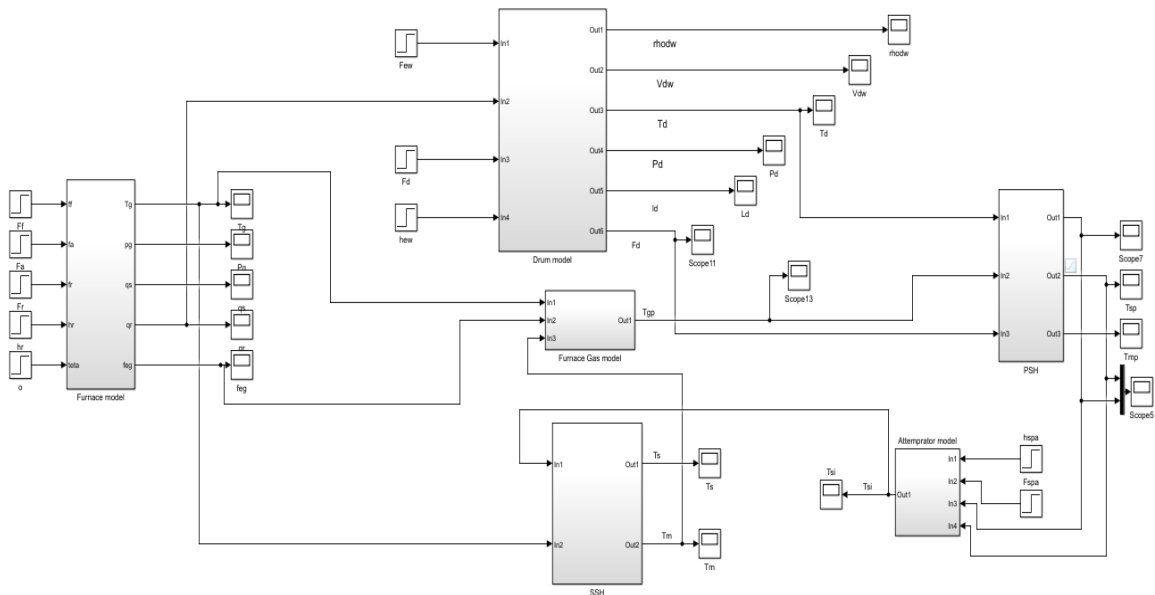
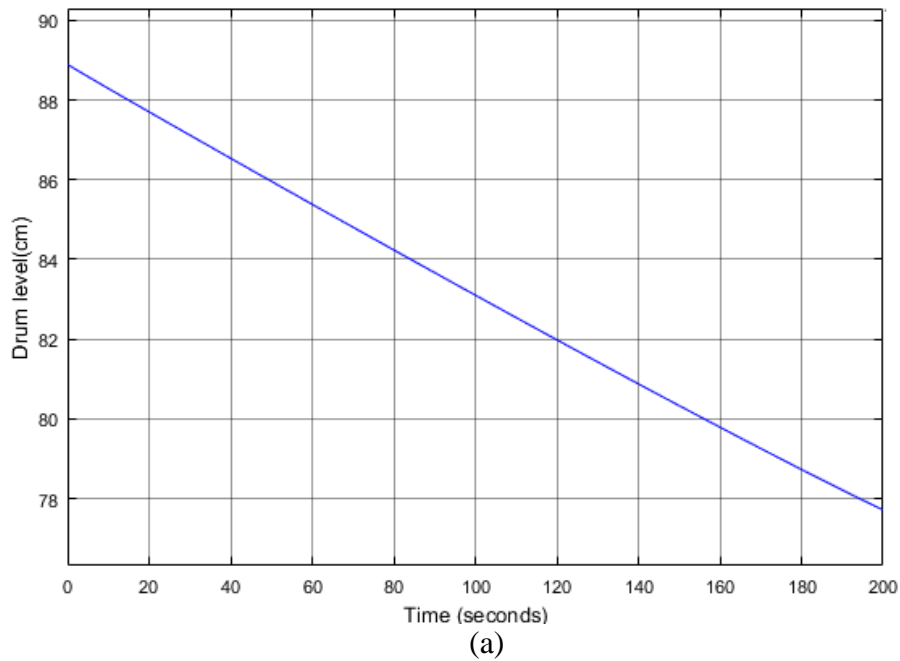
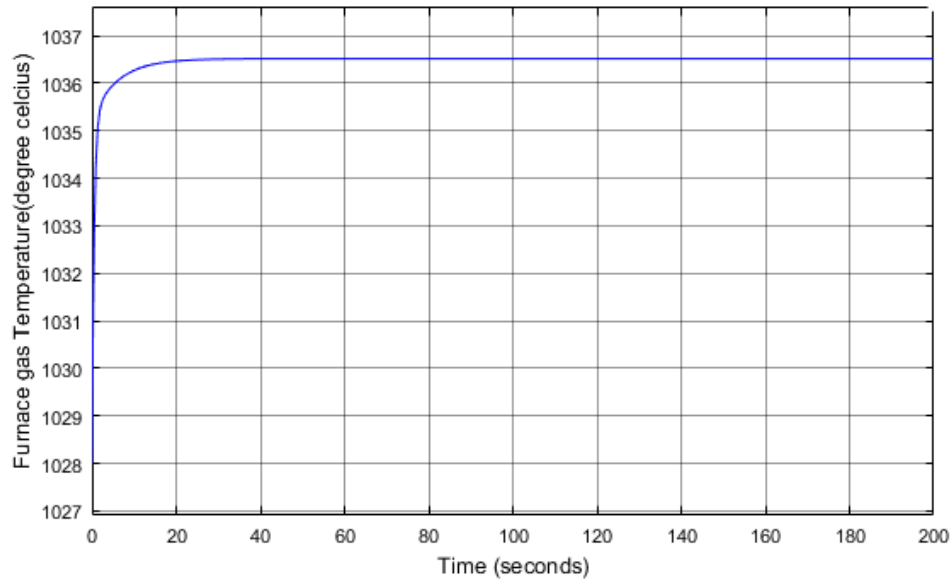


Figure2.12 boiler integrated SIMULINK model

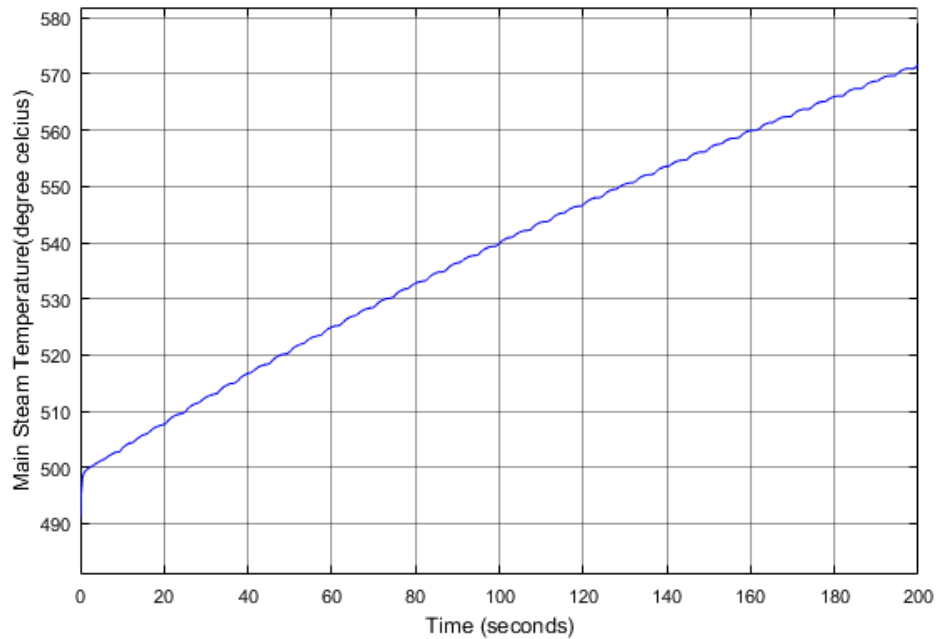
2.7.1 Simulation Results

We'll have a 5% change in the fuel flow and observe the responses of the output variables $I_d(t)$, $T_g(t)$ and $T_s(t)$, results are shown in the figures below:





(b)



(c)

Figure 2.13 Response of (a) $l_d(t)$, (b) $p_d(t)$ and (c) $T_s(t)$ Respectively to 5% increase in fuel flow

From the graph it is inferred that the furnace temperature attains the steady state value quickly, as compared to the main steam temperature.

2.8 Conclusion

In this chapter, the design and development of the 210MW Boiler process is discussed in detail. It is observed that the open loop response of the integrated model is

unstable thus we need to design a closed loop controller; this will be discussed in the next chapter.

Chapter Three

Drum Level Control

3.1 Introduction

The control system for a boiler–turbine unit usually needs to meet the requirement of the amount of water in the steam drum must be maintained at a desired level to prevent overheating of the drum or flooding of steam lines. This is critical for the safe and economic operation of a power plant. The drum level must be controlled to the limits specified by the boiler manufacturer. If the drum level does not stay within these limits, there may be water carryover. If the level exceeds the limits, boiler water carryover into the super-heater or the turbine may cause damage resulting in extensive maintenance costs or outages of either the turbine or the boiler. If the level is low, overheating of the water wall tubes may cause tube ruptures and serious accidents, resulting in expensive repairs, downtime, and injury or death to personnel. A rupture or crack most commonly occurs where the tubes connect to the drum [6].

3.2 Control Strategies

Providing tight water level control in a drum is accomplished by utilizing one of three types of drum level control: single-element, two-element, or three-element [6].

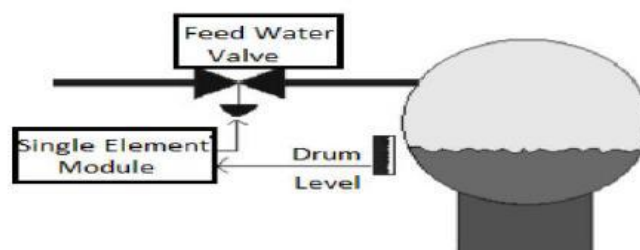


Figure 3.1 Single Element Control

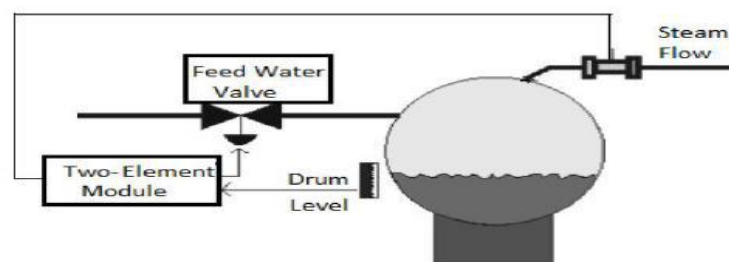


Figure 3.2 Two Element Control

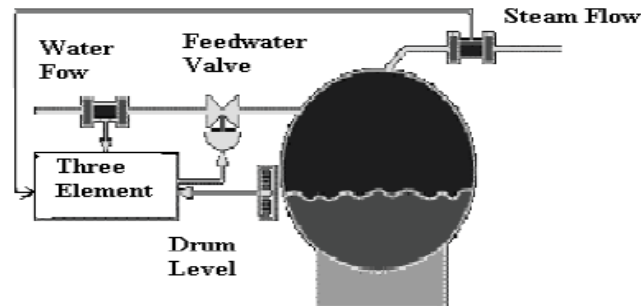


Figure 3.3 Three Element Control

The term 'single-element' is derived from single variable: drum level influence on the feed-water valve position. While single-element drum level control is acceptable for steady boiler load conditions; as load changes become more frequent, unpredictable, or severe; this type of level control cannot respond quickly enough to compensate. The term 'two-element' is derived from two variables: steam flow and drum level influence on the feed-water valve position.

The term 'three-element' is derived from three variables: steam flow, feed water flow and drum level influence on the feed-water valve position. Wide Fast Combination of batch and continuous type operations such that plant steam load characteristics varies continuously and usually unpredictably [7].

3.3 Boiler Drum Level Control

The Boiler drum is a crucial part of the boiler process, in view of modeling and control system design. The Boiler drum mimics the nonlinearity and time varying nature of many industrial applications. Hence, the Boiler drum is chosen to be the process for implementing the concept of Linear Parameter Varying (LPV) [8].

