CONTROL AND OPTIMIZATION OF NOx EMISSION AND EFFICIENCY IN BOILERS

BY

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Dedicated to

My Parents

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LIST OF ABBREVIATIONS

$ANFIS$	Adaptive Neuro-Fuzzy Inference System
AFR	Air to fuel ratio
λ	Air to fuel ratio
T_a	Ambient temperature
$ABMA$	American Boiler Manufacturers' Association
$ASME$	American Society of Mechanical Engineers
$\overline{\alpha}$	Average volume fraction
ξ	Burner tilt angle
$CEPA$	Canadian Environmental Protection Act
CFD	Computational Fluid Dynamics
ρ_w	Density of feedwater
ρ_s	Density of saturated steam
L_d	Desired drum level
P_d	Desired drum pressure
DEB	Direct Energy Balance
V_{dc}	Downcomer volume

$\boldsymbol{P}$	Drum pressure
$\boldsymbol{A_d}$	Drum surface area
$\boldsymbol{V_d}$	Drum volume
$\boldsymbol{\eta}$	Efficiency
$\boldsymbol{h_w}$	Enthalpy of feedwater
$\boldsymbol{EPA}$	Environmental Protection Agency
$\boldsymbol{ELM}$	Extreme Learning Machine
$\boldsymbol{FFNN}$	Feed Forward Neural Network
$\boldsymbol{\dot{m}_{fw}}$	Feedwater flow rate
$\boldsymbol{q_{fs}}$	Feedwater steady state value
$\boldsymbol{FGT}$	Flue gas temperature
$\boldsymbol{FGT}$	Flue gas temperature
$\boldsymbol{FFR}$	Fuel flow rate
$\boldsymbol{\dot{m}_f}$	Fuel flow rate
$\boldsymbol{\dot{m}_f}$	Fuel flow rate
$\boldsymbol{F/A}$	Fuel to air ratio
$\boldsymbol{GA}$	Genetic Algorithm
$\boldsymbol{g}$	Gravity

GCV	Gross Calorific Value
$\mathbf{GCV}$	Gross calorific value of natural gas
Q	Heating rate
Q_s	Heating rate steady state value
h_{fg}	h_g-h_f
HGA	Hybrid Genetic Algorithm
H_2	Hydrogen content in fuel
h_{fg}	Latent heat of vaporization of water
l	Level of the water
LQ	Linear Quadratic
LHV	Lower Heating Value
LHV	Lower Heating Value
m_{md}	Mass of drum
m_{FG}	Mass of flue gas
MCR	Maximum Continuous Rating
MCR	Maximum Continuous Rating
η_{max}	Maximum efficiency
t_p	Metal temperature

$\boldsymbol{NO_{min}}$	Minimum nitric oxide
$\boldsymbol{MPC}$	Model Predictive
$\%\boldsymbol{CO_{2_{mole}}}$	Mole percentage of carbon dioxide in flue gas
$\%\boldsymbol{CO_{mole}}$	Mole percentage of carbon monoxide in flue gas
$\%\mathbf{X_{mole}}$	Mole percentage of component ‘X’
$\boldsymbol{NCV}$	Net Calorific Value
$\boldsymbol{NN}$	Neural Networks
$\boldsymbol{NOx}$	Nitric Oxide
$\boldsymbol{NLSF}$	Nonlinear Least-Squares Fitting
$\boldsymbol{NMPC}$	Nonlinear model predictive control
$\boldsymbol{PI}$	Proportional Plus Integral
$\boldsymbol{PID}$	Proportional-Integral plus Derivative
$\boldsymbol{RBFNN}$	Radial Basis Function Neural Network
$\boldsymbol{RBFNN}$	Radial Basis Function Neural Network
$\boldsymbol{\dot{m}_{dc}}$	Riser and downcomer mass flow rate
$\boldsymbol{m_r}$	Riser metal mass
$\boldsymbol{V_r}$	Riser volume
$\boldsymbol{\dot{m}_r}$	Risers flow rate

$RCJY$	Royal Commission for Jubail and Yanbu
h_f	Specific enthalpy of saturated liquid water
h_g	Specific enthalpy of saturated liquid water
$C_{p_{FG}}$	Specific heat of flue gas
C_p	Specific heat of metal
C_{ps}	Specific heat of superheated steam.
$SEPA$	State Environmental Protection Administration
$\dot{m}_{ct}$	Steam condensation rate
SFR	Steam flow rate
$\dot{m}_s$	Steam flow rate
$\dot{m}_{sd}$	Steam flow rate through liquid surface of drum
x	Steam quality
λ_{st}	Stoichiometric air to fuel ratio
$T-S$	Takagi-Sugeno
T_{FG}	Temperature of flue gas
m_{mt}	Total mass of metal tube and drum tube
m_{st}	Total metal mass
V_{st}	Total volume of steam in the system

$\boldsymbol{V}_{\mathbf{t}}$	Total volume of the drum, downcomer, and risers;
$\boldsymbol{V}_{\mathbf{wt}}$	Total volume of water
$\boldsymbol{V}_{\mathbf{wd}}$	Total volume of water in drum
$\boldsymbol{V}_{\mathbf{sd}}$	Volume of steam in drum under liquid level
$\boldsymbol{V}_{\mathbf{sd}}^{\boldsymbol{o}}$	Volume of steam in the drum in the hypothetical situation when there is no condensation of steam in the drum

ABSTRACT

Full Name : Ahmed Rehan

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Boiler is a steam generating device heavily used to generate electricity and provide heat in process industry and buildings. The generation of steam is carried out by harnessing thermal energy generated via combustion process. The key challenges that are posed in this process are harmful nitric oxide emissions and the energy losses from the total energy contained in the fuel. It is highly desired to reduce these losses to improve boiler efficiency, however, when the operational parameters are adjusted to maximize boiler efficiency, the nitric oxides formation is adversely affected i.e. nitric oxides formation also goes up. This dilemma repeats when operational parameters are manipulated to decrease nitric oxides i.e. efficiency also gets reduced while minimizing nitric oxide emissions. Moreover a little change in demand of steam may cause disturbance in all the dynamics of boiler which may go unstable if not controlled properly. All these issues necessitate measures to be taken to optimize boiler efficiency and nitric oxide as well as to regulate operational parameters like drum pressure and drum level all at the same time.

First and foremost requirement to address the above-stated issues is to have dynamic models of efficiency, NOx and response variables of boiler. To keep track of boiler's operation cost, efficiency needs to be calculated with adequate accuracy by employing

effective mathematical tools. In this thesis work, we have investigated a new modification in conventional mathematical formulation of efficiency based on time varying efficiency using time varying operational variables of boiler. This modification has been accomplished using indirect method of efficiency by applying experimental data of variables for certain time span. Moreover a second order dynamic model of flue gas temperature has been derived to construct the mathematical formulation of efficiency in terms of available inputs only. After modeling, influence of variations in air to fuel ratio and fuel flow rate upon efficiency is discussed and it is shown that time varying efficiency covers deeper aspect of dynamic relation between efficiency and other input of boiler especially air to fuel ratio and fuel flow rate. Moreover it has been established that efficiency interacts with the dynamics of boiler and in this respect a dynamic relation between combustion process and boiler dynamics has been constructed by deriving dynamic efficiency.

After modeling efficiency, a detailed study has been carried out to investigate how thermal nitric oxides emissions, efficiency and dynamics of boiler interact with each other. In this respect, dynamic models of nitric oxides, efficiency and other operational variables of boiler have been investigated and these models have been augmented to form a joint model of whole boiler system. This model is then utilized to form an efficient control of boiler variables along with tradeoff based optimization between efficiency and thermal nitric oxides emission. All the results of modeling, control and optimization have been validated by using a real input data from a typical package boiler.

ملخص الرسالة

الاسم الكامل: احمد ريحان

عنوان الرسالة: التحكم في إنبعاث أكسيد النتريك في الغلايات و تحسين كفاءتها

التخصص: هندسة نظم و تحكم

تاريخ الدرجة العلمية: إبريل 2016

الغلاية هي عبارة عن جهاز لتوليد البخار و يستخدم بكثرة في توليد الكهرباء و كذلك في إمداد الطاقة الحرارية المطلوبة لعمليات الصناعة و المباني. يتم توليد البخار بإستغلال الطاقة الحرارية الناتجة من عملية الإحتراق. بيد أن التحدي الهام في هذه العملية يكمن في إنبعاث غاز أكسيد النتريك (NOx) بالإضافة إلى مفقودات الطاقة من جملة الطاقة الكلية التي يحويها الوقود. الأمر الذي يتطلب منا بصورة حتمية تقليل هذه المفقودات من أجل تحسين كفاءة الغلاية إلا أنه عندما تضبط المتغيرات المطلوبة لزيادة كفاءة الغلاية فإن ذلك يؤثر سلباً على تكوين غاز أكسيد النتريك أي يزيد من تكوين غاز أكسيد النتريك. و هذه المعضلة بدورها تتكرر عندما تضبط المتغيرات المطلوبة لتقليل إنبعاث أكسيد النتريك (أي أنه عند تقليل إنبعاث أكسيد النتريك فإن كفاءة الغلاية تنخفض أيضاً). علاوة على ذلك فإن تغيراً طفيفاً في طلب البخار قد يسبب إضطراباً في كل ديناميكة نظام الغلاية مما يتسبب في عدم إستقراريتها إذا لم يتم التحكم فيها بصورة صحيحة. كل ذلك يجعل من الحوجة بمكان أخذ قياسات لتحسين كفاءة الغلاية و تقليل إنبعاث أكسيد النتريك إلى أقصى درجة ممكنة مع تنظيم المتغيرات المستخدمة مثل ضغط وعاء الغلاية و مستوى المائع داخل وعاء الغلاية في نفس الوقت.

أول و أهم المتطلبات للتعامل مع المشاكل المذكورة أعلاة هو ضرورة الحصول على نموذج ديناميكي للكفاءة، و أكسيد النتريك (NOx) و متغيرات الإستجابة لنظام الغلاية. لتتبع تكلفة عمليات الغلاية نحتاج لحساب الكفاءة بدقة كافية بتوظيف الأدوات الحسابية الفعالة. في هذه الرسالة ، قد قمنا ببحث تعديل جديد في الصيغة الرياضية التقليدية للكفاءة المبنية على الكفاءة المتغيرة زمنياً باستخدام المتغيرات أو العوامل المستخدمة في الغلاية و المتغيرة مع الزمن. هذا التعديل تم إنجازه باستخدام الطريقة الغير مباشرة للكفاءة بتطبيق بيانات التجارب المعملية للمتغيرات لفترة زمنية محددة. علاوة على ذلك تم إستنتاج نموذج رياضي ديناميكي من الدرجة الثانية لدرجة حرارة الوقود

لإنشاء صيغة رياضية للكفاءة بدلالة متغيرات الدخل فقط. بعد عملية الحصول على النموذج، تمت مناقشة تأثير تغييرات نسبة الهواء إلى الوقود و معدل إنسياب الوقود في الكفاءة. و تم إثبات أن الكفاءة المتغيرة مع الزمن تعطي تفسيراً أعمق للعلاقة الديناميكية بين الكفاءة و متغيرات الدخل الأخرى لنظام الغلاية خصوصاً نسبة الهواء إلى الوقود و معدل إنسياب الوقود. علاوة على ذلك قد ثبت أن الكفاءة تتفاعل مع المتغيرات الديناميكية للغلاية و في هذا الصدد تم إنشاء علاقة ديناميكية بين عملية الإحتراق و ديناميكية الغلاية باستنتاج الكفاءة الديناميكية.

بعد عملية الحصول على نموذج للكفاءة، تم إجراء دراسة مفصلة لبحث كيفية الإنبعاث الحراري لأكسيد النتريك، و تفاعل الكفاءة و ديناميكية نظام الغلاية مع بعضهما البعض. في هذا الصدد، قد تم التحقيق في النماذج الديناميكية لأكسيد النتريك، و الكفاءة، و المتغيرات الأخرى المستخدمة في الغلاية و هذه النماذج قد تم دمجها لتشكل نموذج مشترك لنظام الغلاية الكامل. هذا النموذج قد إستخدم بعد ذلك لتكوين تحكم فعال لمتغيرات الغلاية مع التوفيق بين تحسين الكفاءة و تقليل الإنبعاث الحراري لأكسيد النتريك. جميع نتائج النمذجة، و التحكم، و التحسين تم التحقق من صحتها باستخدام بيانات واقعية من غلاية صناعية.

CHAPTER 1 INTRODUCTION

Industrial development is instrumental for civilization's growth as it is the basic way of satisfying human needs. In the past few decades, rapid increase in human population and the corresponding evolution of industry has put an enormous load on process and power industry that produce chemicals, fertilizers, petrochemicals and many other indispensable products. Consequently the requirement of additional capacity of steam and power production has dramatically risen through the world. The steam generators or boilers constitute an essential part of each industry and specifically for process and power plants. Steam generators are regarded as a backbone of their operation. The finiteness of energy resources and their costly consumptions by industrial equipment are the sinew of the innovative ways that researchers conceive to optimize steam generation and fuel consumption.

The fuel bill plays an important role in determining the total budget of a process plant. Specifically in an annual budget the most conspicuous portion of the annual cost belongs to the boiler as being the mainstay of energy generation in a power plant. Hence boiler fuel consumption becomes an essential point to focus for the cost effective and economic operation of process or power plant. For the past few decades, a major portion of the research by scientists, industrialists and engineers is directed towards cultivating and modifying technologies for efficiency enhancement of steam generators to upraise the profitability of the plant [1]. The negative side of fuel energy is that it is not a clean source of energy. Apart from other harmful emissions, nitric oxides top the list because of their extremely hazardous health and environmental effects [2][3]. For emission control, strict standards are being followed at regional and international levels. These standards put quantitative limits on the allowable amounts of pollutants that are released into atmosphere. The standards are imposed for specific time frames and vary for different sources and different emission types. In this respect various authorities like Canadian Environmental Protection Act (CEPA) of Canada, Environmental Protection Agency (EPA) of US, State Environmental Protection Administration (SEPA) of China and Royal Commission for Jubail and Yanbu (RCJY) of KSA operate in respective countries to impose these regulations [4]. Boiler being major part of industrial facilities, the study of emissions with boiler operation has been a subject of interest for researchers for many decades. Various tools are employed for the measurement of emissions on real-time basis and strategies are devised to regulate the emissions along with efficient operation of boilers [5].

1.1 Basic Boiler Operation

A boiler provides high pressure steam that is used for heating purposes or generating electricity. The water does not necessarily boil in boiler system. The fluid leaves the system either in vaporized or liquid form with extremely high thermal energy that is used for various heating purposes and industrial processes [6].

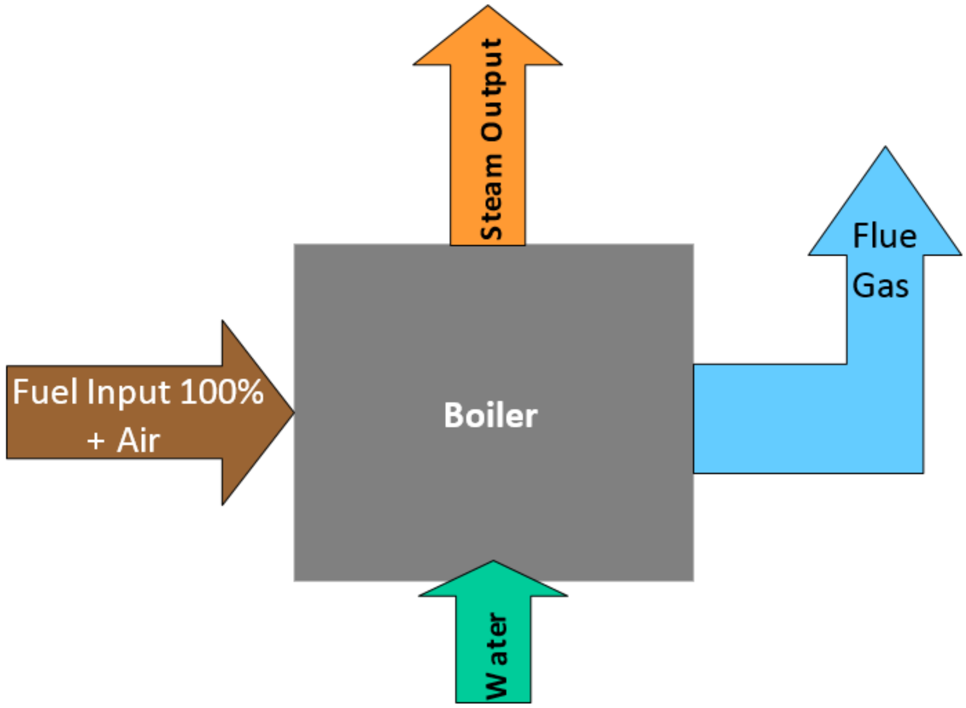

Figure 1 Schematic diagram of a typical boiler [7]

The basic operation of boiler operation is shown in Figure 1. The feedwater enters into boiler system and heat energy is applied to boil it. The steam generated leaves the system. Basically two subsystems operate in boiler process. One subsystem is the air, fuel and flue gas which constitutes the fire side of boiler. This system is responsible for providing heat energy to the boiler through combustion process. The main ingredients of the combustion process are fuel and air whose rates are properly controlled to carry out the combustion. The combustion process operates via proper mixing of air and fuel and their ignition. As a result fuel chemical energy is converted into thermal energy that provides necessary heat for boiling process. The other subsystem of boiler is steam water system also known as the water side of the boiler. Water is introduced into this system as feedwater input and it is boiled while receiving heat energy from the first subsystem. As the steam is generated through boiling, it is directed out of the boiler outlet to steam header.

The heat transfer in combustion chamber takes place through heat transfer tubes of risers in which steam water mixture circulates. These tubes are constantly subjected to thermal radiation and the constant flow of steam water mixture distributes the heat energy throughout the boiler system. As a result of combustion reaction the gaseous products released are called as flue gases. The energy from these gases is extracted via radiation heat transfer surface. As flue gases leave the combustion chamber they are passed through another heating surface of circulation tubes containing steam water mixture. This is the portion of furnace where thermal energy is delivered by convection instead of direct flame contact. Hence this portion is called convection heat surface which aids in additional recovery of heat energy from flue gases. As the gases deliver their energy they are directed out of the boiler into atmosphere [8].

The process of formation of steam begins when heat is transferred to the riser tubes in the combustion chamber. The fluid that leaves the tubes cannot comprise a fully steam phase. Instead there is a mixture of both steam and water phases that flows through the tubes. In order to determine the steam content of the mixture, the quantity used is called as steam quality. The steam quality is mathematically a ratio of mass of steam to the mass of steam water mixture. By the application of heat energy, the steam quality in riser tubes increases and as a result a density gradient is established between the fluids present in the riser tubes and the downcomer tubes. It is natural phenomenon that fluid flows from its high dense side to low dense side. In the same way the fluid or steam water mixture starts flowing from downcomer tubes to the riser tubes. This way of circulation is unforced and purely operates by natural force that arises due to density difference among two portions of boiler.

Hence it is called natural circulation and the boiler that operates with this is called as natural circulation boiler [9].

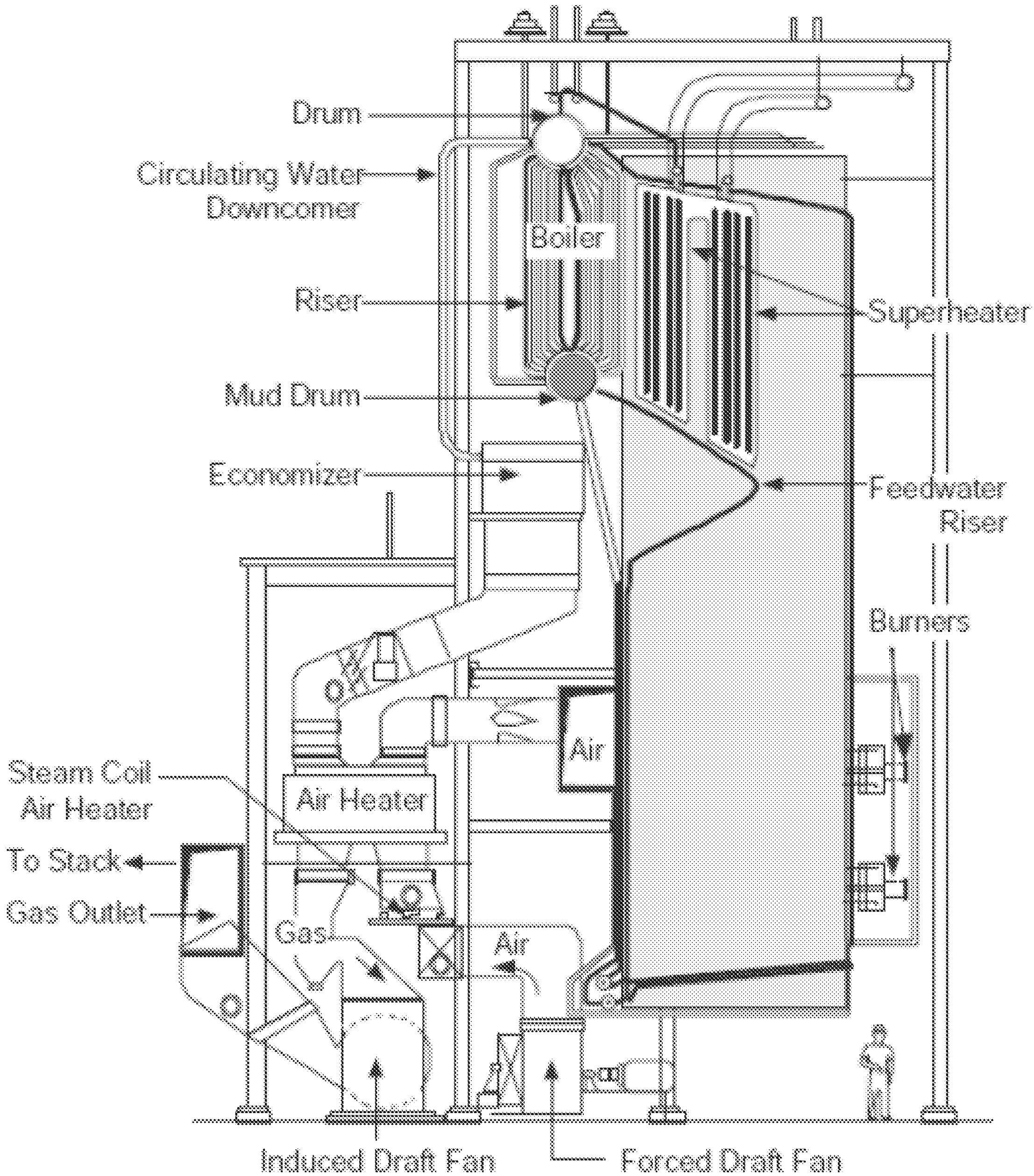

Figure 2 An industrial boiler with all components [9]

A boiler system on the whole is very complicated system that is driven by many subsystems. Figure 2 shows a typical industrial boiler with all of its components which are burners, superheater, mud drum, risers, downcomers, economizer steam coil air heater, forced draft fan, induced draft fan, gas outlet and many others [9]. The major performing subsystems are usually considered as drum, risers, downcomers, combustion chamber, superheater and economizer and these components are essentially considered by researchers for modeling and control perspectives. Besides major subsystems the measureable boiler response variables are water level of drum, steam pressure of common header and excess oxygen in flue gas. The input variables that are under manipulated to control the whole system are fuel flow rate, air to fuel ratio and feed water rate. The variable of steam is regarded as a major disturbance variable in a boiler system.

1.2 NOx Emissions

One of the major air pollutant in boiler systems is nitrogen oxides. Fuel is burnt in the combustion chamber of boiler system due to which oxides of nitrogen are produced by the oxidation of atmospheric nitrogen and fuel-bound nitrogen that are detrimental to nature [2][4]. These chemicals of nitric oxide (NOx) and nitrogen dioxide (NO_2), are collectively termed as NOx. NOx is considered responsible for some of the serious environmental hazards like ozone layer depletion, global cooling, formation of acid rain and photochemical smog [10]. As there is no source of energy like fuel to generate heat for boilers so NOx formation is an inevitable process in a boiler. Owing to pollution control necessity, different regions have different local regulations to limit the emissions under regulatory levels. These regulations provide impetus to advances made in technologies concerning NOx control [11].

Minimization of NOx has also been a subject of researchers for many decades and several schemes have been formulated in this respect to control emissions [3][12][13]. These schemes can be categorized into primary measures and secondary measures. Primary measures are based upon limiting the formation of NOx in combustion phase before its formation whereas secondary measures rely on reducing NOx after its formation. Techniques based on primary measures are Advanced Reburning Technology, Staged Combustion, Bowin Low NOx Technology, Water Injection Technology, Flameless Oxidation and many others. Secondary measures based technologies are Selective Catalytic Reduction and Selective Non-Catalytic Reduction. The major issue of all these techniques are they require abundant material and human resources. One of the primary measures to reduce NOx is to control the operational variables like fuel flow rate, air to fuel ratio, burner tilt angle etc. that directly influence production of NOx [14]. This is a very cost effective method that is dependent on the efficient use of input variables of boiler system to regulate the emissions in any operating conditions. In this context two issues are addressed: one is how to predict or model NOx based on operational variables i.e. formulation of mathematical model to simulate NOx and second is how to reduce NOx based on that mathematical model. Modeling of NOx has been done using both white box models based on first principles and black box models based on input-output data set. Common modeling techniques are based on fuzzy logic, neural network, expert system, generalized regression or analytical models formed from first principles [4]. In literature there are three sources of NOx reported: fuel-NOx, prompt-NOx and thermal-NOx.

1.2.1 Fuel NOx

Fuel NOx is formed when fuel bound nitrogen reacts with atmospheric oxygen of combustion air [15]. The nitrogen content varies for different fuels especially coal and oil have greater amount of nitrogen as compared to gaseous fuels. In case of oil, the fuel NOx may comprise 50% while in case of coal it may compromise 80% of the total NOx produced from the combustion. The formation of this type of NOx is also influenced by local combustion characteristics especially oxygen while flame temperature plays a little role in its formation [16].

1.2.2 Prompt NOx

This type of NOx is formed as a result of chemical break down of fuel hydrocarbons and their reactions with atmospheric nitrogen [15][16]. The formation usually occurs in the preliminary phase of combustion and is preceded by formation of nitrogen containing intermediary species like dihydrogen cyanide (H_2CN), nitrogen monohydride (NH), hydrogen cyanide (HCN) and cyano radical (CN). Prompt NOx formation can occur in specific combustion atmosphere like fuel rich conditions, low temperature zone and low residence time of combustion constituents. The formation is mostly located at flame tip region and contributes an amount of 15-20 ppm to the combustion process. Because of lower amount, the relative significance of prompt NOx is usually undermined as compared to thermal and fuel NOx [17].

1.2.3 Thermal NOx

Thermal NOx is generated as a result of chemical reaction of atmospheric nitrogen with atmospheric oxygen in the presence of high temperature [15]. The temperature is the main influencing agent for its formation and it is observed that the formation rate increases exponentially with the increase in temperature. The formation totally ceases below a specific temperature. Other factors include oxygen concentration, excess air, turbulence and residence time. The diatomic oxygen and nitrogen atoms dissociate themselves at high temperatures and free radicals take part in a series of reactions that result in formation of thermal NOx. This phenomenon is called as Zeldovich mechanism named after the scientist who discovered it [16]. The reactions are as follows:

$$N_2 + O \leftrightarrow NO + N$$

$$N + O_2 \leftrightarrow NO + O$$

$$N + OH \leftrightarrow NO + H$$

1.3 Boiler Efficiency

In process or production industry, boiler is one of the key targets when investigating steam systems for energy efficiency enhancement. Several tools are utilized in order to manage and evaluate boiler performance most important of which is boiler efficiency. Boiler efficiency is the measure of net useful energy that is wholly delivered from fuel to steam [18]. Like any physical system boiler is not an ideal system and a fraction of fuel energy is lost through various means during steam generation process as shown in Figure 3. From the combustion processes the chemical energy contained in the fuel is used to generate steam in a boiler system. The combustion is the commencement of the energy transfer process and a series of other processes follow that accomplish the inter conversion of chemical energy of fuel into heat energy in steam. This energy transfer process is carried out in 3 steps [19]. First, chemical energy of fuel is converted into thermal energy through combustion process, then this thermal energy is delivered to water to increase its enthalpy accompanying change of phase from liquid into steam. The increased enthalpy of steam contains transferable energy in the form of kinetic energy which is then either used for heating purposes or delivered to turbines to form electrical energy. In each stage some part of energy is lost through various means like some amount of energy is lost in burning hydrogen while some energy is carried away by flue gas going into atmosphere. Moisture present in both air and fuel also takes up a fraction of this energy while some carbon content of fuel remains unburnt causing loss of energy. Similarly there are various other minor losses like radiation and convection that reduce the efficiency [6].

The major portion of literature contributes to identify path of each loss, model these losses and create a strategy to minimize these losses. In terms of performance evaluation of boiler, it is customary to evaluate current level of efficiency on regular basis either season to season or day to day. If a simplified analytical model of efficiency is available then it becomes no more difficult to evaluate efficiency on the scale of seconds. Hence it is also required to model instantaneous efficiency like other parameters of boiler i.e. pressure or drum level which can serve as a live indicator of variations occurring in boiler performance under different operating conditions.