3.3.1 Linear Parameter Varying (LPV)

For many processes in a chemical process industry, it is necessary to operate at various working points (scheduling variables). Such processes often show smooth, non-chaotic and non-linear behavior as a function of certain scheduling variables. Often an approximation in the form of Linear Parameter Varying (LPV) systems is sufficient to describe such systems.

The LPV model represents the non-linear behavior of the process as a function of scheduling variables [8]. ‘Scheduling variables’ are referred to as parameters which contribute to the time varying nature of the system.

LPV model is the interpolation of linear transfer function models at different operating conditions [9] [10]. The LPV model is adopted by considering the fact that the Industrial Boiler in the thermal power plant has several operating conditions due to the fluctuations in steam flow based on demands. By assuming that at every operating condition, there are changes in parameters, this model is suitable for covering all operating conditions [11].

The LPV will briefly be described for a Many-input single-output (MISO) process [12]. Let $y(t)$ represent the process output at discrete time t , $u(t)$ the input vector at time t and $w(t)$, the working-point variable (scheduling variable) which determines the working point of the process operation where:

$$\mathbf{w}(t) \in [\mathbf{w}_l, \mathbf{w}_h] \quad (3.1)$$

w_l and w_h are the low and high limits of $w(t)$ which projects the operating trajectory of the process. The identification tests are performed by adding small test signals during normal operation of the process. The test signal amplitudes are determined in such a way that they will not cause any problem in safe operation. Each linear model is identified using the data at each working point. Several linear identification methods can be used, such as prediction error method, subspace method and asymptotic method. Assume that the process has p working points and the linear models are denoted as follows:

$$\begin{aligned} \mathbf{y}_1(t) &= \mathbf{G}_{11}(\mathbf{q})\mathbf{u}_1(t) + \cdots \cdots \cdots + \mathbf{G}_{m1}(\mathbf{q})\mathbf{u}_m(t) & \mathbf{w}(t) &= \mathbf{w}_1 \\ \mathbf{y}_2(t) &= \mathbf{G}_{12}(\mathbf{q})\mathbf{u}_1(t) + \cdots \cdots \cdots + \mathbf{G}_{m2}(\mathbf{q})\mathbf{u}_m(t) & \mathbf{w}(t) &= \mathbf{w}_2 \\ & & & \cdot \\ & & & \cdot \\ & & & \cdot \\ \mathbf{y}_p(t) &= \mathbf{G}_{1p}(\mathbf{q})\mathbf{u}_1(t) + \cdots \cdots \cdots + \mathbf{G}_{mp}(\mathbf{q})\mathbf{u}_m(t) & \mathbf{w}(t) &= \mathbf{w}_p \end{aligned} \quad (3.2)$$

Where: G is the linear transfer function, q^{-1} is the unit delay operator, m is the number of inputs and p represents number of operating conditions along operating trajectories. Then the LPV model is obtained by interpolating the linear models using total data as follows:

$$y(t) = \alpha_1(w)y_1(t) + \alpha_2(w)y_2(t) + \dots + \alpha_p(w)y_p(t) \quad (3.3)$$

Where: $\alpha_1(w)$, $\alpha_2(w)$ and $\alpha_p(w)$ are weights which are functions of the working point variable $w(t)$. These weights can be determined using triangular weighing function which is pre-assigned and needs no estimation.

The LPV model using triangular weighing function for three operating regions [13] is denoted as follows:

$$y(t) = \left\{ \begin{array}{ll} y_1(t) & w(t) \leq w_1 \\ \frac{w_2-w(t)}{w_2-w_1} y_1(t) + \frac{w(t)-w_1}{w_2-w_1} y_2(t) & w_1 < w(t) \leq w_2 \\ \frac{w_3-w(t)}{w_3-w_2} y_2(t) + \frac{w(t)-w_2}{w_3-w_2} y_3(t) & w_2 < w(t) < w_3 \\ y_3(t) & w_3 \leq w(t) \end{array} \right\} \quad (3.4)$$

3.3.2 Linear Parameter Varying (LPV) of Boiler Drum

In our work, the LPV model of the Boiler drum is a single-input single-output (SISO) process and it is obtained by considering the feed-water flow rate as the input and the drum level as both the output and scheduling variable as shown in the Figure 3.4.

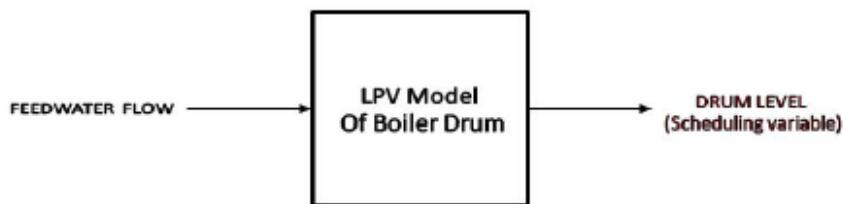


Figure3.4 Input-output representation of the Boiler Drum

The entire operating trajectory of the Boiler drum considered in this work is obtained by perturbing the input variable by 25% from its nominal value. The feed water flow rate of the boiler drum is excited in steps in the entire operating trajectory, and the changes in the drum level as four distinct slope regions are shown in Figure 3.5.

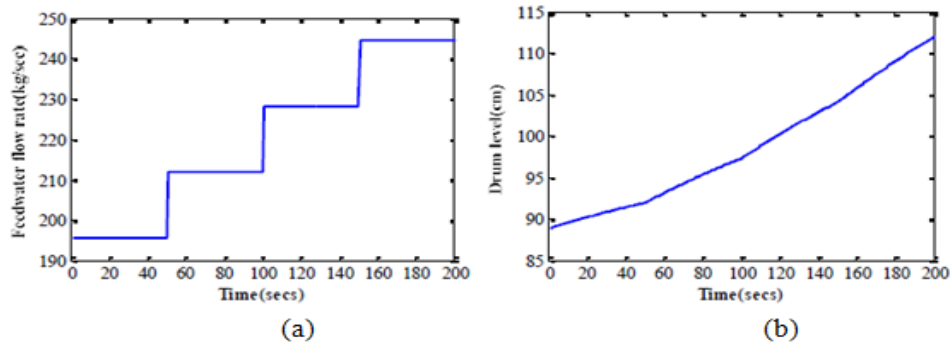


Figure 3.5 Open loop response of the boiler drum system showing variation of (a) the feed water flow rate (input) with (b) drum level (output)

The level of the boiler obtained by the excitation of the first principle model is nonlinear, as shown in Figure 3.5. This non linear response is divided into four linear regions. The four operating points are chosen at a height of 92cm, 97.4cm, 104.2cm and 112.3cm. For individual regions the linear transfer function models are developed, using the System Identification Toolbox for every input output combination. The linear transfer function models are denoted as a first order which has the form: $\frac{K_p}{\tau_p s + 1}$, where k_p the process gain and τ_p is the time constant. The linear transfer function model obtained for the four linear regions is reported as the process model parameters at different operating points, for the boiler drum process in Table 3.1:

Table 3.1 Process model parameters at different operating points for the boiler drum

Operating Region	Feed water Flow rate (kg/sec)	Drum Level (cm)	Process gain (k_p)	Time constant (τ_p) (sec)
Region 1	195.6	92	0.63227	135.31
Region 2	211.9	97.4	1.2384	160.61
Region 3	228.2	104.2	1.8097	186.88
Region 4	244.5	112.3	2.5774	232.10

Each linear transfer function model is identified using the data sets at each working point. The developed linear transfer function models are validated with the help of the first principle model output. Figures 3.6 (a), (b), (c) and (d) show the change in the

drum level in each linear region of the linear transfer function model and the first principle model.

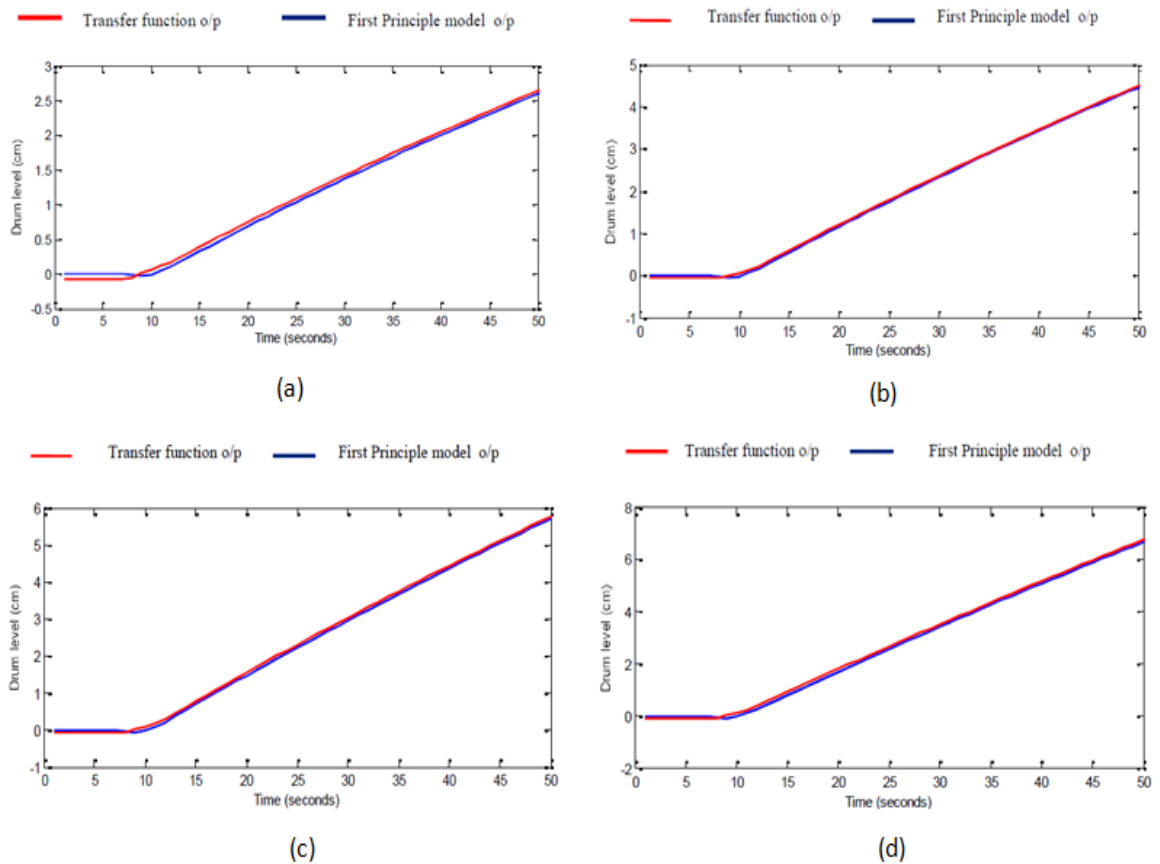


Figure 3.6 Validation of the transfer function using the first principle model in: (a) region 1 (b) region 2 (c) region 3 (d) region 4

3.3.3 LPV Model Identification

The working point variable (scheduling variable) determines the working point of the process operation. Due to the time varying nature of the level of the boiler drum, it is considered as the scheduling variable. The entire operating trajectory of the boiler drum is divided into four regions, and the corresponding scheduling variable values are $w_1 = 92\text{cm}$, $w_2 = 97.4\text{cm}$, $w_3 = 104.2\text{cm}$ and $w_4 = 112.3\text{cm}$.

The weights which are functions of the scheduling variable, drum level, are estimated using the triangular weighting function method and are listed below.

The weights which are functions of the scheduling variable, drum level, are estimated using the triangular weighting function method and are listed below.

$$\alpha_1(l_d) = \left\{ \begin{array}{ll} 1 & l_d(t) \leq 92 \\ \frac{97.4 - l_d(t)}{97.4 - 92} & 92 < l_d(t) \leq 97.4 \\ 0 & l_d(t) > 97.4 \end{array} \right\} \quad (3.5)$$

$$\alpha_2(l_d) = \left\{ \begin{array}{ll} 0 & l_d(t) \leq 92 \\ \frac{l_d(t) - 92}{97.4 - 92} & 92 < l_d(t) \leq 97.4 \\ \frac{104.2 - l_d(t)}{104.2 - 97.4} & 97.4 < l_d(t) \leq 104.2 \\ 0 & l_d(t) > 104.2 \end{array} \right\} \quad (3.6)$$

$$\alpha_3(l_d) = \left\{ \begin{array}{ll} 0 & l_d(t) \leq 97.4 \\ \frac{l_d(t) - 97.4}{104.2 - 97.4} & 97.4 < l_d(t) \leq 104.2 \\ \frac{112.3 - l_d(t)}{112.3 - 104.2} & 104.2 < l_d(t) \leq 112.3 \\ 0 & l_d(t) > 112.3 \end{array} \right\} \quad (3.7)$$

$$\alpha_4(l_d) = \left\{ \begin{array}{ll} 0 & l_d(t) \leq 104.2 \\ \frac{l_d(t) - 104.2}{112.3 - 104.2} & 104.2 < l_d(t) \leq 112.3 \\ 1 & l_d(t) > 112.3 \end{array} \right\} \quad (3.8)$$

Where: α_1 , α_2 , α_3 and α_4 are the weights, which are the functions of the scheduling point variable (boiler drum level). The weights associated with each and every operating point of the scheduling variable are shown in Figure 3.7.