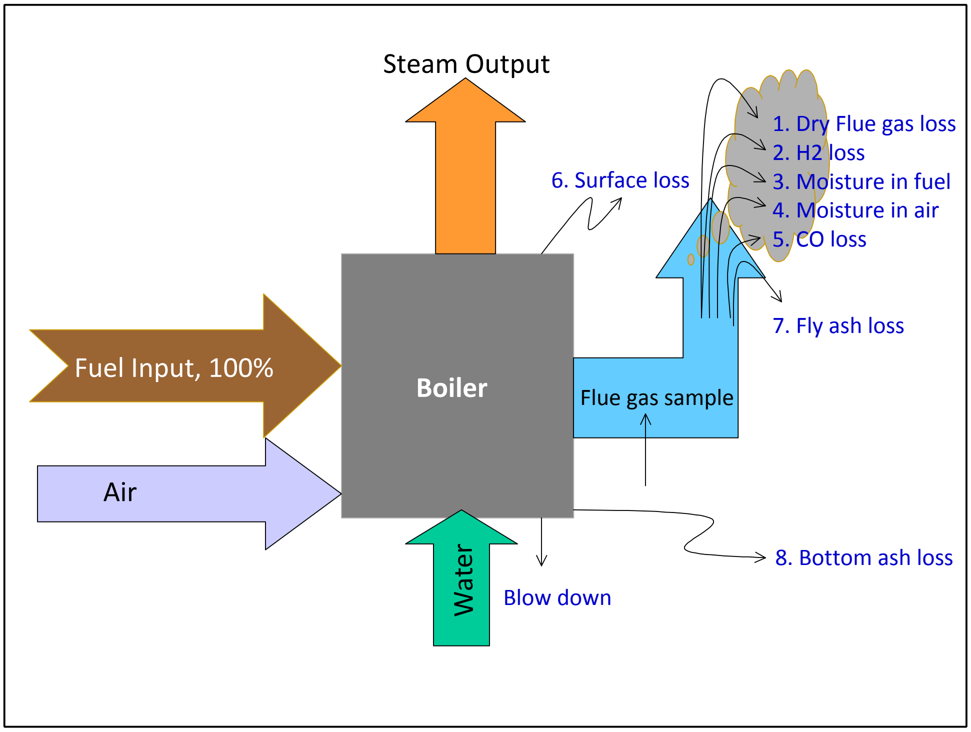

Figure 3 Various losses that reduce boiler's efficiency [7]

1.4 Problem Statement

In order to seek model based relation between efficiency, NOx and boiler's process, the first step is to develop individual models of efficiency, NOx and boiler's process. Dynamic model of boiler can be developed using basic laws of conservation of energy, momentum and mass and a 4th state space model can be formed capturing all the major features of boiler [8]. The model should be tested against experimental data and responses of model parameters should be in agreement with the experimental data. Boiler systems in general are nonlinear systems with instability in all states i.e. small disturbance in any of the inputs can cause all the variables to go violent [8]. Among all the parameters of boiler, drum level and steam pressure are the most important which demonstrate high degree of instability if steam demand changes. Decrease of drum level beyond certain limit causes overheating of boiler components for which boiler shutdown becomes inevitable. Boiler level is subjected to complicated shrink/swell phenomenon that cause unstable variations in drum level. Sometimes high swing rates also cause drum level dynamics to become out of control. It has been reported that 30% of the emergency shut downs in boiler systems are caused because of inadequate control of level of drum water [8]. For these issues, online human control of boiler system is nearly impossible as it requires constant monitoring and constant availability of control effort in order to keep the drum level and steam pressure at desired set points [20]. Hence a boiler should be integrated with a high performance controller to control its level and pressure and it should be capable of generating desired steam rate demand in large operating range of its parameters. Moreover it should be capable of responding quickly to high fluctuations in steam along with keeping all the variables under control. Another issue regarding control formulation in nonlinear systems like boiler is that all the inputs and outputs are coupled for which it becomes difficult to decide which input output pair should be used for each control device to control boiler outputs. The control becomes more difficult when all inputs, states and outputs are constrained which poses limitation on controller to decide values of inputs that must be restricted in small domain of state space. Hence the control scheme should be well enough to work in the presence of these issues and most importantly should be practically realizable [21].

A dynamic model of NOx emissions and efficiency is also required to relate these variables to some mutual operational inputs of boiler. The model should be well enough to capture time based variations of both NOx and efficiency and to be incorporated to formulate an optimization problem based on an efficient tradeoff between improved efficiency and reduced NOx. In literature various techniques have been proposed concerning the minimization of NOx. The most economical way to minimize NOx is to manipulate operational variables of boiler intelligently that are involved in the production of NOx. This can be carried out by using a qualified model that relates operational variables of combustion process to NOx formation process. To optimize boiler efficiency indirect method for modeling efficiency is required that relates efficiency to the parameters of boilers in terms of losses. So the first step is to identify those parameters that contribute in the formation of each loss. After that a mathematical model of each individual loss is required based on the same parameters that affect both NOx formation and boiler operational variables. This model needs to be dynamic i.e. it should be able to calculate time varying efficiency using time varying operational variables of boiler. The resulting input output based dynamic should be in agreement with efficiency calculated from experimental data. After modeling, influence of variations in air to fuel ratio and fuel flow rate upon efficiency also needs to be investigated. Once models of boiler dynamics, NOx and efficiency have been identified, a control cum optimization technique needs to be formulated to maximize boiler efficiency while ensuring that the NOx emission is within a regulatory level, and the operational parameters of the boiler are within the recommended (or its safe) region.

In the light of above mentioned issues, the following contributions have been made in this thesis work.

1. A nonlinear dynamic model of important boiler variables has been investigated to predict the time variations in the boiler process variables, thermal efficiency and NOx emissions. The models of NOx and boiler's process variables are acquired from the literature and a dynamic model of efficiency has been derived with a novel modification in the existing model of efficiency. This dynamic model of efficiency directly relates efficiency with operational inputs of the boiler. As, well all the models of NOx, efficiency and boiler's process variables are tested using an experimental data of a practically working industrial boiler.

2. An optimal control technique has been developed to optimize the two important variables of boiler which are NOx and efficiency. With this optimization technique, a mathematical framework has been provided to either maximize efficiency, minimize NOx or to achieve a tradeoff between the two variables. The optimization process is implemented together with boiler control process and a steam disturbance corresponding to an experimental data of an industrial boiler is applied to validate three important things: First is that boiler efficiency is high enough or atleast at optimum reasonable level. Second is that the NOx emission is within a regulatory level and the final is that the operational parameters of the boiler are within the recommended (or its safe) region.

3. Correlations have been developed between boiler important variables especially thermal efficiency and NOx emissions. This has been done by using a correlation analysis that uses cross correlation formula to describe relations between different operational variables of boiler under dynamic conditions. The analysis has been carried out by using experimental data of variables of boiler.

All the aforementioned objectives of the thesis and the methodologies to achieve them are elaborated extensively in this report. The report is organized as follows:

In Chapter 2, literature review is presented to highlight the work done in the area of boilers, harmful nitric oxide emissions and efficiency. In this regards, some recent techniques regarding modelling of boiler has been discussed. After that, some control techniques have been highlighted that have been implemented in order to control the dynamics of boiler. As well, existing modeling techniques for both efficiency and NOx are discussed. Also, work done in the area of optimization of efficiency and NOx is also highlighted in this chapter.

In Chapter 3, we discuss a nonlinear dynamic model of boiler system. The variables that are involved in the model are discussed and the model is presented in a state space form. Also, an analysis of model is presented to throw some light on the key points regarding the formation of the model.

In Chapter 4, two models of thermal NOx are elaborated. It is demonstrated how these models relate the formation of thermal NOx with the operational inputs of boiler. Also, the behavior of these models is illustrated via plots of NOx with different inputs. The chapter ends with the comparison of both models with the conclusion that which of the two models can best fit in to deal with the control and optimization issues of boiler.

In Chapter 5, we discuss a dynamic model of efficiency. First we represent the basic overview of Direct Method and Indirect Method that are used to calculate efficiency. Then we discuss the important elements that are required to calculate efficiency using Indirect Method. Time variations of all the energy losses are also presented both in descriptive and graphical forms. After that, a dynamic model of efficiency is formed by deriving an empirical model of FGT with respect to operational inputs of boiler. Finally, the utility of this dynamic model is presented based on its use in control and optimization of boiler important variables.

In Chapter 6, a correlation analysis has been provided to discuss how the operational variables of boiler are related to each other. For this, experimental data of important variables of boiler is presented and used to calculate correlations using correlation formula. Along with that, time varying correlations of all the boiler's important variables with respect to different inputs is also illustrated in this chapter.

In Chapter 7, we deal with the control issue of the boiler. First it is discussed why the controller is necessary for controlling the dynamics of boiler. Then a PID based three term control is formulated to control important output variables of boiler. Genetic Algorithm is discussed in this chapter and it is outlined how Genetic Algorithm can be used to optimize the parameters of the controller. Also a unified model of boiler is presented which combines all the models of NOx, efficiency and boiler's efficiency in a single unified form.

In Chapter 8, the issue of optimization is discussed with the aim of optimizing the variables of NOx and efficiency. First the necessity of optimization is outlined and then the optimization approach is formulated using a performance criterion that penalizes low efficiency and high NOx. The chapter concludes with the simulations of control and optimization techniques which are implemented together to regulate boiler variables under the action of steam disturbance.

In Chapter 9, a summary of overall thesis report is presented. The summary aims at providing a concise version of all the methodologies and techniques that have been used in order to model the boiler important variables, as well as control and optimize them using the dynamic models.

CHAPTER 2 LITERATURE REVIEW

The literature of boiler mostly comprises either dynamic modeling or control of boiler, modeling or control of emissions and optimization problem based on maximizing efficiency and minimizing emissions. Based on this we first discuss the latest work done in the area of modeling of boiler's process. Then we highlight some of the control techniques used in the literature for stabilizing operational variables of boiler under dynamic conditions as well as improving boiler's resistance against disturbances. Then we discuss the modelling and control techniques that have been used for NOx and modelling and improvement techniques that have been used for efficiency. Afterwards we present some latest literature regarding optimization techniques for NOx and efficiency. The optimization techniques have been discussed individually as well as collectively for both NOx and efficiency.

2.1 Modeling of Boilers

Modeling of boilers is being done by researchers since many years. Modeling of boilers have been performed by using both white box models based on physical principles and black box models based on input-output data set but generally boiler models can be classified into three categories: simple, moderate and complex models. Complex models are composed of highly nonlinear equations describing sophisticated aspects of each boiler dynamics using distributed parameters. Moderate models are based on some assumptions while simple model are based on many assumptions. A simple non-linear model comprising 4 states was developed by Astrom and Bell [8] to predict various parameters of boiler with very high accuracy and was corroborated against experimental data. This 4th order state space model of boiler described the dynamic behavior of drum pressure, drum steam volume, steam quality and total volume of water in boiler system. The equations of model were derived by using basic laws of conservation of energy and mass for the system globally as well as for individual components of risers and drums**.**

Bond graphs are of interest of researchers as they are capable of describing the power flow between subsystems and how they are coupled on the basis of energy. Moreover the modification in bond graph model is simpler compared to nonlinear state space model as the modification can be augmented easily in the already formed model without the need of change from beginning. Aziz and Nazaruddin [22] an industrial water tube boiler using bond graphs and it was based on same algebraic and differential equations from the work of Astrom and Bell [8]. The whole boiler process was thought of as set of small energy systems of risers, drum, economizer, superheater and flue gases, these energy systems were using word bond graph and a bond graph was formed when all subsystems were interconnected using channels that described the energy flow between the subsystems. Hence the global response of boiler was observed by combined set of all subsystems. The bond graph technique, as pointed out by the author, was adequate in predicting all the dynamics of boiler system however there were some inadequacies in the results of superheater for which proposed technique didn't perform up to the mark either due to limitation of technique or some unaccounted dynamics of parameters of superheater [22].

Hong et al. [23] a marine boiler based upon modeling in modular way i.e. dividing the boiler system into small modules where each module can be independently from others.

For the risers temperature, the two-dimensional steady thermal conductivity was used to calculate the temperature distribution of pipe walls in which distribution was assumed to be uniform. Similarly for convective evaporators and down comers, temperature distribution was also formulated mathematically by author and the resulting models were simulated. The rest of modeling equations were derived from mass, momentum and energy conservation principles. The results produced when compared with experimentally obtained data proved to have a good accuracy and real-time monitoring capabilities for boiler.

Radial Basis Function Neural Network (RBFNN) is relatively a novel technique and so belong to the interest of researchers in solving identification problems in complex nonlinear systems like boilers. In the work of Kouadri et al. [24] modelling of boiler was accomplished using RBFNN. In order to employ this technique the boiler dynamics were first formulated as parametric functional optimization problem and the optimizer that was incorporated to minimize cost function was Hybrid Genetic Algorithm (HGA). In addition to other dynamics, the technique was also capable of emulating shrink/swell in drum level and also the scheme took into account the uncertainty factors that are present in model due to small modelling errors and simplifying assumptions. For this, cost function was formulated to optimize those errors and assumptions with the argument of function being weights to be determined to optimize errors and assumptions. The GA cum gradient descent sought efficiently local minimum of cost function in which GA explored best chromosomes which were further refined by gradient method by progressively moving to global minimum. Furthermore in order emulate the model over large operating range the training samples of RBFNN covered a wide range of input changes which are practically applied in boiler systems. The responses showed in the work exhibited that main variables of boiler like pressure and level can be well captured by the proposed technique.

Adam and Marchetti [25] all dynamics of boiler using the same approach of laws of conservation of mass, energy and momentum. They formed non-linear models for the evaporation in the riser tubes and the steam phase in the drum, and combination of both yielded total dynamic model of whole boiler system. The developed model was successful to simulate the dynamic operation of riser, separation drum and natural circulation of liquid hold-up. The model added with a PI controller exhibited satisfactory performance in controlling the pressure and level of drum and was able to simulating the complicated inverse response of level dynamics of drum mixed phase water.

2.2 Control Techniques for Boiler System

Cogenerations power plants are disposed to the problem of fast fluctuations in steam as flue gases are also utilized to aid production of steam along with generating electricity. The cause of fluctuations can be several e.g. sudden increase in demand of steam by customer or if one or more boilers trip causing burden on other boilers to make up the deficiency of steam demand for the cases where many boilers are connected in parallel with a common steam header. In this scenario the major requirement becomes how fast a boiler can be responsive to fast variations in load while using minimum possible control effort from inputs of firing rate and feed water rate with minimum fluctuations in drum water level. Hence a need stems to improve the response of boiler against wild fluctuations in steam demand under wild operating conditions using a very responsive and accurate controller.

Elshafei et al. [26] solved this problem by tuning three term controller for boiler system by formulating it as an optimization problem. Two PID controllers were used by the author to control level and steam pressure. Both these variables are dependent on incoming feed water and firing rate however feedwater was used to control drum level and firing rate to control drum pressure based on the idea that feedwater-steam coupling and firing rate-level coupling is very mild and can be compensated by the controller. In three term PID controller the problem of tuning gains is quite challenging especially for MIMO nonlinear systems for which genetic algorithm was employed by formulating the control problem as a constrained optimization problem. An objective function was devised by penalizing overshoots in feedwater, heating power, drum level, pressure and differences in level and pressure from their set points. The results obtained from optimized PID gains proved to be superior to unoptimized PID controller as illustrated graphically by author hence the proposed technique not only reduced the overshoots in level and pressure but also the control effort with respect to firing rate and feedwater also becomes minimum by intelligently tuning control parameters.

Pederson et al. [27] applied linear quadratic (LQ) controller along with conventional PI controller to control the variables of boiler. The outputs of both LQ and PI controller were added to achieve a combined control action in order to accomplish a better stabilization and tracking effect. The LQ control action aimed at aiding the PI controller with its process optimization capability. The extended control system proved to give better performance compared to individual PI controlled system.

Horalek and Imsland [28] applied the technique of Nonlinear model predictive control (NMPC) to a nonlinear model of boiler with the motivation that MPCs based on linearized model may not behave efficiently for highly nonlinear systems like boiler. As the boiler model contains high nonlinearities and time delays, so NMPC was designed based on nonlinear boiler model of [29]. The technique used was to control steam pressure and level of water in drum amidst variations in load by using simultaneous method for NMPC which uses all input, state and output variables for the whole prediction horizon resulting in huge number of optimization variables. The predictive controllers have an inherent ability of accommodating wide variety of load and inputs which was tested by applying large changes in pressure of steam. The result was proved to be exemplary based on simulation. The main objective of employing more complexity in predictive controllers is to produce better performance on the cost of computational effort. By comparison with PID controller the response of pressure and level using NMPC showed some improvement but not significant. However the results of different computational times against the complexity of algorithm were tabulated in the research and it was proved that the technique is real-time implementable with the aid of high performance computing system.