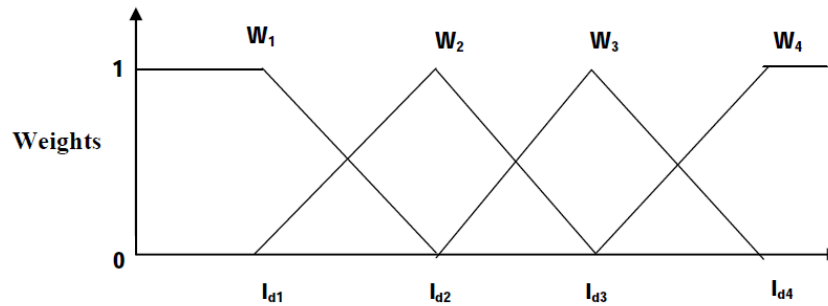


Figure 3.7 the Weighting Function $w(l_d)$

The four linear transfer function models obtained using the data from the first principle model, are fused using the weighting function to obtain the LPV model. A comparison between the response of LPV models using the triangular weights and that of the first principle models is shown in Figure 3.8.

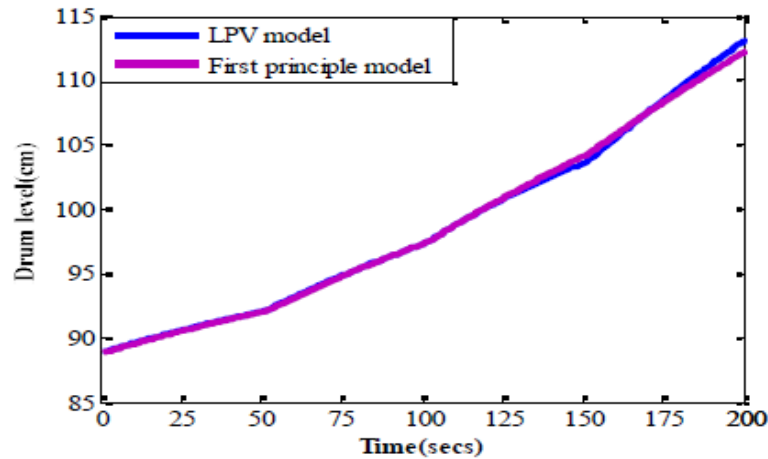


Figure 3.8 Comparison of the open loop responses of the first principle model with the LPV model

3.3.4 Design of the PI Controller

Conventional PID controllers are widely used in the process industry as they are easy to implement and maintain. There is a number of techniques for tuning the parameters of the PID controllers. Among them, and the most effective [1], used tuning method is the Internal Model Control (IMC) based PID method. The IMC based PID design procedure for a first order process has resulted in a PI control law. The major difference is that there are no longer two degrees of freedom in the tuning parameters (k_c, τ_i). The IMC based procedure shows that only the proportional gain needs to be adjusted. The integral time is simply equal to the process time constant. Based on the values, the system response can be fast or sluggish. The PI controller settings are given as follows [9]:

$$k_c = \frac{\tau_p}{k_p \lambda} \quad (3.10)$$

$$\tau_p = \tau_i \quad (3.11)$$

A single PI controller is designed, using the IMC method for each region of the four regions.

3.3.5 Design of the Multi-Model PI Control Scheme

Because the LPV model represents the approximated nonlinear boiler drum model, the PI controllers should operate in their corresponding regions in order to provide better performance. In the entire operating trajectory, for every change in set point, the

respective controller parameters are selected. The triangular weighting function is used for switching different controllers, which will help in the smooth transition from one controller region to another controller region. At each sampling instant, the weighting function will assign weights for each PI controller output, and the weighted sum of this output will be applied as input to the first principle model of the boiler drum. The weighting function that determines the weights w_1 , w_2 , w_3 and w_4 is based on the scheduling variable, drum level. The weights are in the range of 0 to 1. This is represented in Figure 3.9.

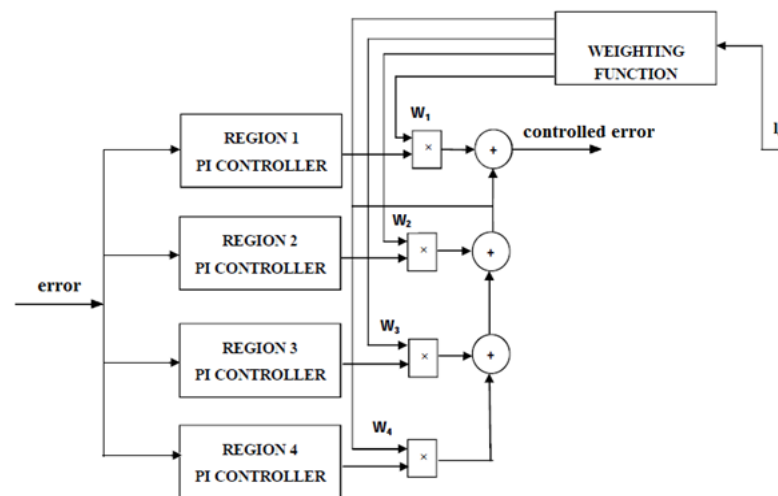


Figure 3.9 Multi-Model PI Controller Scheme

3.4 Drum control simulation using MATLAB/SIMULINK

The PI controllers, that have been previously developed, are attempted implement in MATLAB/SIMULINK. We worked on two boiler drum control techniques which are: 'single-element control' and 'three-element control'.

3.4.1 Single Element Control

In this strategy, the system drum level is measured using a single measurement device and provides a control signal to the feed-water regulator in direct relation to the current operating drum level. The system that has been built is shown in the Figure 3.10.

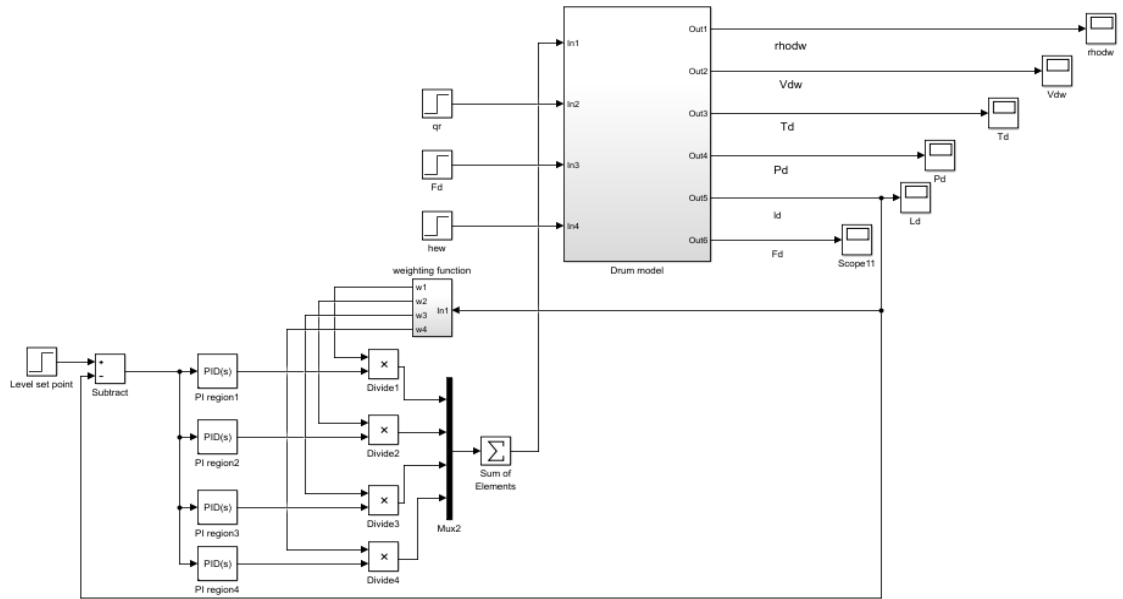
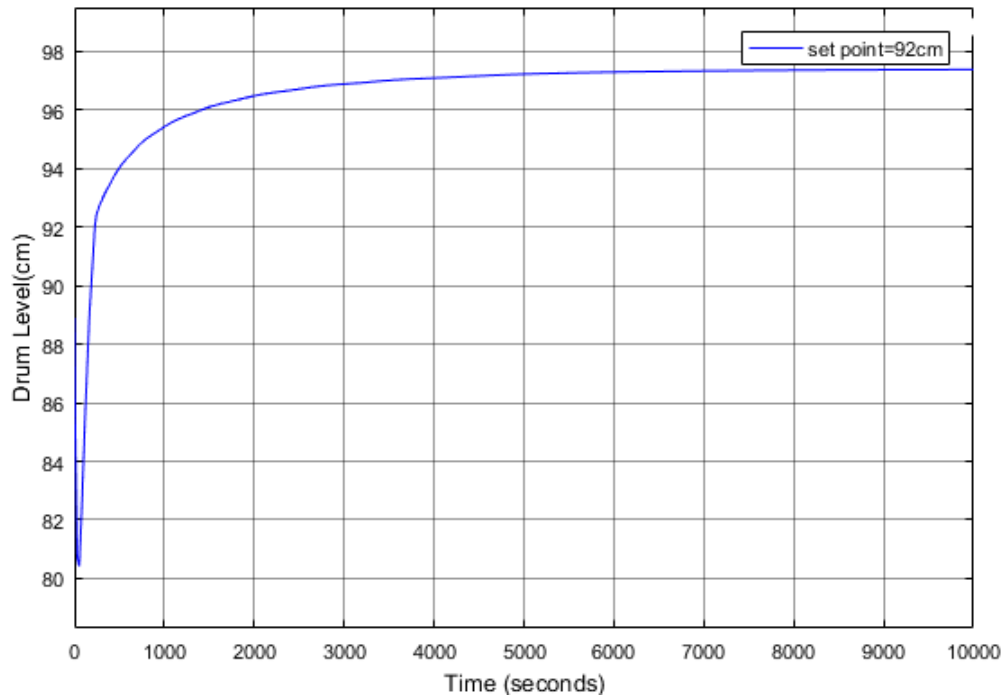
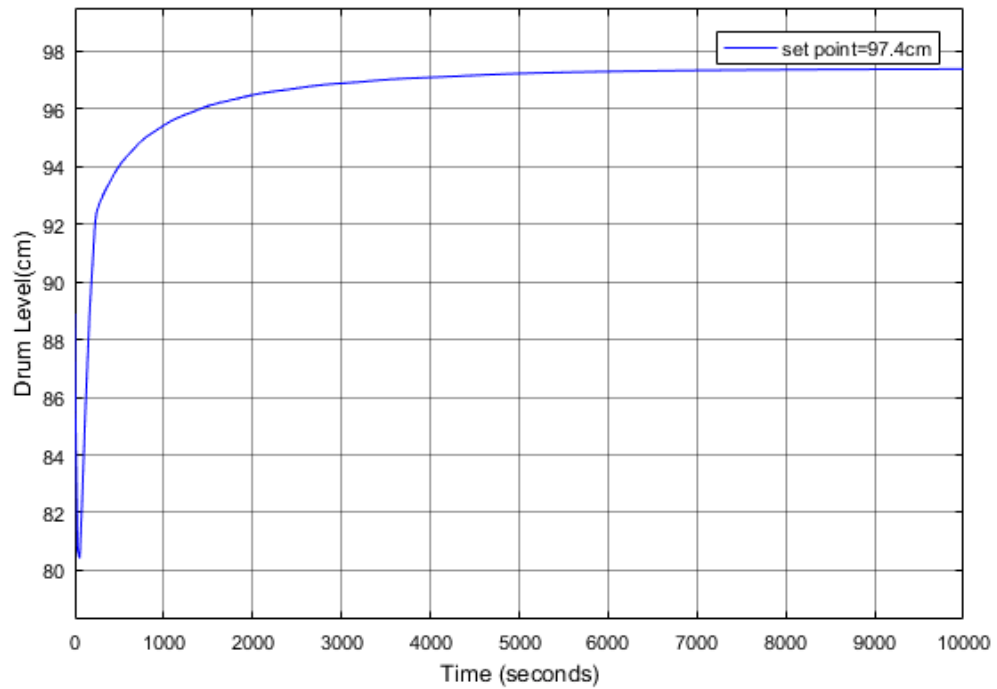


Figure 3.10 Single Element Control using MATLAB/SIMULINK

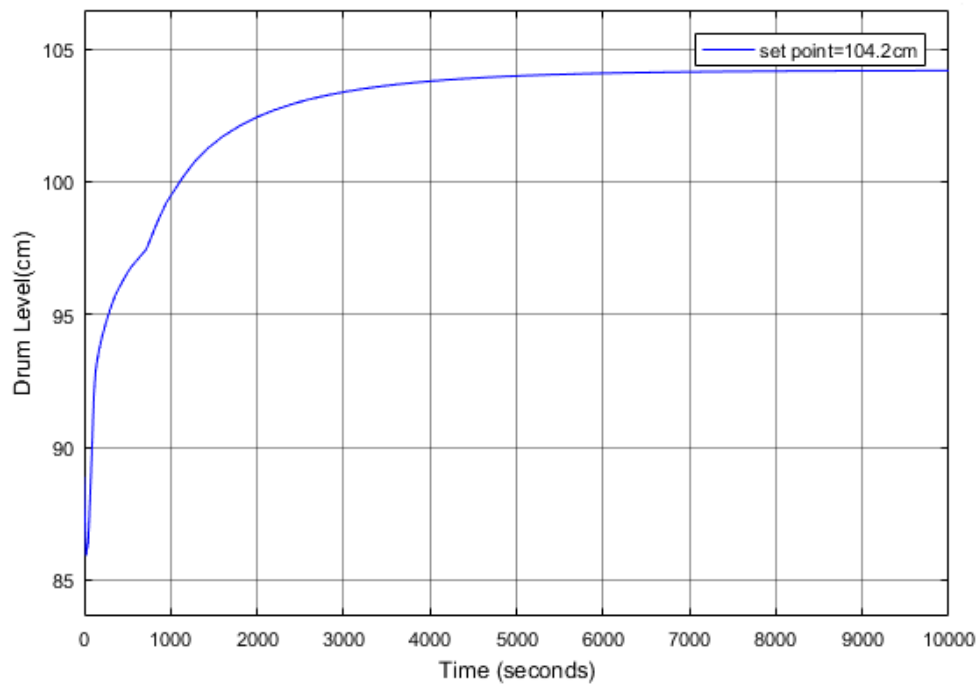
The set point has been set at different values; the results of the simulation are shown in the Figure 3.11:



(a)



(b)



(c)

Figure 3.11 Single element Control at different Level Set Points (a) 92cm (b) 97.4cm (c) 104.2cm

After the simulation, we observe:

- The steady state error is zero in all the regions of interest.
- The response of the system is slow.
- When the input control is applied, the water level falls down then starts to get to the desired level. This behavior is really dangerous for the system and cause massive damage.

3.4.2 Three Element Control

This system uses two variables, drum level and steam flow to mass balance the feed-water demand, and this is the two-element control. A control loop, in which a multi PI controller is set, is added to control the feed water entering the drum to implement the three-element control. The assumption that has been made is that the steam demand is set at the nominal value provided by the manufacturer.

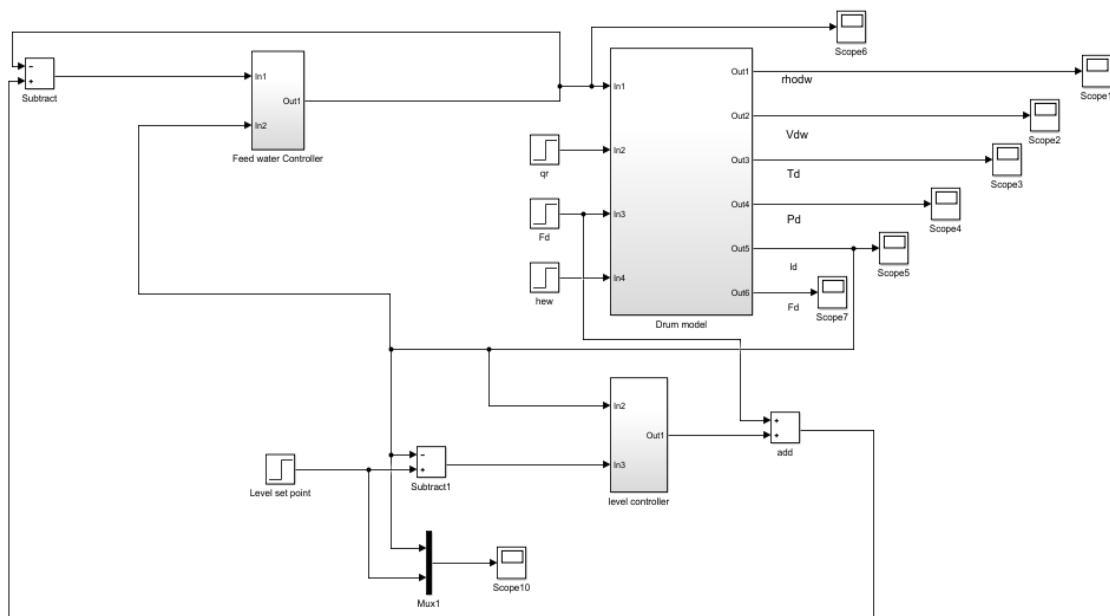
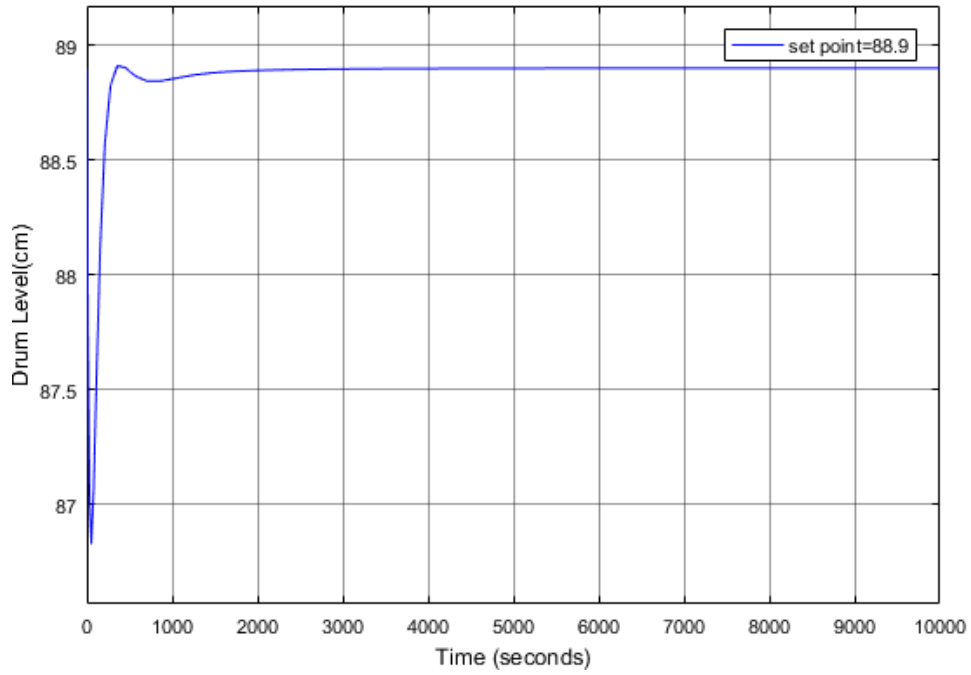
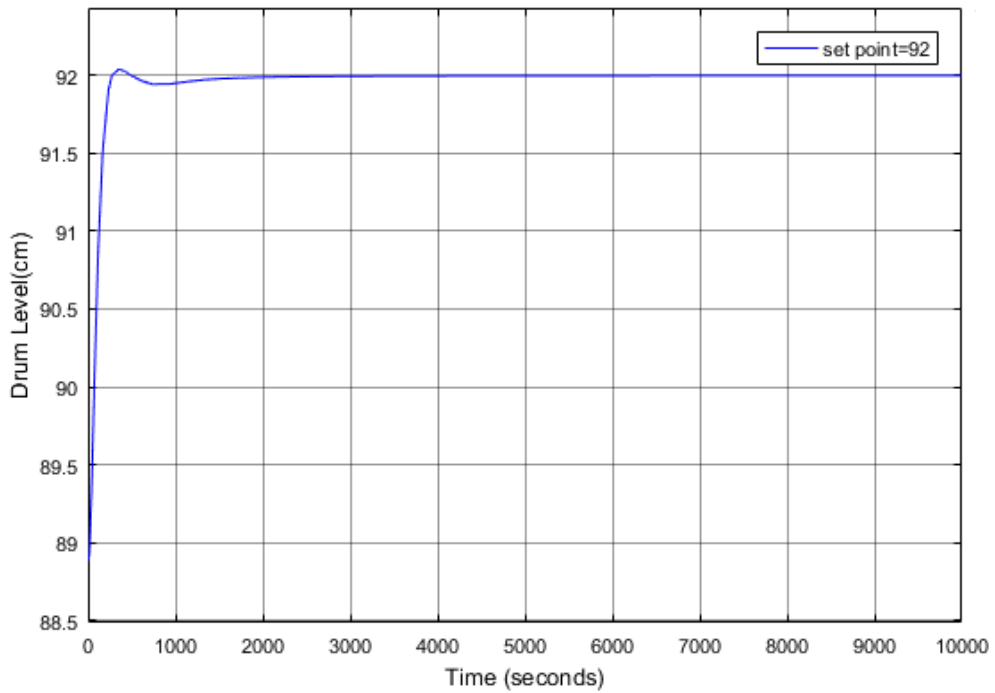


Figure 3.12 Three Element Control using MATLAB/SIMULINK

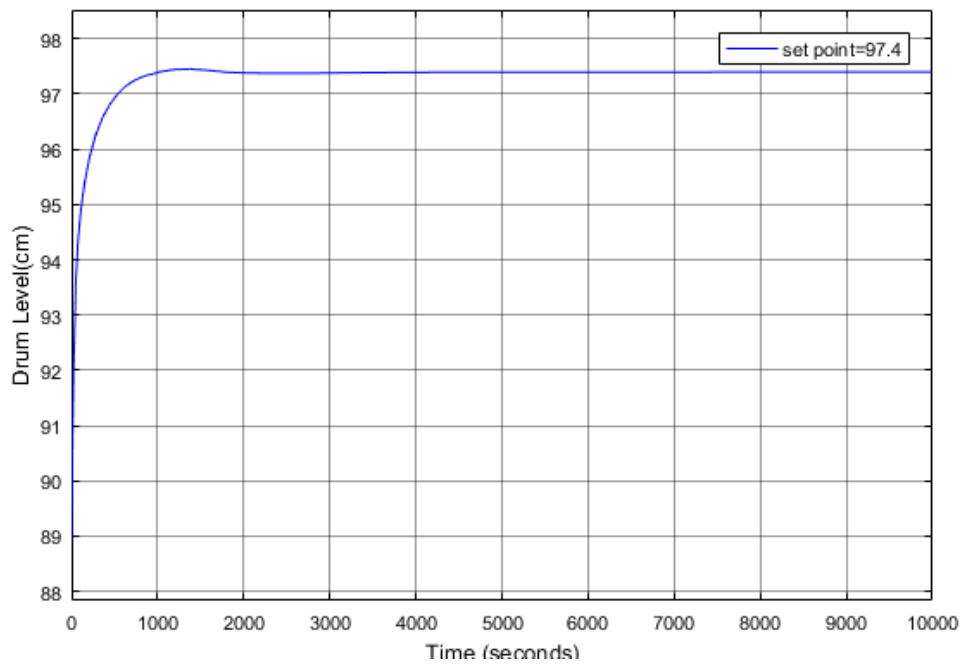
The set point has been set at different values; the results of the simulation are shown below:



(a)



(b)



(c)

Figure 3.13 Three Element Control at different Level Set Points (a) 88.9cm (b) 92cm (c) 97.4cm

After the simulation, we observe the steady state error is zero in all the regions of interest and the response of the system is remarkably faster than the one of single element.