Thermal shock and fatigue are the phenomena that cause deterioration of metal subjected to intense heat radiation. In the boiler, riser tubes are the main components most prone to this deterioration. Various research papers exist in literature that deal with designing and controlling boiler systems in a way to make them more resilient to thermal shocks and fatigue [30][31]. Habib et al. [32] investigated the dependence of thermal stresses on heat flux and friction coefficient. High swing rates or rapid variations in steam demand are the main agents that affects the dynamics of all the state variables in boiler system so the theme of research was to investigate the pressure and level dynamics dependency on high swing rates and computationally compute temperature distribution and thermal stresses along riser tubes. The boiler model used for the case study was based on model of [8] except for the riser tubes in which a modification was done in order to investigate the influence of thermal stress and friction coefficient on thermal stress. A particular ‘abnormal riser tube’ was so as to categorize the irregularities in risers geometry (bends, variable diameter) and variations in heat flux along with other normal riser tubes so that its coefficient of friction and heat flux also become abnormal compared to other normal riser tubes. Swing rates are the main reasons that cause oscillations in dynamics of all state variables. The response of pressure was analyzed by authors for closed loop system for a certain swing rate for different values of heat fluxes along the abnormal riser tubes. It was found that pressure in riser tubes and drum has no dependency on heat fluxes whereas temperature distribution along the riser tubes has significant dependency. Increasing the heat flux on abnormal riser tube increases its temperature which in turn increases thermal stresses generated in tubes causing more susceptibility to rupture of tubes. Pressure however is dependent on overall gross heat flux on all the riser tubes which remains constant and hence causing independency of pressure. This context gives another idea that looking into the just pressure doesn’t give the picture of what is happening in the temperature distribution of riser tubes so it is advised to consider thermal stresses irrespective of pressure to avoid failure of riser tubes in abnormal swing rates. Another main result of the research was investigation of maximum allowable swing rate that an operator can allow for boiler based on the knowledge of heat flux and friction factor of boiler under operation i.e. the analysis of author poses limits on maximum swing rates which were mathematically derived and presented in a graph. Based on this information boiler can be run within safe limits of swing rates without danger of failure or rupture of boiler riser tubes.

In [33] passive fuzzy logic control was used to control the dynamics of boiler. Takagi-Sugeno (T-S) fuzzy model was used to model the nonlinearities associated with the boiler system while line-integral fuzzy lyapunov functions were formed to investigate the stability of controller. The conditions of fuzzy lyapunov functions were transformed into LMI forms which were solved via convex optimal programming approach. To deal with external disturbances passive theory was used and the proposed technique was successfully tested on the ship drum-boiler system.

Daren and Zhiqiang [34] used the feedback linearization technique to control superheater pressure along with power output of 350-MW, 16.8-Mpa coal-fired unit. The intention was to achieve better coordinated nonlinear control in comparison with conventional direct energy balance (DEB) control strategy. By implementing the proposed technique a significant improvement was achieved in terms of steam pressure regulation, improved dispatch rate as well as potential maintenance reduction for large variety of operating conditions.

Yang et al. [35] proposed internal model control augmented with neural network to control drum level of boiler. The controller also incorporated feedforward compensator for the steam flow rate in order to aid resistance again fluctuations in steam flow. This considerably enhanced the performance of internal model controller as it tackled efficiently the shrink swell phenomenon of drum steam water mixture. The model was compared with cascade PID controller and proven to give better results.

2.3 Modeling and Control of NOx

Like modeling of boiler the area of formation, modelling and controlling of NOx has been widely researched especially the issue of predicting emissions of combustion process using software sensors has been enormously discussed in the literature of boiler. Most industrial systems rely on installing hardware sensors for continuous emission monitoring which are costly and not much efficient. Compared to these, software based sensors known as inferential sensors or soft sensors are gaining popularity owing to their better usability and low cost. Based on this Iliyas et al. [12] proposed Radial Basis Function Neural Network (RBFNN) for online prediction of NOx and O_2 with the capability of self-adaptability with time. In order to train neurons of RBFNN the 3D Computational Fluid Dynamics (CFD) was developed by the author to mimic actual temperature and NOx distribution in boiler furnace for various operating conditions. Ten different operating conditions based on different air to fuel ratio (AFR) values were used for learning process of neurons. The resulting structure was capable of predicting NOx and oxygen with agreement with the measured data especially the inferential sensor outperformed continuous emission monitoring system with high accuracy of results. Moreover another advantage of the proposed technique was discussed based on the online tune-ability of soft sensor i.e. the sensors can be updated easily if the operating conditions and physical parameters of boiler changes with ageing and wear and tear hence can perform very capably if integrated with online boiler system.

Elshafei and Habib [36] used the idea of soft sensors in order to model steam quality of boiler which otherwise is difficult to measure using hardware sensors or nonlinear state estimation methods. The proposed scheme was implemented by first modeling of boiler system using Astrom and Bell [8] model equations. After validation of model results with data from actual boiler system a set of data was created covering wide range of operating conditions to perform training of basic Feed Forward Neural Network (FFNN). The network was fully able to mimic the modeling equations by predicting the steam quality with correlation coefficient of 0.998. Along with that, the proposed technique was proved to be capable to identify critical limits of steam quality for riser tubes subjected to more heat flux. For this, graphical analysis was provided by the author in order to aid operator to identify those limits and to operate boiler within those limits.

In real-time boiler operation high swing rates may vary steam in extremely violent manners for which fuel rate has to respond quickly in order to regulate pressure. The emission of NOx is also affected in the process as it depends on the fuel rate indirectly through temperature. In this context, the behavior of NOx was researched for different swing rates by Alzaharnah et al. [37] for the natural circulation boiler. The work was based on how swing and NOx production rates are correlated. In the research author's focus was on sole emission of nitric oxide 'NOx' for which an analytical model of thermal NOx was investigated based on the work of Li and Thompson [38]. In order to control pressure three term PID controller was employed to manipulate firing rate in order to stabilize the pressure at desired set point. Swing rates varying from 5 to 40% of the maximum continuous rating (MCR) steam flow rate per minute were applied and correspondingly response of NOx emission was illustrated amidst the control action of firing rate for pressure control. Responses of NOx illustrated by author established that swing rates variations only affect the transients of NOx, afterwards all NOx curves for different swing rates settle at the same steady state. Moreover swing rate and overshoots in NOx response reflect an opposite behavior i.e. maximum overshoot occurs for minimum 5% of swing rate and vice versa. In this context the optimization problem can be formulated by employing an objective function which penalizes the overshoots in NOx formation by variations in firing rate. Although the optimization problem was not formulated mathematically in the work however graphical responses of NOx against different swing rates were provided to give an insight into NOx minimization problem.

The NOx model and boiler model gives a set of equations which can be organized to form a single augmented nonlinear state space model for both NOx and boiler dynamics. Minhajullah et al. [39] used this idea and employed the analytical model of NOx developed by Li and Thompson [38] to optimize the performance of boiler along with reduced NOx. Model Predictive Control (MPC) was applied by the author to control pressure, level and NOx concentration at desired set points. Results were compared with PI controller to show the efficacy of MPC in controlling the states of pressure, level and NOx at desired reference points.

Like modeling of boiler, neural networks (NN) are also applied to emulate nonlinear NOx models. The ANN methods have the advantage that they are smart to cope with variations in operating conditions of equipment for which boilers are susceptible due to ageing, wear and tear etc. This is so because training of ANN’s can be carried out online based on experimental data. In contrast with experimental measurement of emissions by using costly devices, ANN provides a cheap mean to measure NOx emission based on operational variables of boiler with very high accuracy. This idea of measuring NOx using ANNs was applied by Ilamathi et al. [40] for a pulverized bituminous coal fired boiler. As stated by author the online ANN modeling of NOx can be accomplished very fast in terms of computational effort so optimal tuning can be carried out to tune combustion parameters in order to minimize NOx emission. For optimal solution search genetic algorithm was employed to control flue gas oxygen, nozzle tilt, flue gas outlet temperature, and secondary air burner damper in order to minimize cost function and hence NOx emission. For learning process of ANN, experimental data was used and neurons were successfully trained to emulate relation between NOx and combustion parameters. The ANN modeling of process and optimization carried out by GA exhibited the good performance of technique in terms of modeling accuracy and low NOx emission**.**

Zhou et al. [41] used ANN to relate boiler parameters with NOx for a pulverized coal boiler. The aim of research was to provide quick online prediction and minimization of NOx with ANN as opposed to slow CFD technique which is computationally hectic and time consuming. A novel form of genetic algorithm (GA) i.e. the micro-GA was used by authors to construct the ANN model while micro-GA was employed after to search for lowest NOx based on the optimum conditions of over fire air, secondary air burner damper opening and oxygen concentration in flue gas.

2.4 Modeling and Improvement Techniques for Boiler's Efficiency

Boiler's efficiency is a widely used tool to measure the performance of boiler [42]. Boiler system, like any system, is not an ideal system and a fraction of fuel energy is lost through various means during steam generation process. Boiler efficiency is used as a measure to approximate these losses and to evaluate net useful energy that is delivered to water from the fuel. It is therefore important to investigate sub processes in combustion that contribute to degradation of energy transfer from fuel to steam. Efficiency has remained most beneficial tool in literature to assess the performance of boiler combustion process and many approaches have been sought to evaluate and maximize it. In [43], direct method for calculating efficiency was explored, and case study was provided to calculate efficiency of coal fired boiler. It was established that the direct method equations can be used to calculate the real time thermal efficiency of boiler. Huang et al. [44] used three dimensional Computational Fluid Dynamics (CFD) to model combustion chamber as well as heat exchanger in a boiler system. The combustion chamber model was formulated by integrating individual models of gaseous combustion, fluid flow and radiative heat transfer. Afterwards the direct method was used to evaluate the thermal efficiency of boiler using the parameter values as predicted by CFD model as well as by experimental data to validate the calculation. In [45] efficiency of pellet boiler was investigated with the aim of optimizing field performance of boiler compared to laboratory performance. Five operating boilers in residential buildings were monitored to determine monthly and annual efficiencies. A difference of 7-25% was observed in efficiencies of laboratory based tests and field based tests revealing a considerable margin of efficiency improvement for field boilers. The efficiency was calculated using direct method and the operating conditions influencing efficiency incorporated load modulation, flame stabilization, stand by and ignition phase. Specifically empirical relation between efficiency and load factors alongside number of ignitions was established for two case study boilers. Based on this relation it was argued that the efficiency increases exponentially with increasing load factor and stabilizes at some asymptotic point afterwards.

The indirect method of calculating efficiency can be specifically used to study the effects of operating conditions on boiler efficiency. In this regard, effect on average efficiency by variations of unit load, excess air and fuel quality was examined by using indirect method in [46]. It was discussed that losses due to flue gas, incomplete combustion and unburnt carbon vary with different amounts of excess air while other losses do not change. This point led to locate the optimum excess air for which efficiency was maximum. Thermal efficiency was also found to vary with varying loads, particularly an increasing trend was observed by decreasing the load factor. It was also established based on indirect method that raising the lower heating value by employing high quality fuel also improves the efficiency. Li and Gao [47] improved the indirect method of calculating efficiency by calculating excess air coefficient from air leakage coefficient of air preheater. The basic motivation was that limitations of sensor devices makes it difficult for monitoring air leakage rate hence it was indirectly calculated by using quality and heat balance between the air preheater gas side and air side. In [19], indirect method for calculating thermal efficiency was presented using average experimental data. The fuel used was coal and constituents of combustion products were evaluated using ultimate analysis of fuel. All the losses were calculated based on the constituents of combustion reaction and the average temperature of flue gas. After calculating efficiency corrective actions were suggested in order to improve efficiency. These were based on effective monitoring of concerned parameters as well as periodic adjustment and analysis of components and fuel. In [48] lower heating value of coal was determined online with the motivation that lower heating value is subjected to variations as the coal quality changes dynamically during real-time operation of boiler. For this the author employed dynamic energy balance equations for the major components of boiler which were economizer, superheater, exhaust air, air preheater, steam drum, water wall and downcomer. The identified model of lower heating value was then used to evaluate thermal efficiency of boiler by indirect method.

Modeling of efficiency is also carried out using empirical models. This is usually done by employing direct method to generate data set of efficiency against various different operating parameters. Li et al. [49] used empirical modeling scheme to model combustion efficiency of coal-fired boiler. For this Extreme Learning Machine (ELM) was used to obtain empirical relation between combustion efficiency and operational variables of boilers. Adaptive Neuro-Fuzzy Inference System (ANFIS) was used to improve the accuracy of model while Particle Swam based Artifical Bee Colony (PS-ABC) was employed to optimize ELM model. The model was trained and validated using experimental data.

The correlation of coal fired boilers efficiency with loss due to hydrogen in fuel was formed in [50]. Monthly data of average values of both quantities was recorded for 12 months to form correlation. It was established that loss due to hydrogen content of fuel can be used to predict whole efficiency and a linear regression was developed for this based on models of linear, exponential, power, and polynomial with order 2. Similarly in [51] regression analysis was done to derive relations between flue gas loss versus excess air coefficient and unburnt carbon versus excess air for coal fired boiler. It was also pointed out that the regression coefficient may change with different batches of coal due to disproportionate composition. Dedovic et al. [52] investigated the influence of recirculation of combustion products, air flow rate and residence time of fuel on efficiency of boiler fueled by wheat straw bale. Nonlinear regression analysis was employed to form mathematical model of efficiency using a Gaussian function while t-test and F-test were carried out to fit the model with the experimental data. To calculate efficiency direct method was used along with measured data of concerned variables.

Besides modeling boilers efficiency, it is also sought to improve the boilers efficiency based on proposed model. In [53] influence of equivalence ratio and steam power on bagasse-boiler efficiency was investigated. Optimal ranges of equivalence ratio and steam power were defined in the sense of optimizing efficiency. The calculation of efficiency was carried out by forming a bagasse-boilers Industrial Test Code derived from general rules of ASME and GHOST indirect method of calculating efficiency. As the exhaust gas losses is the biggest of all hence a heat recovery scheme was formulated based on the optimization of exhaust gas loss. In this respect an optimized combination of heat transfer surfaces was presented using cost analysis to increase the efficiency. Song and Kusiak [54] and optimize combustion efficiency of electric-utility boiler by deriving a non-analytical relation between the efficiency and other controllable and uncontrollable boiler variables using data mining approach. Different methodologies were proposed for control configuration and control variables manipulation. These were based on manipulating controllable and uncontrollable input variables and using response variables including efficiency in the clustering algorithm to optimize efficiency. Moreover coupling between various response variables of boiler was addressed and it was argued that coupling phenomenon can be considerably reduced by introducing more response variables into clustering algorithm. Treedet and Suntivarakorn [55] tried to improve the boiler efficiency by controlling the air flow rate. For this he used fuzzy logic controller to control the air flow rate by taking input of measure oxygen content in flue gas. An improvement of 4.34% was achieved by the implemented control scheme. In [56], 25 kW pellet boiler was tested in laboratory to investigate the effect of combustion air supply ratio and heat losses on the efficiency of boiler. Using tests, polynomial regression based relations were formed as boiler efficiency versus excess oxygen and carbon monoxide emissions versus excess oxygen. These relations were employed to locate the optimum points where efficiency was maximum and carbon monoxide was minimum with respect to the air supplied as an input to combustion. The results were practically applied to optimize the performance of 100kW boiler. A 2% improvement in efficiency was achieved by adjusting the air flow rate by using the proposed technique.

2.5 Optimization of NOx and Efficiency with Boiler Dynamics

In boiler system efficient operation can be achieved by optimizing more than one parameter which demands taking optimal decisions that need compromise between two or more objectives that are in conflict with each other. This class of optimal problem is more realistic and is needed for many multifaceted engineering optimization problems. The complex nature of boiler dynamics hence also attracts this multi-objective optimization problem as boiler complex behavior in which optimizing one parameter leads other parameters go unstable or out of bound of satisfactory limits. For these type of optimizations a set of optimal solutions is sought that is acceptable to all the objectives without being biased towards one solution. Lot of multi-objective optimization techniques have been proposed in the literature like the multi-objective programming approach, the weighted sum method, the evaluation function method etc. For boilers efficiency and NOx problem the idea of multi objective optimization problem is very attractive as both NOx and efficiency conflict with each other as maximizing efficiency and minimizing NOx simultaneously is not physically possible. In this context several papers address collectively the issue of modeling and optimization of efficiency and NOx.

Among optimization techniques Particle swarm optimization (PSO) is very famous optimization technique which uses the concept of birds flock to locate the optimal solution for a given optimization problem. Zhao and Wang [5] used an improved Center PSO to boost the search performance of conventional PSO and employed it to maximize efficiency and reduce NOx. A joint objective function was developed by the authors and prior to optimization of NOx and efficiency, a hybrid model relating support vector regression (SVR) with basic boiler efficiency model was developed to formulate a relation of operational parameters of combustion process with NOx and efficiency. The resulted model was able to predict efficiency and NOx in agreement with the actual measurements and also was successful in optimization of both parameters. However the model was static and totally empirical in nature, i.e., neither NOx nor efficiency were modelled using physical principles. In [57] air to fuel ratio and different over fired air techniques were analyzed for examining the behavior of efficiency and NOx for a coal fired boiler. It was shown that efficiency decreases under rich fuel conditions as well as NOx. In extreme air rich conditions efficiency decreases again and based on that optimum point of efficiency was sought. NOx on the other hand showed a monotonic increase by increasing the excess air in limited range. It was concluded that a balance between both variables was subject to proper adjustments of damper openings, secondary air distribution pattern and more importantly quantity of excess air supplied. Weiqing [58] utilized least square support vector machine and the NSGA-II jointly to model combustion process of boiler and a multi objective optimization problem was formulated to optimize both NOx and Efficiency after their modelling. NOx versus efficiency was formulated graphically and optimal and non-optimal regions were defined to depict safety limits of NOx and efficiency. A Pareto non-dominated optimal solution set was presented in NOx versus efficiency graph that optimized a certain multi objective function optimizing both efficiency and NOx. Zhang et al. [59] investigated the combustion parameters of over fired air, air distribution mode, primary air velocity and oxygen content on efficiency along with NOx. Different adjustments of these parameters we tried in order to improve the efficiency of tangentially fired boiler fueled by coal.

Combustion is the process that generates the required heat to convert water into steam in boiler system. Improving combustion efficiency corresponds to improving overall boiler efficiency. The combustion process is highly dependent on amount of oxygen present in the combustion as oxygen is the main agent to degenerate fuel to produce energy. The air contains 78% nitrogen which carries away some amount of oxygen for NOx forming reactions. In this context it is tempting to increase the oxygen concentration of combustion air in order to improve efficiency of combustion process. Yuhua et al. [60] implemented the idea of locally enriched oxygen air to improve the efficiency and minimize the concentration of NOx emissions. He formulated the technique of enforcing non-uniform concentration of oxygen in the furnace which is summarized as: lower the oxygen concentration in air in main combustion region in order to restrain formation of NOx, increase the oxygen concentration near and above the furnace wall, use enriched oxygen wind as the over flame air to ensure full combustion of carbon fly ashes. In order to validate the proposed idea 3D simulation of temperature distribution, coal particle trajectories and NOx and oxygen concentration in the furnace were analyzed. The temperature distribution revealed that using the proposed technique the flame length increased causing more uniformity in temperature in whole furnace region which in turn caused lower formation of NOx as compared to increased temperature in the localized region for combustion process without local enriched oxygen technique. The coal particles trajectory diagrams exhibited more recirculation of coal particles towards the burning area instead of going out along with flue gas thereby causing more efficient fuel burning. In this way by using local enriched oxygen supporting combustion technique minimization in NOx formation was successfully achieved.

In all of the aforementioned works, the modeling methodology of NOx was based on measurements and empirical models were derived and used further for optimization and control processes. To the best of our knowledge, boiler’s efficiency has never been calculated in instantaneous form while on the other hand boiler’s efficiency is a dynamic variable which changes instantaneously under dynamic operating conditions. The usual approach in the literature is to calculate average form of efficiency which limits the scope of it to only evaluating fuel economy. The problem of efficiency dynamics need to be addressed as the efficiency is the only variable that relates the combustion process of boiler with dynamic process of boiler.

Hence a concrete mathematical model is required to relate NOx emissions and efficiency to the operational variables of Boiler. The model should be capable to capture time based variations of both NOx and efficiency and to be incorporated to formulate an optimization problem based on an optimal tradeoff between improved efficiency and reduced NOx.

CHAPTER 3 BOILER MODELING

In this chapter we discuss the nonlinear dynamic model of boiler system. The purpose of this model is to develop mathematical framework that can simulate essential variables of boiler under different operating conditions. As discussed in Chapter 1 there are several components of a boiler that are integrated together in an industrial setup of boiler. However the main components that contribute most in steam generation process are few which are drum, risers and downcomers. These components are mostly aimed while modeling the dynamics of boiler.

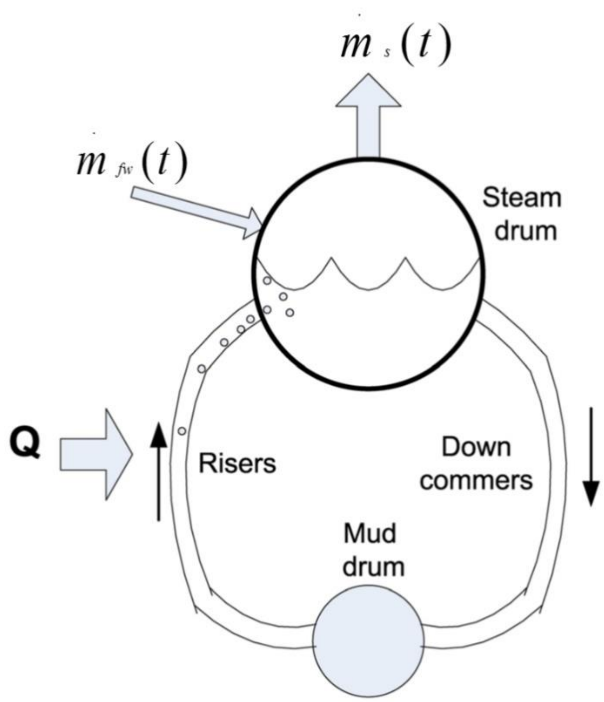

Figure 4 Schematic diagram of boiler's operation [20]

Figure 4 shows the simplified model of whole drum boiler system. Typical boilers contain large number of risers and downcomers but to avoid complexity they have been simplified by two single tubes one for each riser and downcomer. Steam is collected from the drum at a certain rate $\dot{m}_s$ which is constantly replenished by feed water coming at a rate $\dot{m}_{fw}$. The steam flow rate is considered as a disturbance as the variations in steam is responsible for the dynamic behavior of all the variables of boiler.

The fuel is burnt in combustion chamber to generate the required heat energy. This heat energy enters the boiler system through riser tubes at a certain rate Q. The heat energy boils water into steam in risers and steam water mixture enters drum section through riser drum junction. Drum contains the steam water mixture. Portion of steam is continuously being carried out to steam header which is compensated by feedwater. Due to less density in the risers the water circulates in the direction from downcomers to risers. Hence in this way the heat is distributed out in water of whole boiler system through natural circulation and boiling takes place.

3.1 Mathematical Formulation

In accordance with Astroms and Bell [8], the total dynamics of all the subprocesses of boiler system are representable by four states of total volume of water, drum pressure, steam quality and steam volume in drum. The equations of model are derived by using basic laws of conservation of energy and mass for the system globally as well as for individual components of risers and drums. These 4 states are assembled into one set of nonlinear state space model given as:

$$a_{11}\frac{dV_{\mathrm{wt}}}{dt}+a_{12}\frac{dp}{dt}=\dot{m}_{fw}-\dot{m}_s, \tag{3.1}$$

$$a_{21}\frac{dV_{\mathrm{wt}}}{dt}+a_{22}\frac{dp}{dt}=Q+\dot{m}_{fw}h_{fw}-\dot{m}_s h_s, \tag{3.2}$$

$$a_{32}\frac{dp}{dt}+a_{33}\frac{dx}{dt}=Q-xh_{fg}\dot{m}_{\mathrm{dc}}, \tag{3.3}$$

$$a_{42}\frac{dp}{dt}+a_{43}\frac{dx}{dt}+a_{44}\frac{dV_{\mathrm{sd}}}{dt}=\frac{\rho_s}{T_d}(V_{\mathrm{sd}}^o-V_{\mathrm{sd}})+\frac{h_{fw}-h_w}{h_{fg}}\dot{m}_{fw} \tag{3.4}$$

Where the coefficients a_{ij}*'s* are

$$a_{11}=\rho_w-\rho_s$$

$$a_{12}=V_{wt}\frac{\partial\rho_w}{\partial p}+V_{st}\frac{\partial\rho_s}{\partial p}$$

$$a_{21}=\rho_w h_w-\rho_s h_s$$

$$a_{22}=V_{wt}\left(h_w\frac{\partial\rho_w}{\partial p}+\rho_w\frac{\partial h_w}{\partial p}\right)+V_{st}\left(h_s\frac{\partial\rho_s}{\partial p}+\rho_s\frac{\partial h_s}{\partial p}\right)-V_t+m_{mt}C_p\frac{\partial t_m}{\partial p}$$

$$a_{32}=\left(\rho_w\frac{\partial h_w}{\partial p}-xh_{fw}\frac{\partial\rho_w}{\partial p}\right)(1-\bar{\alpha})V_r+\left((1-x)h_{fg}\frac{\partial\rho_s}{\partial p}+\rho_s\frac{\partial h_s}{\partial p}\right)\bar{\alpha}V_r$$

$$+(\rho_s+(\rho_w-\rho_s)x)h_{fg}V_r\frac{\partial\bar{\alpha}}{\partial p}-V_r+m_{mt}C_p\frac{\partial t_p}{\partial p}$$

$$a_{33}=\big((1-x)\rho_s+x\rho_w\big)h_{fg}V_r\frac{\partial\bar{\alpha}}{\partial x},$$

$$a_{42}=V_{\mathrm{sd}}\frac{\partial\rho_s}{\partial p}+\frac{1}{h_{fg}}\left(\rho_s V_{\mathrm{sd}}\frac{\partial h}{\partial p}+\rho_w V_{\mathrm{wd}}\frac{\partial h_w}{\partial p}-V_{\mathrm{sd}}-V_{\mathrm{wd}}+m_{md}C_p\frac{\partial t_p}{\partial p}\right)$$

$$+x(1+\beta)V_r\left(\bar{\alpha}\frac{\partial\rho_s}{\partial p}+\frac{(1-\bar{\alpha})(\partial\rho_w)}{\partial p}+\frac{(\rho_s-\rho_w)(\partial\bar{\alpha})}{\partial p}\right),$$

$$a_{43}=x(1+\beta)(\rho_s-\rho_w)V_r\frac{\partial\bar{\alpha}}{\partial x},$$

$$a_{44}=\rho_s \tag{3.5}$$

The parameters used in equations (3.1)-(3.5) are described in Table 1

Table 1 Description of Astrom's boiler model parameters

$\bar{\boldsymbol{\alpha}}$	Average volume fraction
$\boldsymbol{\rho_w}$	Density of feedwater
$\boldsymbol{\rho_g}$	Density of saturated steam
$\boldsymbol{V_{dc}}$	Downcomer volume
$\boldsymbol{P}$	Drum pressure
$\boldsymbol{A_d}$	Drum surface area
$\boldsymbol{V_d}$	Drum volume
$\boldsymbol{h_w}$	Enthalpy of feedwater
$\dot{\boldsymbol{m}}_{\boldsymbol{fw}}$	Feedwater flow rate
$\boldsymbol{q_{fs}}$	Feedwater steady state value
$\dot{\boldsymbol{m}}_{\boldsymbol{f}}$	Fuel flow rate
$\dot{\boldsymbol{m}}_{\boldsymbol{f}}$	Fuel flow rate

$\boldsymbol{g}$	Gravity
$\boldsymbol{Q}$	Heating rate
$\boldsymbol{Q_s}$	Heating rate steady state value
$\boldsymbol{h_{fg}}$	h_g-h_f
$\boldsymbol{l}$	Level of the water
$\boldsymbol{m_{md}}$	Mass of drum
$\boldsymbol{t_p}$	Metal temperature
$\boldsymbol{\dot{m}_{dc}}$	Riser & downcomer mass flow rate
$\boldsymbol{m_r}$	Riser metal mass
$\boldsymbol{V_r}$	Riser volume
$\boldsymbol{\dot{m}_r}$	Risers flow rate
$\boldsymbol{h_f}$	Specific enthalpy of saturated liquid water
$\boldsymbol{h_g}$	Specific enthalpy of saturated liquid water
$\boldsymbol{C_p}$	Specific heat of metal
$\boldsymbol{C_{ps}}$	Specific heat of superheated steam.
$\boldsymbol{\dot{m}_{ct}}$	Steam condensation rate
$\boldsymbol{\dot{m}_s}$	Steam flow rate
$\boldsymbol{\dot{m}_{sd}}$	Steam flow rate through liquid surface of drum
$\boldsymbol{x}$	Steam quality
$\boldsymbol{m_{mt}}$	Total mass of metal tube and drum tube
$\boldsymbol{m_{st}}$	Total metal mass
$\boldsymbol{V_{st}}$	Total volume of steam in the system

$\boldsymbol{V}_{\mathrm{t}}$	Total volume of the drum, downcomer, and risers;
$\boldsymbol{V}_{\mathrm{wt}}$	Total volume of water
$\boldsymbol{V}_{\mathrm{sd}}$	Volume of steam in drum under liquid level
$\boldsymbol{V}_{\mathrm{sd}}^{\boldsymbol{o}}$	Volume of steam in the drum in the hypothetical situation when there is no condensation of steam in the drum

3.2 Model Background and Analysis

The first two equations (3.1)-(3.2) constitute modeling of two states of total volume of water and drum pressure using global mass energy balance equations. These two states are not dependent on the rest of states and moreover if modeling of boiler level is not desired then this two state model suffice to predict the dynamic behavior of pressure and total water volume in boiler system.

Among all the variables, drum level is one of the most important variables, which is measureable and provides a mean to observe the dynamics of boiler [61]. Modeling of level creates the necessity to analyze the distribution of steam and water in whole system which expands the state space by inclusion of two more states of steam quality and volume of steam in drum. The steam quality plays its role to determine how much energy or mass content of either steam or water is present in given steam water mixture. The last two equations of Astrom and Bell’s model constitute modeling of steam quality and volume of steam in drum and are derived based on sophisticated steam water interconversion and as well as mass energy balance phenomenon for both risers and downcomers. A linear distribution of steam and water is assumed in risers for simpler modeling with slope depending on heating rate, tubes surface area and downcomer flow rate. A lumped parameter model is used to describe the dynamics of steam water mixture in risers and downcomers on the basis of total mass or energy (of steam water mixture) coming in and total mass or energy going out. This way of modeling avoids the complex modeling of evaporation and condensation phenomena as these cause additional flows (evaporation flow from water into steam and condensation flow from steam into water) which need to be taken into account while deriving mass and energy balance equations. The distribution of stream in drum, represented by V_{sd}, is based on four different flows that contribute in mass balance of drum. These flows are:

1. Flow of steam and water mixture coming from risers
2. Flow of steam going out from liquid surface of drum
3. Condensation flow from steam to water in drum
4. Feed water flow from external water supply.