3.5 Conclusion

The water level inside the drum is controlled using both techniques (One and Three element control). However, the three element control is preferable since it can enhance the performance of our system.

Chapter Four

LabVIEW Simulation

4.1 Introduction to LabVIEW

LabVIEW programs are called virtual instruments, or VIs, because their appearance and operation imitate physical instruments, such as oscilloscopes and multi meters. LabVIEW contains a comprehensive set of tools for acquiring, analyzing, displaying, and storing data, as well as tools to help us troubleshooting code writing. In LabVIEW, we build a user interface, or front panel, with controls and indicators. Controls are knobs, push buttons, dials, and other input mechanisms. Indicators are graphs, LEDs, and other output displays. After we build the front panel, we add code using VIs and structures to control the front panel objects. The block diagram contains this code. [15]

4.2 LABVIEW Control Design and Simulation Module

Due to the increase in computer power, simulation is quickly becoming a tool of choice for design engineers who need to quickly evaluate and iterate on the typical design process. Simulation tools that used to run on workstations a mere decade ago now run on desktop computers meant for households. As part of the LabVIEW graphical development platform, the LabVIEW Control Design and Simulation Module offers the following benefits:

- ✓ **Hardware and software integration:** You can use the integration of NI hardware and software to easily move from the design/simulation space to adding real-world data – both inputs and outputs.
- ✓ **Interactive user interface:** One of the main benefits of simulation is the ability to modify system parameters to check how the performance of a system changes. By using the front panel in LabVIEW, you can change these parameters while the simulation is running.
- ✓ **Full programming language:** Because the LabVIEW Control Design and Simulation Module is part of the LabVIEW graphical development environment, we can integrate other LabVIEW modules and toolkits into our applications.
- ✓ **MathScript RT Plug-In:** The LabVIEW Control Design and Simulation Module have a specific plug-in for the LabVIEW MathScript RT Module so we can combine our existing .m files with a flexible LabVIEW UI using a LabVIEW MathScript Node. Particularly in our system development we made

use of this feature to model the drum's subsystem's model, an example of a MathScript feature is shown below:

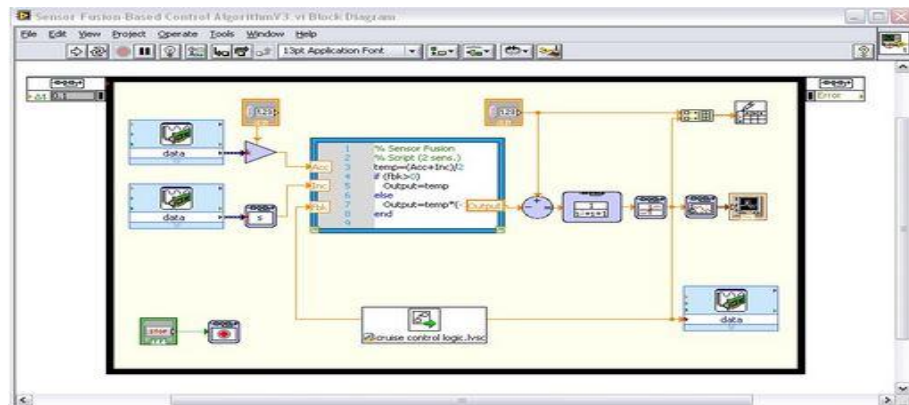


Figure 4.1 LabVIEW MathScript example

4.3 Boiler Simulation and PID using LabVIEW

4.3.1 User interface and simulation results

We start first by implementing our model in the block diagram window of the LabVIEW VI as shown in Figure 4.3:

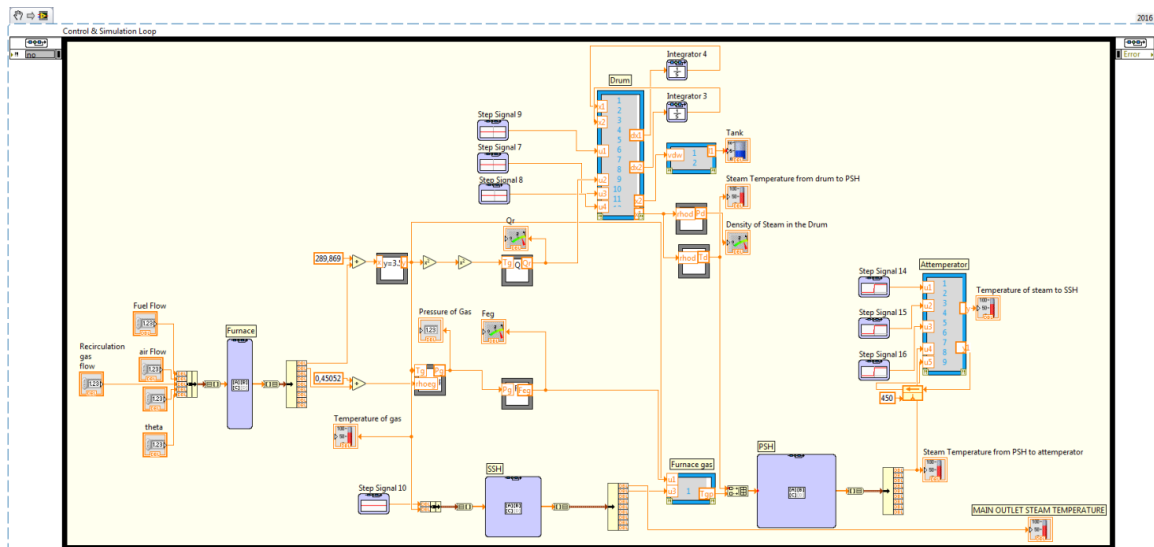


Figure 4.2 Model of the boiler using LabVIEW Ccontrol & Simulation Module

The corresponding front panel is the following:

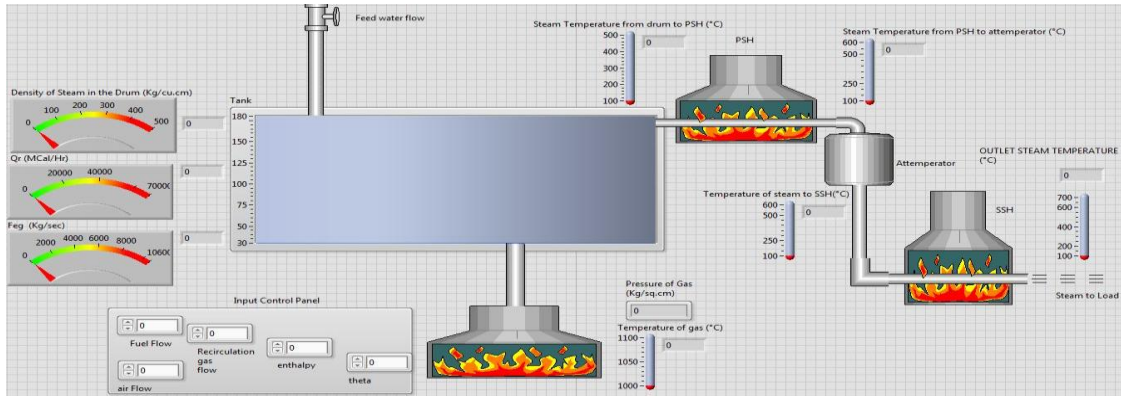


Figure 4.3 User interface/Front panel of the boiler

To see the dynamics of the system we try different changes in the input variables that are F_f , F_a , F_r , h_r and θ , first by making a 5% decrease in the fuel flow (F_f) and noticing the change in the output variables shown in the front panel:

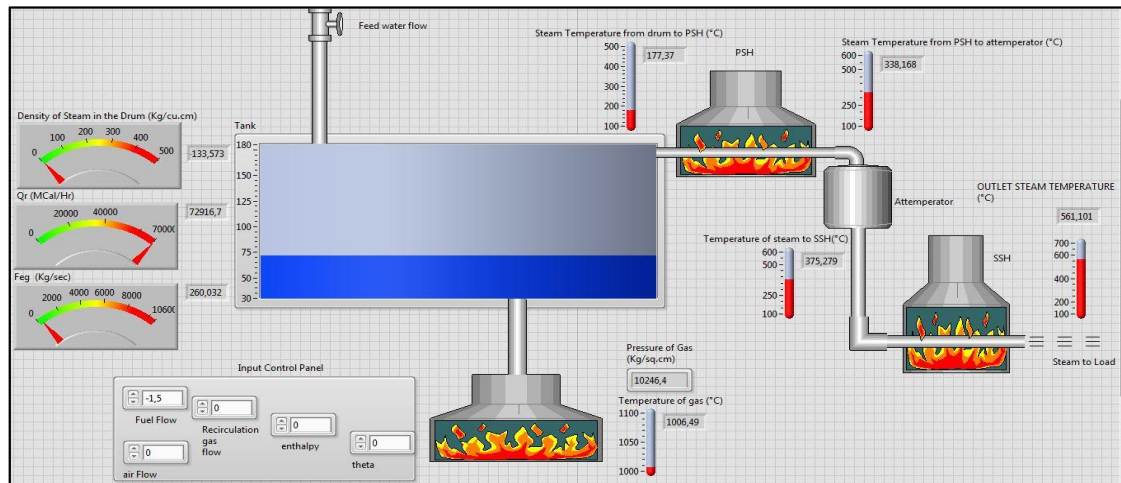


Figure 4.4 Response of the boiler system to -5% change in fuel flow

Again with a 5% increase in the fuel flow we see the following changes:

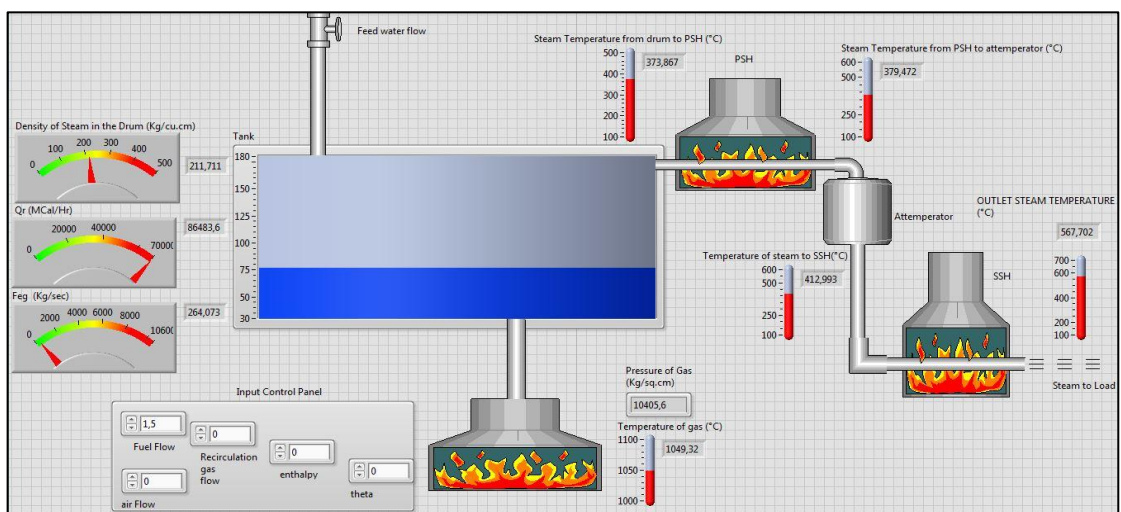


Figure 4.5 Response of the boiler system to 5% change in fuel flow

We see that for increasing fuel flow input, both the pressure and the temperatures along the boiler system increase to a steady state value, but the water level in the drum goes down from 89cm to 75cm after 200sec and keeps decreasing if we increased the simulation time, this can cause immense damage to our system thus we need to design a closed loop pid controller to control the level.

4.3.2 Design and implementation of the controller

4.3.2.1 Single element control

Single element control, as discussed in the previous chapter, is the simplest method to control the boiler drum level using multi PI model. This controller is implemented on LabVIEW as follows:

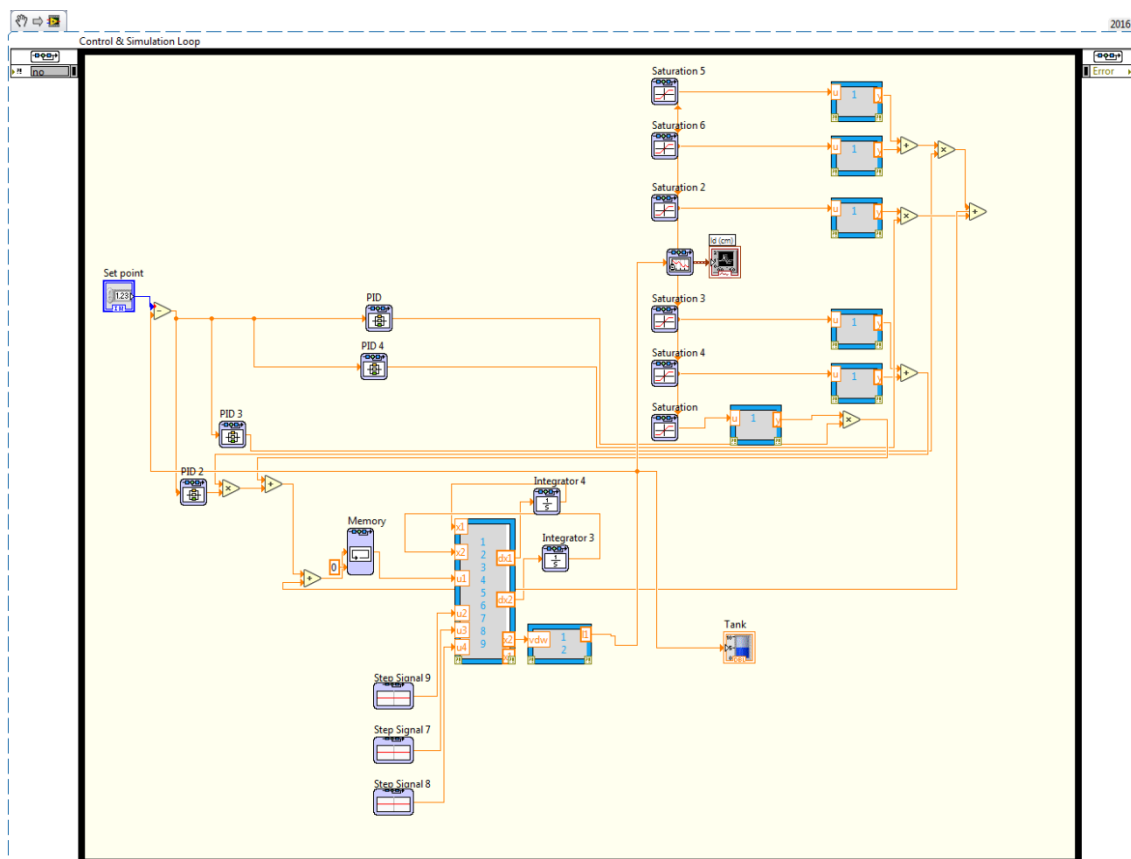


Figure 4.6 Implemented multi model controller

Varying the Set point to 90cm and checking the response of the Drum level:

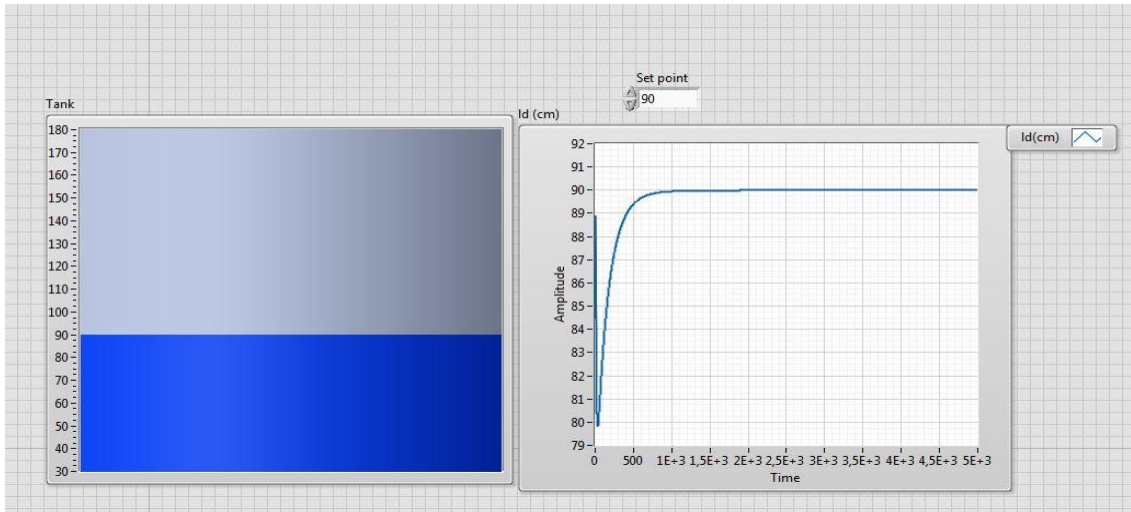


Figure 4.7 Response of the Drum level to a set point of 90cm

It is seen that the response first goes to a minimum value that is 79.9cm then increases to the steady state value 90cm, which is the setpoint, this behaviour is undesirable and can cause damage to the system that’s why we try to enhance it by implementing the two element Drum level control.

4.3.2.2 Two element control

The theory behind two element control was already explained in the previous chapter, that’s why in this chapter, we’re only presenting the implementation of this control method on LabVIEW and showing the response of the drum level after the control signal is applied.

The following figure shows the implemented VI:

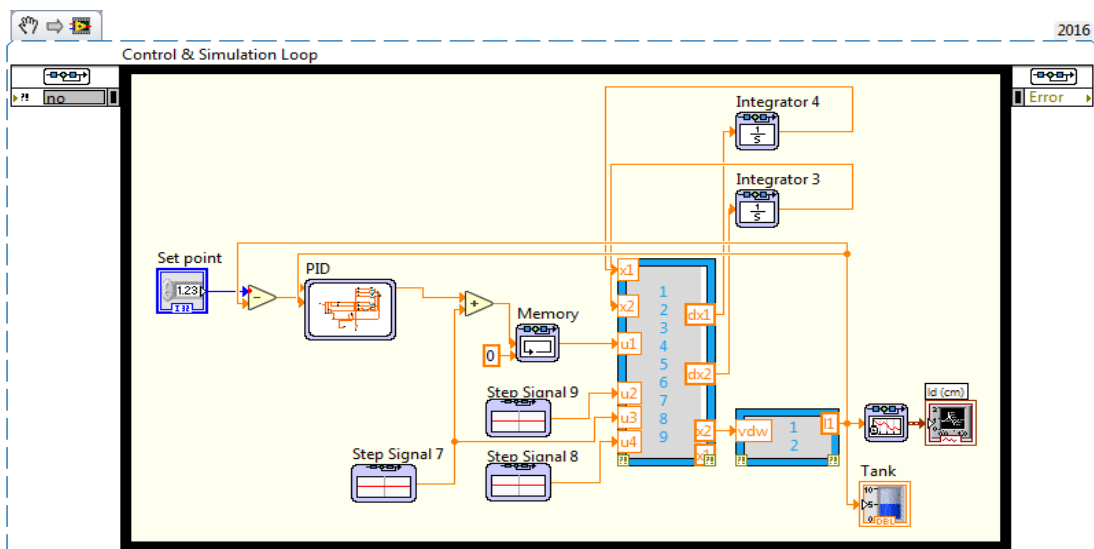


Figure 4.8 Two element control VI

After simulating for a set point of 95(cm) we observe the response in Figure 4-9.

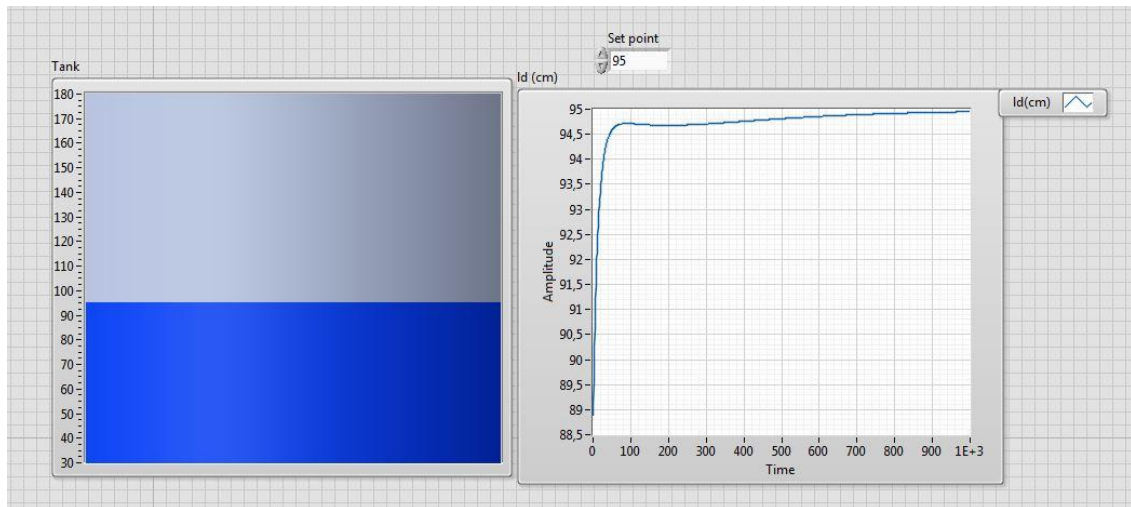


Figure 4.9 Response of the Drum level to a Set Point of 95cm using Two Element Control

It is clear that the response is enhanced, system responds faster and the undesirable effects have vanished.

4.4 National Instrument acquisition card USB-6009

4.4.1 Introduction to DAQ USB-6009

The NI USB-6009 is a USB based data acquisition (DAQ) and control device with analog input and output and digital input and output. The main features of NI USB-6009 are as follows:

- ✓ **Analog input (AI):** 8 inputs with referenced single ended signal coupling or 4 inputs with differential signal coupling. Software-configurable voltage ranges: $\pm 20V$, $\pm 10V$, $\pm 5V$, $\pm 4V$, $\pm 2.5V$, $\pm 2V$, $\pm 1.25V$, $\pm 1V$. Max sampling rate is 48kS/s (48000 samples per second). 14 bits AD converter (USB-6008: 12 bits).
- ✓ **Analog output (AO):** 2 outputs. Voltage range is 0 - 5V (fixed). Output rate is 150Hz (samples/second). 12 bits DA converter.
- ✓ **Counter:** 32 bits. Counting on falling edge.
- ✓ **Configuring and testing:** USB-6009 can be configured and tested using MAX (Measurement and Automation Explorer) 4.0, which is installed with NI-DAQ 8.0.

4.4.2 Labeling the I/O terminals

Before we start using the USB-6009, we should attach labels to the analog and digital terminals. Figure 5.1 below shows the *analog* I/O terminals with labels assuming differential signal coupling. (In general, differential signal coupling is preferable to single ended coupling due to better DC noise suppression).



Figure 4.10 The analog I/O terminals with labels assuming differential signal coupling

4.4.3 USB-6009 and LABVIEW

The functions needed for programming I/O operations for USB-6009 are found on the Functions / NI Measurements (Measurements I/O in LABVIEW 8) / DAQmx palette (not DAQmx Base, if you happen to have the latter installed). Figure 4.11 shows the contents of the DAQmx palette.