The circulation in the boiler is considered natural which is by downcomer flow rate '$\dot{m}_{dc}$' using momentum balance equation giving a differential equation model. This circulation is *unforced* and is determined by density gradient between high dense mixture in downcomer and low dense mixture in riser. Response of differential equation shows that transients governed by differential equation are very quick because of low time constant and hence are ignored so steady state model of circulation is derived from differential model.

The state space model of equation set (3.1)-(3.4) doesn’t explicitly define the output variable of level as a state which necessitates the idea of either replacing any state with level state or to do a states-level mapping. The latter approach was employed in this thesis work. The level is dependent on total volume of water in drum, volume of downcomer, average volume fraction of steam, volume of riser and volume of steam in drum through following relations:

$$V_{wd} = V_{wt} - V_{dc} - (1 - \bar{\alpha})V_r \tag{3.6}$$

$$l = \frac{V_{wd} + V_{sd}}{A_d} \tag{3.7}$$

Another noteworthy point regarding the model is that the last two states do not appear mathematically in first two state equations, whereas all the states are functions of first two states. This motivates the idea of modularizing the state space into smaller subspaces of (V_{wt} P) or (V_{wt} P x) or (V_{wt} P x V_{sd}) where each module can be independently used based on which state set serves the given problem. Equation (3.5) shows that all the states are complicated nonlinear functions of boiler geometrical parameters as well as pressure based enthalpy of steam ‘h_s’, enthalpy of water ‘h_w’, density of steam ‘ρ_s’ and density of water ‘ρ_s’ which are interpolated through steam tables for simulation.

3.3 Summary

In this chapter dynamic model for boiler has been investigated. The modeling equations have been derived from Astrom's model of boiler that presents a fourth order state space model with response variables of drum pressure, steam quality, total water volume and volume of steam in drum. For calculation of level, Astrom's work provide a nonlinear expression that relates the states of boiler to output level. The comprehensive mathematical steps regarding model formation has been avoided and can be referred in [8]. Basic framework and assumptions that govern the modeling steps have been elaborated to provide an insight into model formulation.

CHAPTER 4 NITRIC OXIDES MODELING

Modeling of NOx is carried out by using white box model using physical principles or black box models based on empirical relations between input and output dataset. Any model can serve in optimization and control of NOx as long as it predicts accurately with large span of operating conditions. There are three types of NOx as discussed in Chapter 1 and all types are differently modelled as they are formed by different chemical phenomena. In literature it is reported that in typical combustion of gaseous fuels especially natural gas, the formation of fuel NOx is almost insignificant. This is because gaseous fuels intrinsically lack fuel bound nitrogen. Moreover the fuel lean combustions involving excess amount of air also leads to insignificant formation rate of prompt NOx for gaseous fuels. Hence thermal NOx is the major pollutant in our case where the fuel being employed is natural gas for the investigated boiler. Hence we focus on modeling, control and optimization of thermal NOx. The main influencing parameters that affect the formation of thermal NOx are FFR, AFR and some other design parameters of combustion chamber where the formation takes place. This chapter discusses two models that have been used in literature for calculating thermal NOx. We highlight some of the basic principles that are involved in model formulation while details of these can be visited in [38] and [62].

4.1 Li and Thompsons Model

Li and Thompson [38] derived a simplified model to relate thermal NOx with operational variables of boiler. This analytical model was derived from Zeldovich mechanism according to which thermal NOx formation goes through a series of reactions among oxygen, nitrogen and hydrocarbons. The reactions can take place only in the presence of high temperature and thus formation of NOx has rigorous dependence on temperature. The three principle reactions of the mechanism are:

$$O + N_2 \leftrightarrow NO + N \tag{4.1}$$

$$N + O_2 \leftrightarrow NO + O \tag{4.2}$$

$$N + OH \leftrightarrow NO + H \tag{4.3}$$

The activation energy of reaction (4.1) is highest and it is also considered as limiting step in NOx formation. Due to continuous flow of flue gas the NOx is quickly carried out along with the flow in combustion chamber hence its amount is far less than equilibrium amount i.e.

$$[NO] << [NO]_{EQ} \tag{4.4}$$

Moreover it is also assumed that nitrogen atoms flow is in quasi steady state i.e. $\frac{d[N]}{dt} = 0$. Because of these assumptions the rate of formation of NOx is given by following equation:

$$\frac{d[NO]}{dt} = 2k_1[N_2][O] - [NO] \tag{4.5}$$

Where the concentrations are of units (mol/m^3). k_1 is the reaction rate constant and is highly correlated with temperature of combustion zone. The concentration of oxygen atom and molecules can be related by following equation:

$$k_O = \frac{[O]}{[O_2]^{\frac{1}{2}}} \tag{4.6}$$

Where k_0 is also temperature dependent constant. Equations (4.5) and (4.6) can be combined to give following:

$$\frac{d[NO]}{dt} = 2k_1k_0[N_2][O_2]^{\frac{1}{2}} - [NO] \tag{4.7}$$

The concentration of both oxygen and nitrogen molecules is proportional to AFR. Skipping the detailed derivation, the relation of O_2 and AFR as given in [38] is:

$$[O_2] = \frac{\beta}{v_a}(1/\lambda_{st} - 1/\lambda)^{\frac{1}{2}} \tag{4.8}$$

Using equation (4.8) in equation (4.7), and combining other parameters into one variable of α, the rate of NOx modifies as:

$$\frac{d[NO]}{dt} = \alpha(1/\lambda_{st} - 1/\lambda)^{\frac{1}{2}} - [NO] \tag{4.9}$$

The parameter $'\alpha'$ determines the rate of reaction. Higher the α, higher the rate of NOx. This parameter was declared to be dependent on variables that are determined by design specifications of burner and fuel inputs of the combustion chamber. The true nature of α was evaluated by experiments from the authors. It was found out that equation (4.9) can turn into a simplified relation of thermal NOx that connects NOx to 3 basic inputs: Fuel

Flow Rate (FFR), Air to fuel Ratio (AFR) and burner tilt angle. The relation is presented in final form using first order stable differential equation:

$$\frac{d[NO]}{dt} = \alpha_0 \dot{m}_f^r \left(1 + \alpha_r \frac{\xi - 55}{90}\right) \left(\frac{1}{\lambda_{st}} - \frac{1}{\lambda}\right)^{\frac{1}{2}} - [NO] \tag{4.10}$$

Where 'α_0', 'α_r', and 'r' are empirical constants that are determined by fitting the equation to the experimental data. $\dot{m}_f$ represents fuel flow rate, λ represents air to fuel ratio while λ_{st} is the stoichiometric air to fuel ratio. ξ is the burner tilt angle and for the present case we use it as 55% in accordance with the middle position with respect to the investigated boiler. Equation (4.10) calculates rate of thermal NOx, hence to calculate the concentration of NOx we integrate the equation in a certain time span which gives the thermal NOx with units of parts per million (ppm).

The equation (4.10) represents a semi empirical model of NOx formation. The NOx formation rate is profoundly dependent on temperature of combustion zone and the equation (4.10)takes this fact into account by using direct relation between rate of NOx and FFR. This relation also leads FFR responsible for dynamic trends in NOx during normal operation of boiler. The FFR is mainly employed to regulate pressure of boiler which is subject to dynamic variations as the stream demand changes or one of the parallel boiler trips. It's therefore observed that dynamics trends of NOx are similarly affected with FFR as a disturbance in steam occurs. Moreover equation (4.10) calculates rate of thermal NOx, hence to calculate the concentration of NOx we integrate the equation in a certain time span which gives the thermal NOx with units of parts per million (ppm).

Examining equation (4.10), the AFR appears to be free input variable and it is noticeable that equating AFR to AFR_{st} reduces the rate of formation to zero. However practically, using $AFR=AFR_{st}$ causes less efficient combustion which, later on, leads to the loss of capital due to extravagant fuel consumption. Hence AFR is kept higher than AFR_{st} at the cost of NOx formation. The equation (4.10) shows that increasing AFR increases rate of NOx. If we divide the equation by amount of flue gas it is observed that increasing AFR beyond certain point decreases the formation of NOx. This is caused by excessive dilution of NOx in exhaust gas. Hence the NOx curve with AFR has a peak at some point of AFR, away from which NOx formation rate decreases by either increasing or decreasing AFR. This trend of NOx poses a conflict with boiler efficiency as efficiency also exhibits a similar behavior with respect to AFR. Hence under dynamic conditions the operating point of AFR is varied in the range 105-115% of AFR_{st} to operate between efficient combustion and high NOx formation.

For minimization of NOx formation, different approaches are used ranging from recirculation techniques to sophisticated burner designs but in terms of regulating NOx using inputs, it turns out that AFR is the decisive variable to regulate NOx as the FFR is totally dedicated to control output variable of pressure. In this respect different optimization approaches are tried by manipulating the AFR especially on real time basis under dynamic variations of output variables.

The results of [38] are reproduced in Figure 5 to Figure 7. Figure 5 shows the variation of NOx with AFR under steady state condition. An average value of FFR is used to plot this curve. In Figure 6 we digitize the plots of input variables and NOx from the reference [38] which corresponds to an experimental data of a boiler. In Figure 7 we replot NOx using the equation (4.10) to show the validation of model. The theoretical AFR used in the model is of natural gas which has been calculated in Section 5.7.1.

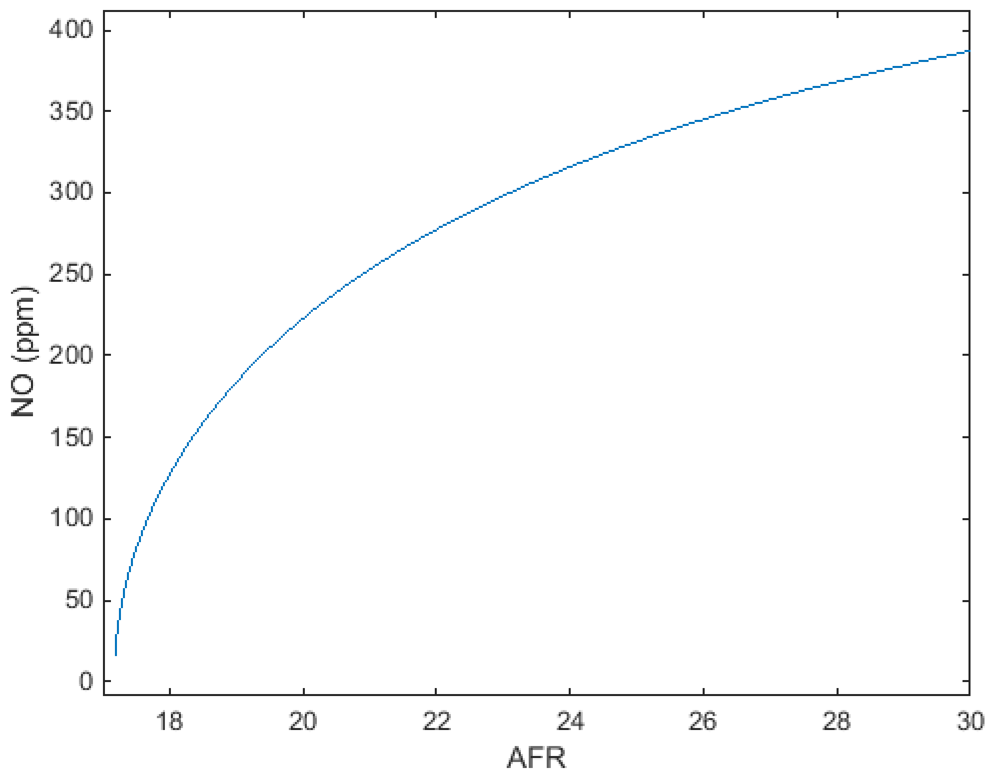

Figure 5 Influence of air to fuel ratio (AFR) on steady state NOx using fuel flow rate of 2.35 kgs [38]

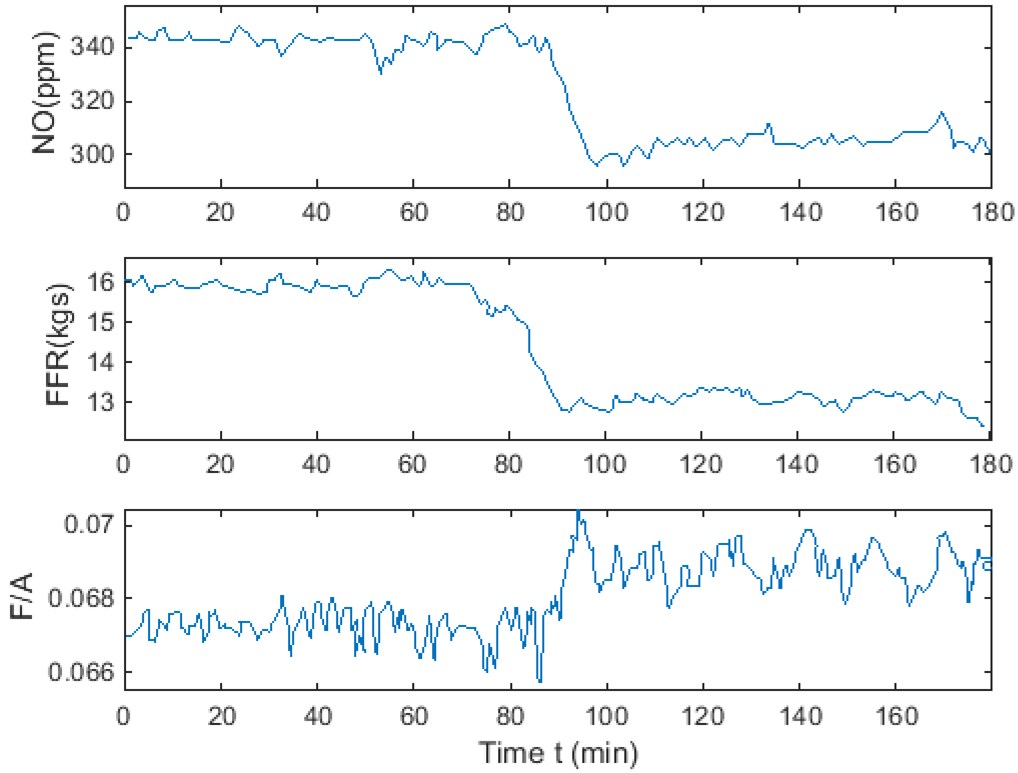

Figure 6 Digitized plots from reference [38] for the variables of NOx, fuel flow rate (FFR), fuel to air ratio (F/A) with time