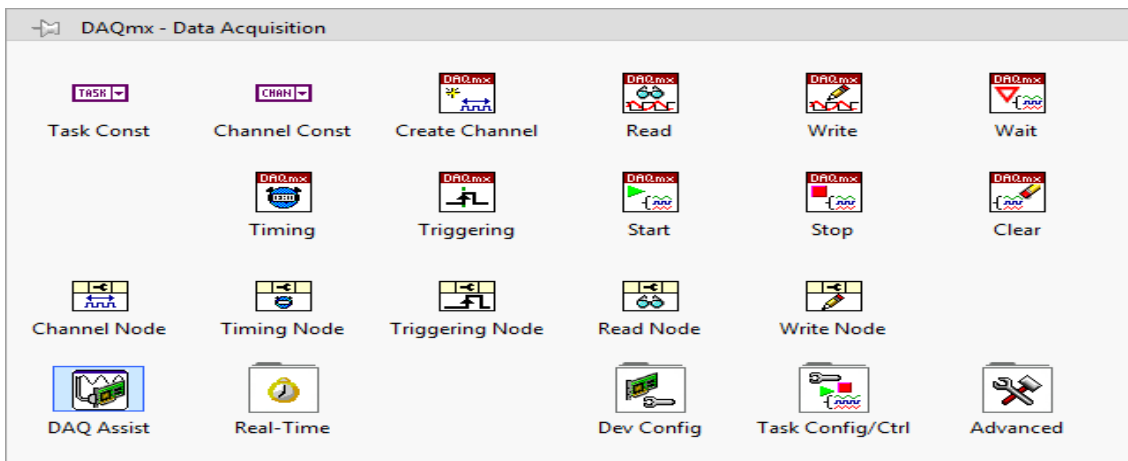


Figure 4.11 The DAQ palette on the Functions palette

4.5 Interfacing & Implementing the DAQ with LabVIEW

We first build the Drum system in a new VI since the drum level is the output to be controlled, and then add two DAQ assistant blocks, the first configured on the analog

output pin a_{o0} to generate the output voltage, the second configured on the analog read pin a_{i0} to acquire the control signal the configurations are shown below:

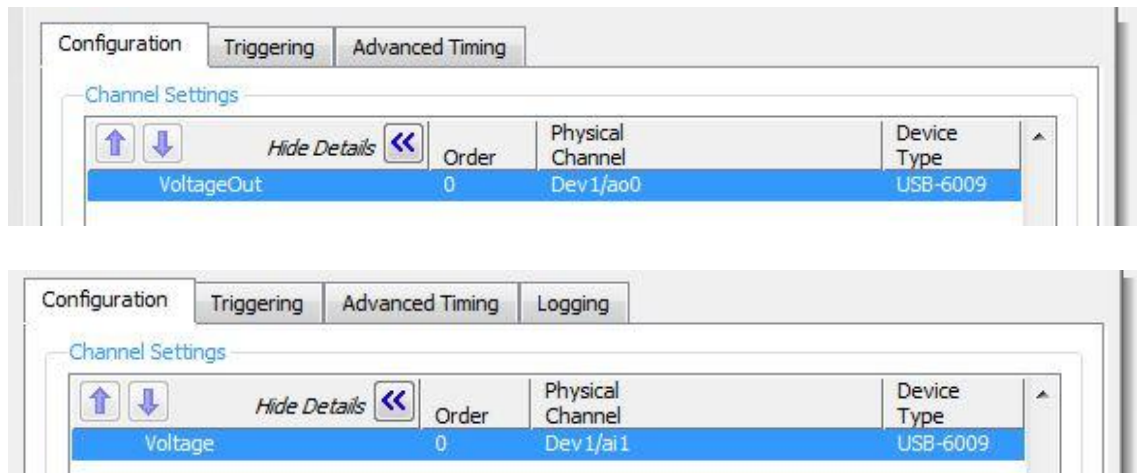


Figure 4.12 DAQ Configuration for the system

Mapping Functions are used to map the output values of the drum level and the PID values from the controller to a voltage between 0-5v are used. This is shown in Figure 4.13 below:

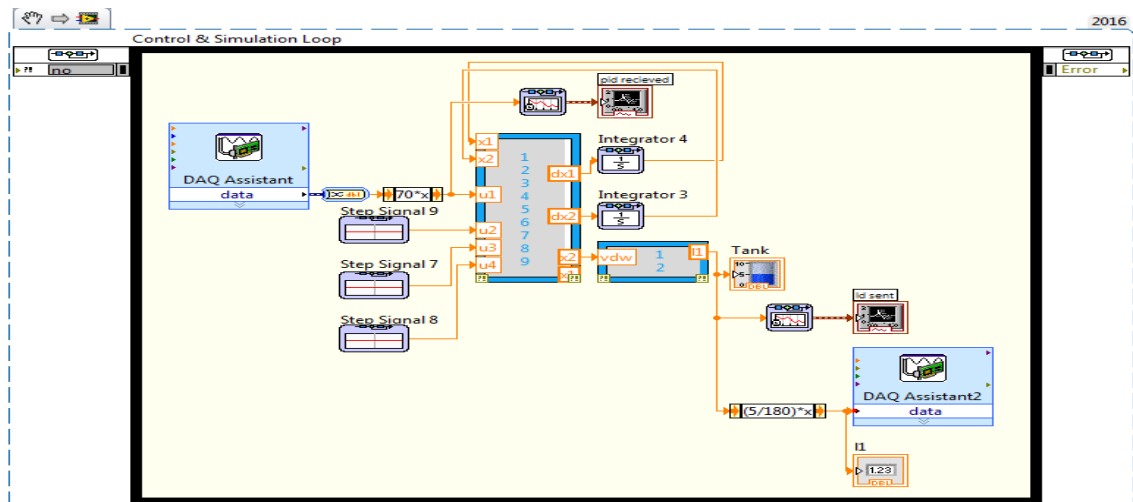


Figure 4.13 System LabVIEW VI

Then we build the Control vi, the control vi receives data from the system (values of I_d mapped between 0-5v) converts it using an inverse mapping function, calculates the control signal, maps the output values again between 0-5v and then send it back to the system.

Using a second DAQ, we configure its pins the same way as the first and connect them as shown in the Figure 4.15.

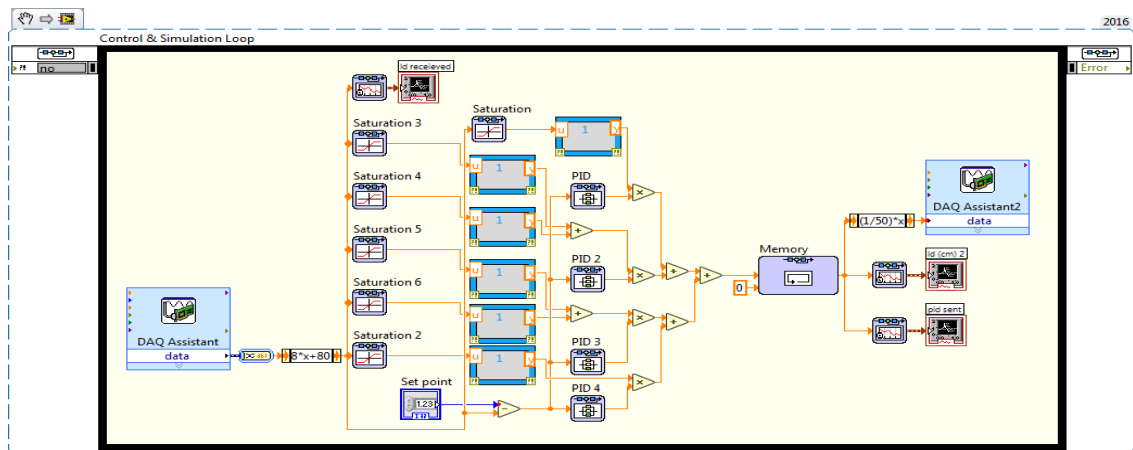


Figure 4.14 Control LabVIEW VI

The simulation discussed above has been implemented and shown below:

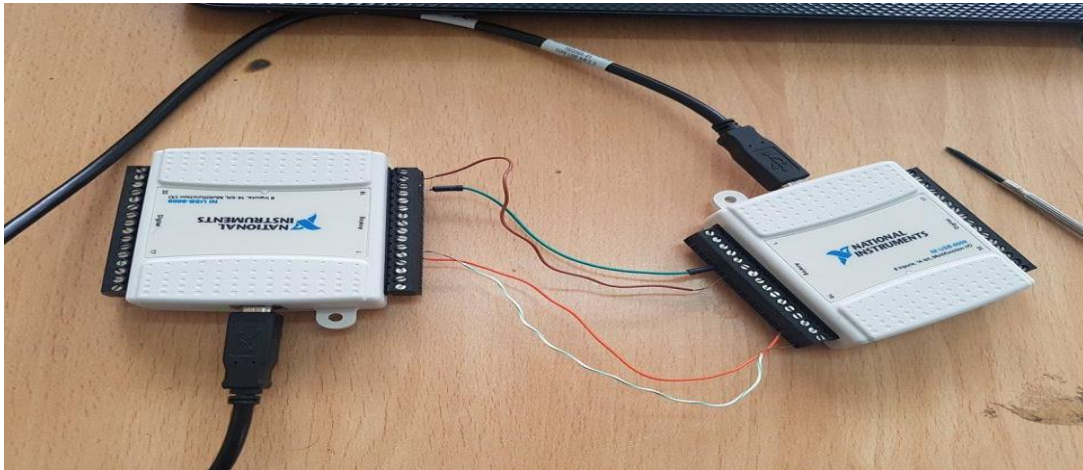


Figure 4.15 Implemented circuit

Simulating Both VI's for a set point of 90(cm) and checking the signals sent and received, results are then shown in the following figures:

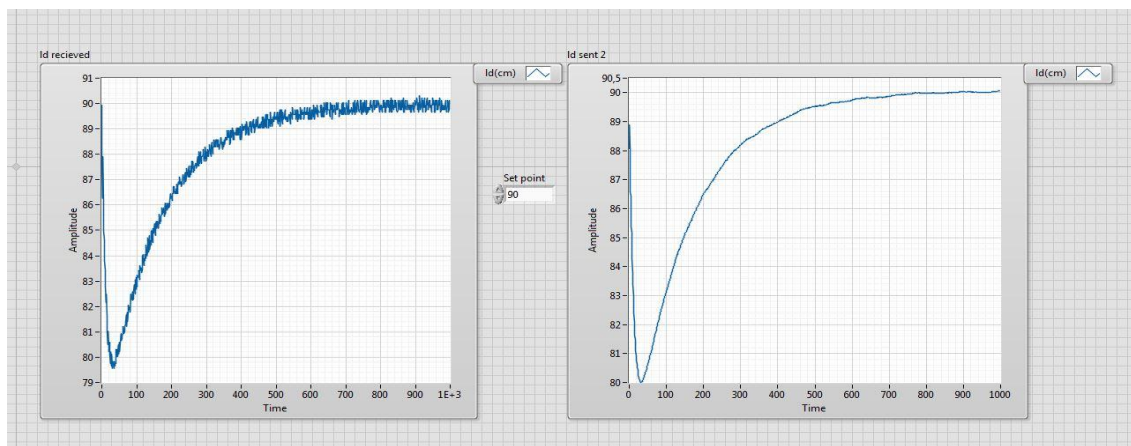


Figure 4.16 Drum Level Sent and Received

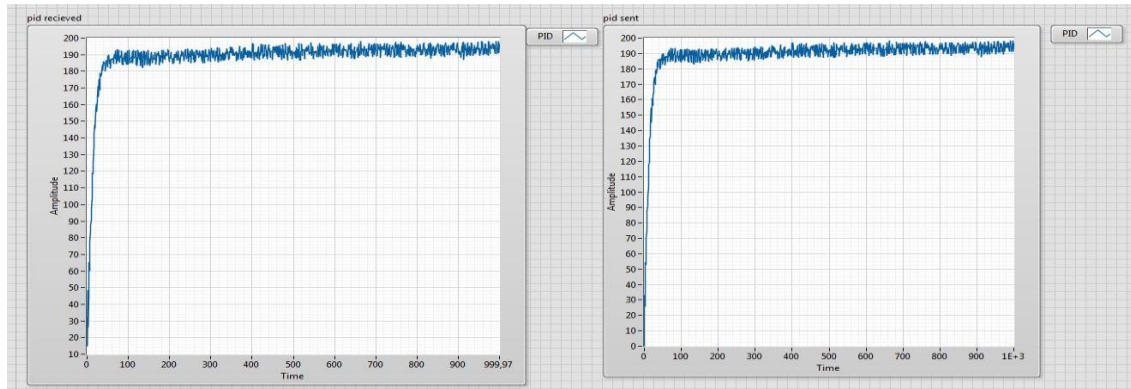


Figure 4.17 PI values Sent and Received

We see that the drum level is being sent correctly, but the received L_d is subjected to small noises that are due to first: Measurement accuracy [16], and second the large scale of the mapping functions which give slightly different values in the output for large differences in the input. The noise in the PI is due to the noises in the drum level since it is the main variable to calculate the PI values.

4.6 Conclusion

LabVIEW once again proved itself a powerful tool in the field of control engineering with its control and simulation module discussed in this chapter, it allowed us to build our Boiler simulator, study its dynamics, and design a controller for it.

LabVIEW benefits don't stop here, as we can also use Data Acquisition cards to interact with our system.