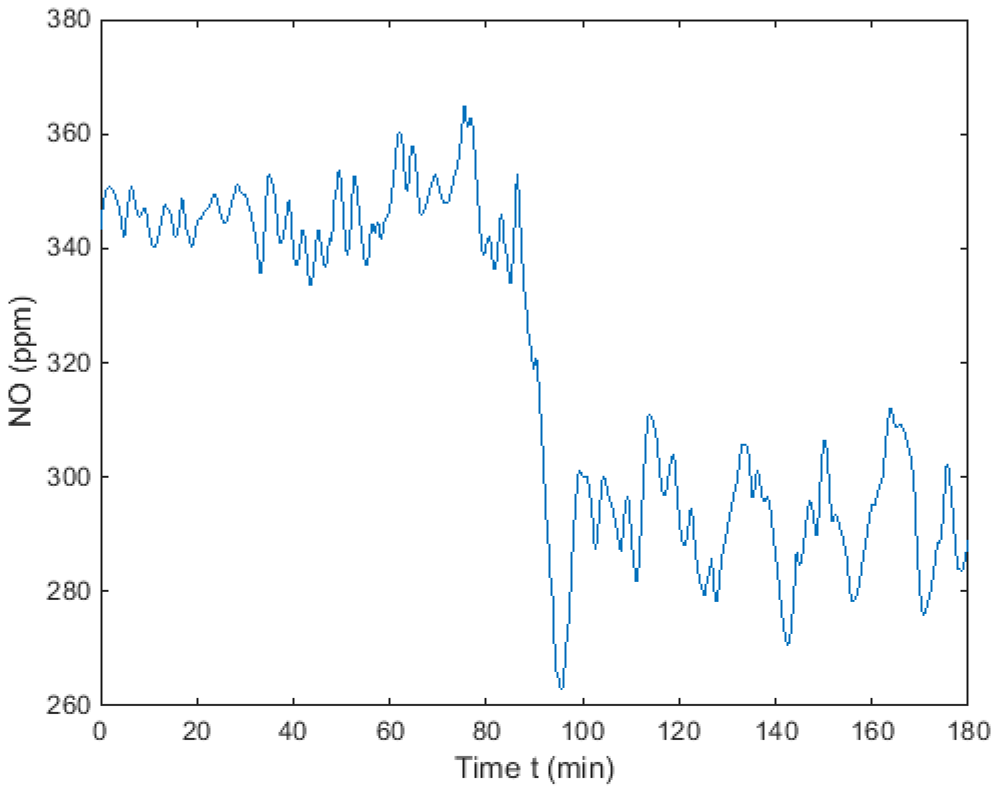

Figure 7 Time variations of NOx using Li and Thompson's model

4.2 Dolanc's Model

Dolanc et al. [62] gave a semi empirical model of thermal NOx that relates combustion parameters to the concentration of NOx in combustion chamber. The model is non-dynamic in nature as it predicted steady state value of NOx. Equation (4.7) is the building block of the model as the governing phenomenon behind the formulation is the same Zeldovich mechanism. The model, in final form, is given as:

$$[NO] = K_C \cdot e^{-b(AFR+1025)} \times$$

$$\frac{(0.97 \cdot AFR) \cdot (0.21 \cdot AFR - 2.075)^{\frac{1}{2}}}{AFR + 1.025} \tag{4.11}$$

The model explicitly relates NOx concentration with AFR and two empirical constants K_C and b whose values are determined by fitting the equation with experimental data by using nonlinear least-squares fitting (NLSF). The temperature dependence of NOx is implicitly covered in this model by denominator expression of equation (4.11) as the denominator expression is an outcome of a temperature model. Dolanc et al. used an empirical regression based modeling of temperature based on the input of AFR. This model is given by following equation:

$$T = \frac{A_0}{AFR + 1.025} \tag{4.12}$$

The exponential term in equation (4.11) is because Arrhenius law was used in model development to express the dependence of reaction rate on combustion zone temperature. Mathematically this dependence is given by Arrhenius law equation as:

$$K(T) = A \cdot e^{(\frac{B}{T})} = A \cdot e^{-B_0(AFR+1025)} \tag{4.13}$$

Where A, B and B_0 are empirical constants.

We reproduce the results of model's reference by plotting the equation (4.11) as in Figure 8. The skewed bell shape curve of the plot validates the practical behavior of NOx with AFR. Just like Li and Thompsons model, the NOx formation as predicted by this model is exactly zero at theoretical AFR. The AFR for this model has been formulated on volumetric basis hence the theoretical AFR of natural gas in this case is 9.88. Similarly the concentration of NOx again converges to zero as AFR is increased unbound which is to take into account the fact that the flame temperature is affected adversely with profuse amount of excess air.

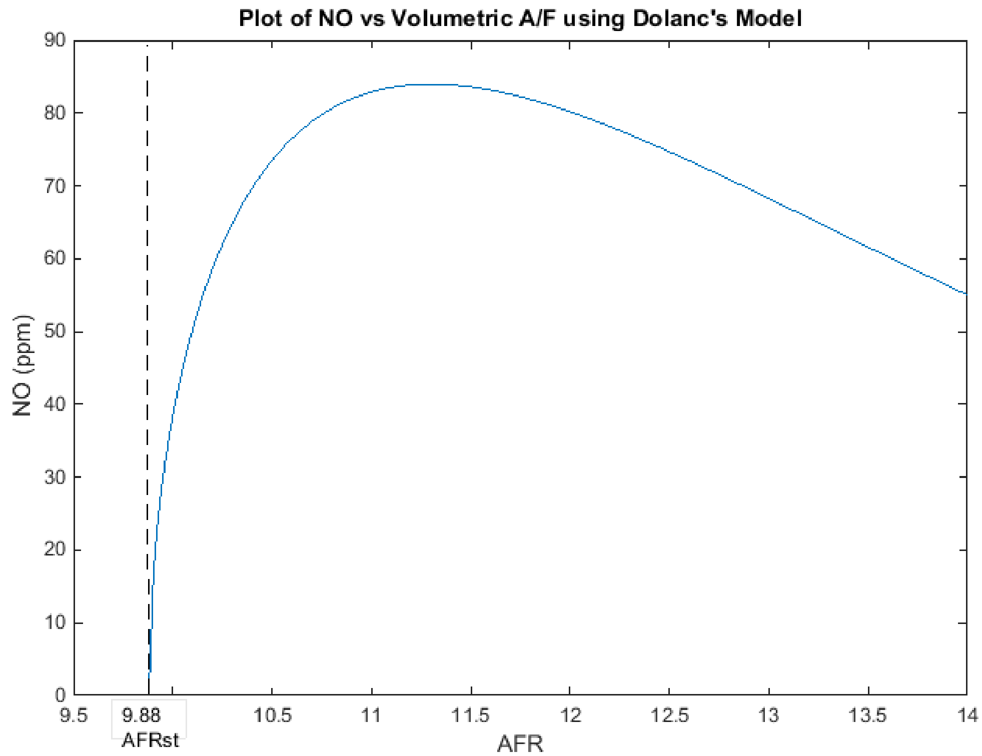

Figure 8 Influence of air to fuel ratio (AFR) on NOx using the model of [62]

4.3 Comparison of Models

For comparison we plot the NOx using the equations of both models with AFR as an independent variable. In Figure 9 it is noticeable that the curves of both models are behaving different as one curve is going unbound while other is tending to converge to zero. The difference in plots may be ascribed to the reason that both models are based on two different boilers with different design configurations of burner and furnace chamber. Both models are semi empirical models and they are made to fit the particular scenarios of boiler for which they have been developed. The empirical constant present in the modelling equations can be changed for different fuels and different boiler configuration. The model of Li and Thompson is more comprehensive as it shows dynamic dependence of NOx on FFR as well as burner tilt angle while Dolanc's model only work for limited operational variables i.e. only AFR. The Dolanc's model is also a steady state model and doesn't show the transient variations of NOx for dynamic operating conditions. However Dolanc's model behaviour of NOx w.r.t AFR is more realistic as it shows decreasing trend of NOx with increasing AFR beyond a certain AFR whereas Li and Thompson's model has limitation that it is only satisfactory for limited range of AFR.

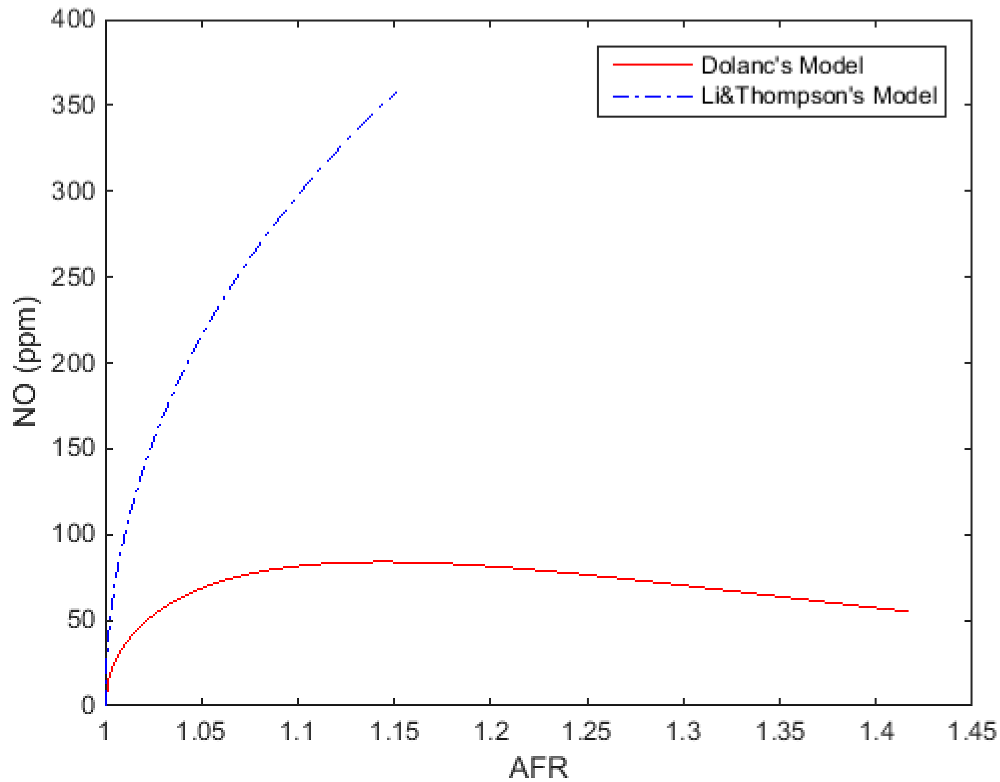

Figure 9 Comparative plots of NOx using the models of [38] and [62]

4.4 Summary

In this chapter two mathematical models for calculating thermal NOx have been discussed. The models relate the formation of thermal NOx with operational inputs of AFR and FFR. The behavior of NOx as predicted by these models has been plotted to reproduce the results of model references. A brief comparison of both models has been provided and based on that it has been concluded that analytical model of Li and Thompson is more appropriate for the dynamic optimization of NOx with efficiency as it is a dynamic model and it also relates NOx with FFR.

CHAPTER 5 BOILER EFFICIENCY MODELING

Like any physical system, boiler is not an ideal system and a fraction of fuel energy is lost through various means during steam generation process. Boiler efficiency is used as a measure to approximate these losses and to evaluate net useful energy that is delivered to water from the fuel. It is therefore important to investigate sub processes in combustion that contribute to degradation of energy transfer from fuel to steam. Efficiency has remained most beneficial tool in literature to assess the performance of boiler combustion process and many approaches have been sought to evaluate and maximize it.

In literature, the mathematical formulations calculate efficiency based on average values of variables that determine average efficiency. The demerit of this approach is that we cannot investigate time based dynamic relationship between boiler inputs and its efficiency based on average measurements of variables. Compared to average efficiency, an input output based dynamic model of efficiency is far better in providing a clear illustration of behavior of efficiency under wide variety of operating conditions. Dynamic modeling of efficiency is also necessary for investigation of dynamic behavior, control and optimization of boiler important parameters. In the context of optimization of efficiency with NOx modeling is required to relate both these variables to the operational variables of boiler. The model should be capable enough to capture time based variations of both NOx and efficiency and it should be usable in optimization to seek an optimal tradeoff between efficiency and NOx. Unfortunately conventional models calculate average behavior of efficiency for a certain time span as efficiency is calculated using average values of variables. The resulting efficiency lacks the information of all dynamic changes that it has undergone in certain time span and hence it is difficult to achieve precise control and optimization of boiler dynamics based on conventional models.

In this chapter we discuss a new mathematical formulation of efficiency. This new approach is based on time varying efficiency using time varying operational variables of a typical package boiler. This approach is accomplished using indirect method of efficiency by applying experimental data of variables for certain time span. The chapter also provides a second order dynamic model of flue gas temperature that is used to construct the mathematical formulation of instantaneous efficiency in terms of available inputs only. The instantaneous efficiency is stronger tool compared to average efficiency as it is capable of capturing all variations of efficiency in given time span. By definition it provides value of efficiency at each instant of time. It is calculated based on operational inputs of boiler whose time data is recorded using measurement devices for a certain time range. Using instantaneous efficiency it becomes possible to calculate efficiency of boiler in a continuous form as opposed to conventional discrete form.

We organize this chapter by first presenting an introductory formulation of efficiency in Section 5.1. A brief description regarding direct method of efficiency is then discussed in Section 5.2. In Section 5.3-5.9 we extensively discuss indirect method of efficiency and all the elements necessary to be examined and calculated for indirect method. In Section 5.10 all the losses concerning the indirect method are outlined and calculated. Simulations and discussions are provided in Section 5.11, while in Section 5.12 we formulate an input output based model of efficiency. Finally a brief overview of influence of AFR and FFR on boilers efficiency using the proposed model is discussed in Section 5.13.

5.1 Mathematical Formulation

The most basic way of calculating overall efficiency for any system is to take the ratio of output energy to the input energy. For instantaneous efficiency this ratio is determined using instantaneous input and output energy as following:

$$\eta(t) = \frac{dE_{out}(t)}{dE_{in}(t)} \tag{5.1}$$

Where $dE_{in}(t)$ is the fractional energy supplied as an input to the system and $dE_{out}(t)$ is the fractional energy delivered by the system. Generally both input and output energies are calculated with reference to some physical quantity like time or mass of fuel hence are represented using units of calories per second or calories per kg of fuel. In the context of boiler input energy refers to the energy produced through combustion of fuel at instant ‘t’ while output energy is the useful energy delivered to the steam at instant ‘t’.

Based on above formula two approaches are used in literature to calculate efficiency:

1. Direct Method
2. Indirect Method

5.2 Direct Method

The direct method takes into account only the useful energy delivered to steam and the total energy produced by the fuel. For this method combustion process is like a black box as it only considers the net energy that is achieved from the combustion and not the processes that contribute in the loss of energy. That is why this method is less informative as it doesn't give a full picture of the variables that influence efficiency. Moreover it is more affected by the measurement errors as compared to indirect method. The biggest advantage of the direct method over indirect method is simplicity of its calculations. Mathematically it implements the equation (5.1) in simple form as:

$$\frac{dE_{out}(t)}{dE_{in}(t)} = \frac{\dot{E}_s(t) - \dot{E}_w(t)}{\dot{E}_f(t)} \tag{5.2}$$

Where $\dot{E}_f(t)$, $\dot{E}_w(t)$ and $\dot{E}_s(t)$ represent rate of energy of fuel, feedwater and steam respectively. The rate of energy of steam is dependent on steam flow rate and specific enthalpy of steam at particular temperature and pressure. Whereas rate of energy of feedwater is dependent on feed water flow rate and specific enthalpy of water at particular temperature and pressure. The difference of these two quantities determine the net useful energy delivered to steam from fuel.