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Furnace:**TableA.1** Nominal values of the boiler furnace variables

Constants	Values	Unit
F_f	33.13	Kg/sec
F_a	198.83	kg/sec
F_r	30.52	kg/sec
F_{eg}	262.5	kg/sec
θ	0.88041	Radians
V_{bf}	5200	m^3
ε	6	-
e_x	5	%
η_f	$3.08 \cdot 10^{-3}$	m^2/sec
η_g	0.76256	m^2/sec
O_a	0.1	-
C_{pg}	0.282	Kcal/kg °C
μ	29.2488	$m^2/°C$
a_r	2109.87	m^2
σ	$4.8785 \cdot 10^8$	Kcal/(hr. $m^2/°C^4$)
η	1.26312	-
η^1	2.6584076	-
C_f	4400	Kcal/kg
h_a	59.7515	Kcal/kg
h_r	164.92	Kcal/kg

Where:

$$\dot{x}_1 = f_1$$

$$\dot{x}_2 = f_2$$

Linearization of state space equations of the furnace:

A and B are Jacobian matrices evaluated at (X_0, U_0) as given below:

$$A = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} \end{bmatrix}; \quad B = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \frac{\partial f_1}{\partial u_2} & \frac{\partial f_1}{\partial u_3} & \frac{\partial f_1}{\partial u_4} & \frac{\partial f_1}{\partial u_5} \\ \frac{\partial f_2}{\partial u_1} & \frac{\partial f_2}{\partial u_2} & \frac{\partial f_2}{\partial u_3} & \frac{\partial f_2}{\partial u_4} & \frac{\partial f_2}{\partial u_5} \end{bmatrix};$$

Where:

$$\dot{x}_1 = f_1$$

$$\dot{x}_2 = f_2$$

$$\frac{\partial f_1}{\partial x_1} = \frac{1}{\rho_{eg} V_{bf}} \{ F_f - F_a - F_r + [1 - \varepsilon (1 + \frac{e_x}{100})] \left(\frac{\eta_f h_{eg} \nu \rho_{eg}}{C_{pg}} + F_{eg} \right) - \frac{4a_r \sigma T_g^3}{C_{pg}} (\eta \theta + (1 - \theta) \eta^1) \}$$

$$\frac{\partial f_1}{\partial x_2} = \frac{1}{\rho_{eg}^2 V_{bf}} \left\{ (C_f - h_{eg}) F_f + (h_a - h_{eg}) F_a + (h_{ar} - h_{eg}) F_r + h_{eg} F_{eg} - q_r - q_s - F_{eg} \varepsilon \left(1 + \frac{e_x}{100} \right) h_{eg} \right\} + \frac{\eta_f \nu T_g h_{eg}}{\rho_{eg} V_{bf}} \left[1 - \varepsilon \left(1 + \frac{e_x}{100} \right) \right]$$

$$\frac{\partial f_2}{\partial x_1} = - \frac{\eta_f \nu \rho_{eg}}{V_{bf} C_{pg}}$$

$$\frac{\partial f_2}{\partial x_2} = - \frac{\eta_f \nu T_g}{V_{bf}}$$

$$\frac{\partial f_1}{\partial u_1} = \frac{1}{\rho_{eg} V_{bf}} (C_f + h_{eg} F_{eg} \left[\frac{F_a + O_a F_r}{F_f^2} \right] - \varepsilon \left(1 + \frac{e_x}{100} \right) h_{eg})$$

$$\frac{\partial f_1}{\partial u_2} = \frac{1}{\rho_{eg} V_{bf}} (h_{af} - \frac{h_{eg} F_{eg}}{F_f} - \varepsilon \left(1 + \frac{e_x}{100} \right) h_{eg})$$

$$\frac{\partial f_1}{\partial u_3} = \frac{1}{\rho_{eg} V_{bf}} (h_r - \frac{h_{eg} F_{eg} O_a}{F_f} - \varepsilon \left(1 + \frac{e_x}{100} \right) h_{eg})$$

$$\frac{\partial f_1}{\partial u_4} = \frac{F_r}{\rho_{eg} V_{bf}}$$

$$\frac{\partial f_1}{\partial u_5} = \frac{a_r \sigma}{\rho_{eg} V_{bf}} (\eta^1 (T_g^4 - T_m^4) - \eta (T_g^4 - T_w^4))$$

$$\frac{\partial f_2}{\partial u_1} = \frac{1}{V_{bf}}$$

$$\frac{\partial f_2}{\partial u_2} = \frac{1}{V_{bf}}$$

$$\frac{\partial f_2}{\partial u_3} = \frac{1}{V_{bf}}$$

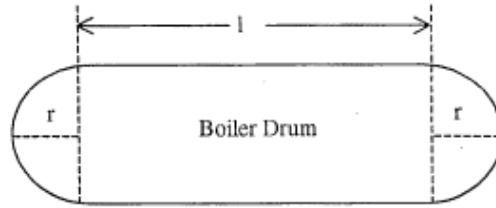
$$\frac{\partial f_2}{\partial u_4} = 0$$

Drum:**TableA.2** Nominal values of the boiler drum variables

Constants	Values	Unit
R	88.9	Cm
ρ_{dv}	63.097×10^{-5}	kg/cm ³
F_{ev}	195.5	kg/sec
h_{ev}	131.97	kcal/Kg
F_d	175.014	Kg/sec
l_d	88.9	Cm
X_q	0.95	-
ρ_d	176.8	Kg/cm ²
δ_{hdw}	1128547.11	Kcal.cm ³ /Kg ²
T_d	354	°C
V_d	40185469.46	Cm ³
V_{dw}	20092734.73	Cm ³
l	1500	Cm

Computation of drum level:

In order to calculate the drum level l_d from the drum water volume V_{dw} , the boiler drum is considered as a cylinder with hemispherical ends laid horizontally as shown in FigureA.1.



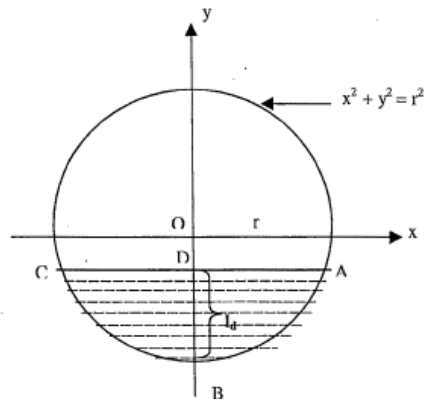
FigureA.1 Shape of the boiler drum is a horizontal cylinder with hemispherical ends

Let r and l denote the radius and the length of the cylindrical portion of the drum respectively. The volume of water contained in the drum V_{dw} is calculated as the sum of two volumes V_1 and V_2 . V_1 is the volume of a spherical segment of height l_d of a sphere of radius r as depicted in FigureA.2 and is given by

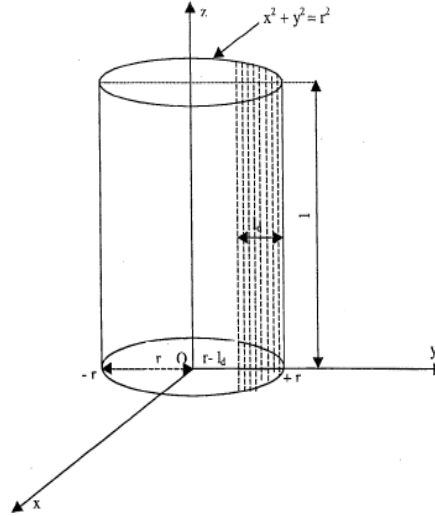
$$V_1 = 2\pi \int_{y=r-l_d}^r \int_{x=0}^{\sqrt{r^2-y^2}} x \, dx \, dy$$

V_2 is the volume of a cylindrical portion shaded in FigureA.3 V_2 is given by

$$V_2 = 2 \int_{y=r-l_d}^r \int_{x=0}^{\sqrt{r^2-y^2}} 1 \, dx \, dy$$



FigureA.2 The shaded portion ABCDA is rotated about the y – axis to obtain volume V_1



FigureA.3 The shaded cylindrical section represents volume V_2

Evaluation of V_1 and V_2 gives an expression for V_{dw} as a function of l_d .

$$V_{dw} = \frac{1}{3} \Pi l_d^2 (3r - l_d) + l \left\{ \frac{\Pi r^2}{2} + r^2 \sin^{-1} \left(\frac{l_d - r}{r} \right) + (l_d - r) \sqrt{2r l_d - l_d^2} \right\}$$

Let us define a new function,

$$f(l_d) = \frac{1}{3} \Pi l_d^2 (3r - l_d) + l \left\{ \frac{\Pi r^2}{2} + r^2 \sin^{-1} \left(\frac{l_d - r}{r} \right) + (l_d - r) \sqrt{2r l_d - l_d^2} \right\} - V_{dw}$$

The first derivative of $f(l_d)$ is given by

$$f^1(l_d) = 2l \sqrt{l_d(2r - l_d)} + \Pi l(2r - 1)$$

From the two previous equations, l_d is computed using Newton – Raphson method iteratively during every sampling instant of the model run. The algorithm for the computation of l_d is written as given below:

$$l_d^{k+1} = l_d^k + \frac{f(l_d^k)}{f^1(l_d^k)}, k = 1, 2, 3, \dots$$

l_d converges to the correct value within 8 iterations during every cycle of the model run.

PSH and SSH:**TableA.3** Nominal values of the boiler primary superheater variables

Constants	Values	Unit
V_s	23	m^3
γ_{sp}	50.50	kg/m^3
U_{sp}	500	kcal/kg
T_{sp}	420	$^{\circ}C$
T_{mp}	430	$^{\circ}C$
F_{sp}	191.66	Kg/sec
a_{ip}	20100.25	m^2
a_{op}	2254	m^2
α_{msp}/α_{ms}	3316	Kcal/(hr.m ² . $^{\circ}C$)
α_{gmp}/α_{gm}	58.9	Kcal/(hr.m ² . $^{\circ}C$)
M_{mp}	242000	Kg
C_{mp}/C_m	0.15	kcal/kg. $^{\circ}C$
η_{ps}	1.90968	(Kcal/sec)/ $^{\circ}K(kg/sec)^{0.6}$

TableA.4 Nominal values of the boiler secondary superheater variables

Constants	Values	Unit
F_s	191.66	Kg/sec
F_{spa}	8.328	Kg/sec
h_{si}	706.20	kcal/kg
h_{sp}	720	kcal/kg
h_{spa}	131.97	kcal/kg
T_{si}	450	$^{\circ}C$
C_{si}	0.4634	Kcal/kg. $^{\circ}C$
C_v	0.4634	Kcal/kg. $^{\circ}C$
a_0	2454	m^2
C_s/C_{sp}	0.4634	Kcal/kg. $^{\circ}C$
M_m	252000	Kg
P_s	176.8	Kg/cm^2

Linearization of state space equations of PSH and SSH:

A and B are Jacobian matrices evaluated at (X_0, U_0) as given below:

$$A_S = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} \end{bmatrix}; \quad B_S = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \frac{\partial f_1}{\partial u_2} \\ \frac{\partial f_2}{\partial u_1} & \frac{\partial f_2}{\partial u_2} \end{bmatrix}$$

Where:

$$\dot{x}_1 = f_1$$

$$\dot{x}_2 = f_2$$

Then we get:

$$A_S = \begin{bmatrix} \frac{-(a_i \alpha_{ms} + F_s C_s)}{V_s \gamma_s C_v} & \frac{a_i \alpha_{ms}}{V_s \gamma_s C_v} \\ \frac{-a_i \alpha_{ms}}{M_m C_m} & -\frac{a_0 \alpha_{gm} + a_i \alpha_{ms}}{M_m C_m} \end{bmatrix}; \quad B_S = \begin{bmatrix} \frac{F_s C_{si}}{V_s \gamma_s C_v} & 0 \\ 0 & \frac{-a_0 \alpha_{gm}}{M_m C_m} \end{bmatrix};$$

The intermediate variables for drum state space

$$q_1 = \delta_{hd} \rho_d (V_d - V_{dw}) + \delta_{hdw} \rho_{dw} V_{dw}$$

$$q_2 = V_d - (1 - \delta_{\rho dw}) V_{dw}$$

$$q_3 = \frac{1}{q_2} \left\{ \frac{q_1}{h_d - h_{dw}} - \delta_{\rho dw} V_{dw} \right\}$$

$$q_4 = 1 + q_3 \left(1 - \frac{\rho_d}{\rho_{dw}} \right)$$

TableA.5 PI values for Level controller

Operating Regions	Proportional Gain K_p	Integral Gain K_i
Region1	8.1057	0.0584
Region2	4.1384	0.0251
Region3	2.832	0.0148
Region4	1.9884	0.0084

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