Each rate of energy, is given in kCal/s and mathematically it is related to enthalpy and flow rate as:

$$\dot{E}_w(t) = h_w \dot{m}_w$$

$$\dot{E}_s(t) = h_s \dot{m}_s \tag{5.3}$$

Where h_w and h_s represent specific enthalpies of water and steam respectively and $\dot{m}_w$ and $\dot{m}_s$ represents their mas flow rates. The input heat energy in boiler is total energy produced by the combustion of fuel and is determined by type of fuel as well as fuel flow rate. Mathematically instantaneous input energy $\dot{E}_f(t)$ is calculated as:

$$\dot{E}_f(t) = GCV\ \dot{m}_f \tag{5.4}$$

Where GCV is Gross Calorific Value of fuel and is discussed in more detail in next section.

5.3 Indirect Method

The indirect method is more accurate as compared to direct method of efficiency and is calculated by taking into account all the losses that contribute in lowering the net energy that is delivered from the fuel to the steam. These losses are:

1. Loss due to dry flue gas
2. Loss due to hydrogen in fuel
3. Loss due to moisture in air
4. Loss due to moisture in fuel
5. Loss due to Partial combustion of C to CO
6. Loss due to radiation and convection

These losses are dependent on many variables: some variables can be manipulated while some cannot. For example variables like humidity, ambient temperature or design constants are totally independent parameters. They are not chosen by operator and hence their influence on the losses is totally inevitable. However variables like AFR and FFR are the ones whose influence can be controlled to regulate all the mentioned losses. The indirect method gives us the opportunity to regulate all the losses by intelligently using the inputs of boiler system.

For calculation of time variations of efficiency we used time data of 3 important variables: flue gas temperature, fuel flow rate and excess oxygen. The boiler under study is an industrial boiler operating in eastern province in Saudi Arabia. It is a water tube boiler that uses natural gas as fuel input. We are using measurements of 21600 samples with sampling time of 1 second which are sufficient to calculate wide range of dynamic variations in efficiency.

Before presenting the mathematical formulation of losses, it is important to discuss some basic elements that are essential for calculations of losses. These elements are.

1. Boiler Flue Gas Temperature
2. Heating value of Fuel
3. Boiler Fuel Analysis
4. Excess Air
5. Thermal properties of flue gas constituents.
6. Ambient air temperature, pressure and humidity

These elements need to be analyzed before using them to calculate efficiency. Also some prior calculations for these elements will be discussed in the next section.

5.4 Boiler Flue Gas Temperature (FGT)

Flue gas temperature is the temperature of products of combustion that are identified as exhaust gas or flue gas. The exhaust gas carries a major portion of heat energy that is undelivered to the steam hence it is responsible for majority of the losses. In order to reduce losses from exhaust gas, the boiler includes a superheater and economizer to recover some energy from it. Flue gas temperature plays its role in determining the energy content of exhaust gases. Because of this FGT is considered as measure of energy itself as higher FGT implies lower efficiency and lower FGT implies higher efficiency. For calculation of efficiency variations in a certain span of time it is required to have time data of flue gas temperature as it is involved in the calculations of various losses [19].

5.5 Fuel and Flue Gas Analysis

Chemical composition of fuel and flue gas are very important to be known as different components have different thermal properties that impact differently on efficiency. For instance, the water vapors carry away significant amount of energy in combustion hence for the fuels with high hydrogen content like natural gas, more water vapors are formed and more energy is lost compared to fuels with low hydrogen content. Even the composition of natural gas is different in different regions that need to be accounted. Each component of natural gas contributes in losses hence it is required to measure the amount of each component to calculate losses.

For the industrial boiler under investigation, the fuel employed is natural gas and its composition is shown in Figure 10.

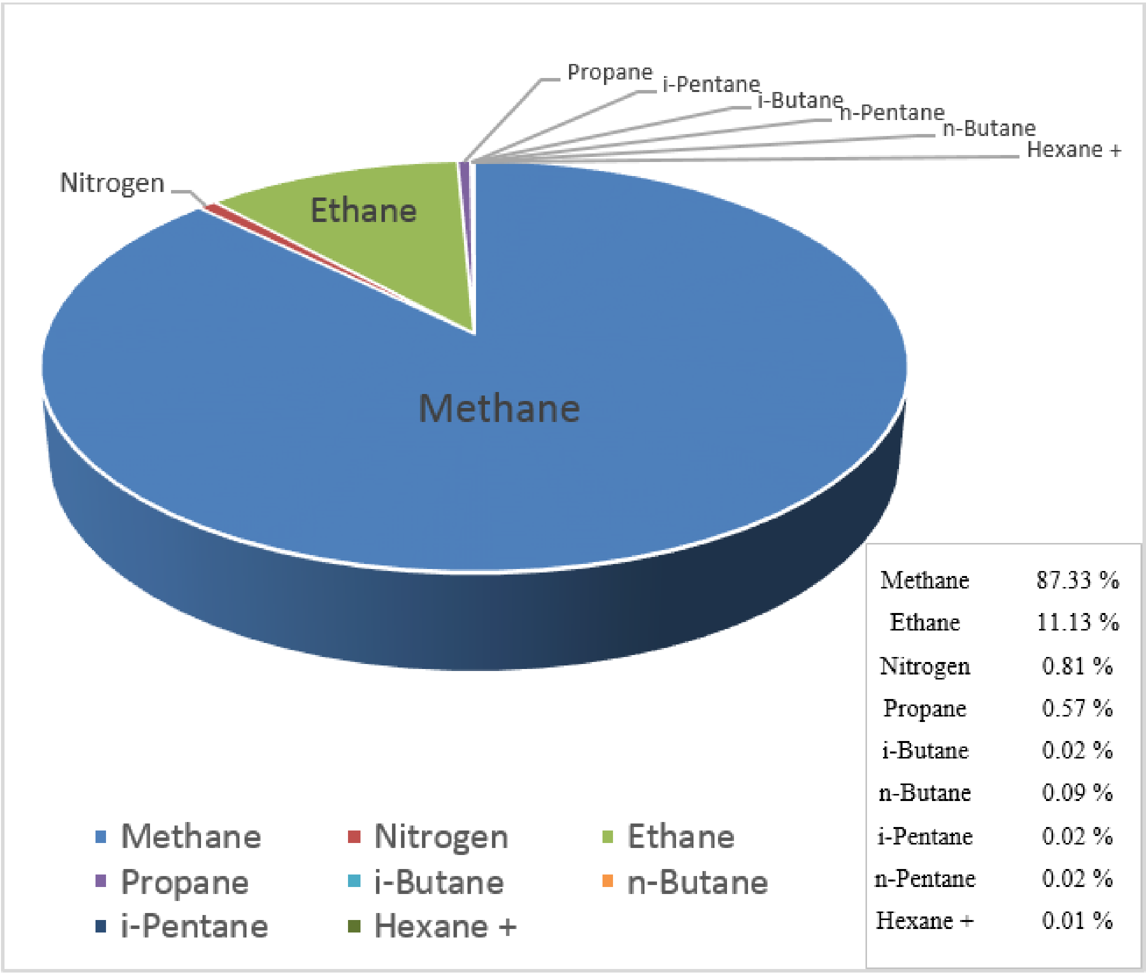

Figure 10 Fuel Composition by volume %

Methane forms the highest constituent of natural gas. The higher order hydrocarbons (butane, pentane and hexane) constitute a relatively small fraction of total composition (around 0.16 %) which are neglected for computational convenience. For the major four components, the mole fractions have been balanced in order to maintain total of 100% of composition as in Table 2.

Table 2 Fuel Composition of Four Components by Mole Basis

Component	$\%\boldsymbol{X}_{\boldsymbol{i}_{\boldsymbol{mole}}}$
Methane	87.41%
Ethane	11.21%
Propane	0.57 %
Nitrogen	0.81 %

The molecular weight of natural gas, MW_{NG} is calculated as:

$$MW_{NG} = \left(16 \times \%CH_{4_{mole}} + 30 \times \%C_2H_{6_{mole}} + 44 \times \%C_3H_{8_{mole}} + \%N_{2_{mole}} \times 28\right) = 17.8262\ g/mol \tag{5.5}$$

The mass fraction of carbon content in fuel is given as:

$$\%C_{mass} = \left(1 \times \%CH_{4_{mol}} + 2 \times \%C_2H_{6_{mol}} + 3 \times \%C_3H_{8_{mol}}\right) \times \frac{12}{MW_{NG}} = 75.085\% \tag{5.6}$$

Calculating hydrogen content by mass, we get:

$$\%H_{mass} = \left(4 \times \%CH_{4_{mol}} + 6 \times \%C_2H_{6_{mol}} + 8 \times \%C_3H_{8_{mol}}\right) \times \frac{1}{MW_{NG}} = 23.6427\% \tag{5.7}$$

5.6 Heating Value of Fuel:

Heating value of fuel is measure of total energy contained in a fuel. It is determined by either Lower Heating Value (LHV) or Higher Heating Value (HHV) as defined next.

5.6.1 The Lower Heating Value or Net Calorific Value (NCV)

LHV represents energy released by combusting specific quantity of fuel at 25 °C and bringing the temperature of combustion products back to 150 °C. The LHV doesn't include the latent heat of vaporization of water in products.

5.6.2 The Higher Heating Value or Gross Calorific Value (GCV)

HHV represents energy released by combusting specific quantity of fuel at 25 °C and bringing the temperature of combustion products back to 25 °C. The HHV does include the latent heat of vaporization of water in products.

HHV is always higher than LHV. Both LHV and HHV represent the energy input from the fuel and there is disagreement on which one of them represents the actual energy of input. Anyhow for calculations both are valid and we choose HHV for our purpose.

For the case when fuel is mixture of different components the HHV of fuel is determined by knowledge of mole fractions as well as heating values of individual fuel in kCal/mol. Mathematically it is calculated as:

$$HHV = GCV = \sum_{i=1}^{4} \%(X_i)_{mole} \frac{M_i}{MW_F} HHV_i \tag{5.8}$$

Where M_i, $\%X_{i_{mole}}$ and HHV_i represent molar mass, mole fraction and higher heating value of individual component. MW_F represents molecular weight of fuel. For natural gas HHV is calculated to be 231 kCal/mol or 12983 kCal/kg.

5.7 Excess Air

Excess air is one of the most important factors that influence efficiency. By definition it represents extra air that is provided in addition to theoretical air. Theoretical air is the exact amount of air required to completely combust a given quantity of fuel. It is calculated in such a way that fuel and air are in exact balance according to stoichiometric calculation with no oxygen in products. Practically theoretical air is not sufficient to execute full combustion and produces smoke, soot and carbon monoxide along with other emissions and surface fouling. If air supplied is even lesser than theoretical air, the emissions increase intensely causing severe decrease in efficiency. To avoid this, excess air is supplied in order to increase oxygen content in combustion chamber so that fuel is combusted completely without any emissions. But we cannot keep increasing the excess air to raise the efficiency because after some point of excess air a dramatic decrease in efficiency is observed. This happens because increasing the air supply increases the content of flue gas which carries away more energy. This effect becomes more and more significant as the excess air is increased more and more. The terms excess air, excess oxygen and actual air to fuel ratio are used interchangeably as all serve the same purpose. For a given fuel it is required to calculate the theoretical air to fuel ratio AFR_{th} which is required to determine the minimum amount of air required for the oxidation of fuel. Theoretical air for our case of natural gas is calculated as in subsequent section.

5.7.1 Theoretical AFR for Ideal Combustion

The general combustion reaction for any hydrocarbon is given as:

$$\begin{aligned} \sum_{i=1}^{k}(a_i C_{ni} H_{mi}) + \sum_{i=1}^{k}\left(a_i n_i + \frac{a_i m_i}{4}\right) O_2 + \sigma N_2 \\ \rightarrow \sum_{i=1}^{k}(a_i n_i\ ) CO_2 + \sum_{i=1}^{k}\left(\frac{a_i m_i}{2}\right) H_2 O + \sigma N_2 \end{aligned} \tag{5.9}$$

Where a_i represents number of moles of ith hydrocarbon in a fuel, *ni* and *mi* refers to the number of atoms of carbon and hydrogen in ith hydrocarbon and σ is the molar amount of nitrogen in fuel. With no excess oxygen considered in above equation, it serves to calculate theoretical air to fuel ratio, AFR_{th}. The number of moles of nitrogen are represented by σ and is given as:

$$\sigma = \frac{79}{21}\sum_{i=1}^{k}(a_i n_i + \frac{a_i m_i}{4}) + \sigma_F \quad (5.10)$$

Where $\frac{79}{21}$ represents ratio of moles of nitrogen to moles of oxygen in atmosphere and σ_F is the quantity of N_2 in fuel.

Based on molar composition of fuel as in Table 2, the combustion reaction equation takes the following form:

$$\begin{aligned} &0.874\, CH_4 + 0.112\, C_2H_6 + 0.006\, C_3H_8 + 0.008\, N_2 + 2.17 \\ &\quad \times \left(O_2 + \frac{79}{21}\, N_2\right) \\ &\quad \rightarrow 1.116\, CO_2 + 2.108\, H_2O + 0.008\, N_2 + 2.17 \times \frac{79}{31} N_2 \end{aligned} \quad (5.11)$$

Where $\sum_{i=1}^{k}(a_i n_i) = 1.116$ and $\sum_{i=1}^{k}(a_i m_i) = 4.216$.

The minimum O_2 required for complete combustion is given as ratio of mass of oxygen to mass of fuel:

$$\frac{(O_2)_{mass}}{(NG)_{mass}} = \frac{\sum_{i=1}^{k}\left(a_i n_i + \frac{a_i m_i}{4}\right) \times M_{O2}}{\sum_{i=1}^{k} a_i \times MW_{C_{ni}H_{mi}} + \sigma_F M_{N2}} \quad (5.12)$$

The AFR_{th} is simply $\frac{1000}{233}$ times minimum oxygen:

$$AFR_{th} = \frac{(air)_{mass}}{(NG)_{mass}} = \frac{1000}{233} \times \frac{(O_2)_{mass}}{(NG)_{mass}} \tag{5.13}$$

For our case of natural gas, based on equation (5.11), it is calculated to be:

$$AFR_{th} = 16.7111$$

5.7.2 Actual AFR for Full Combustion

In practical combustion, excess air is applied for proper oxidation of fuel. In full combustion reaction, it is assumed that all the carbon in fuel is converted into carbon dioxide and no carbon monoxide is formed. With no amount of carbon monoxide in products, AFR can be easily evaluated using stoichiometric calculations.

In the case when excess air is provided, actual air to fuel ratio is calculated by adding excess oxygen as “βO_2” in combustion reaction as following:

$$\sum_{i=1}^{k} (a_i C_{ni} H_{mi}) + \left(\sum_{i=1}^{k} \left(a_i n_i + \frac{a_i m_i}{4} \right) + \beta \right) O_2 + \sigma N_2 \rightarrow$$

$$\sum_{i=1}^{k} (a_i n_i) CO_2 \ + \sum_{i=1}^{k} \left(\frac{a_i m_i}{2} \right) H_2O \ + \ \beta O_2 + \sigma N_2 \tag{5.14}$$

Where moles of nitrogen, σ, are given as:

$$\sigma = \frac{79}{21} \times \left(\sum_{i=1}^{k} (a_i n_i + \frac{a_i m_i}{4}) + \beta \right) + \sigma_F \tag{5.15}$$

The actual air to fuel ratio is given as:

$$AFR = \frac{\left(\sum_{i=1}^{k} \left(a_i n_i + \frac{a_i m_i}{4} \right) + \beta \right) \times M_{O2}}{\sum_{i=1}^{k} a_i \times MW_{C_{ni} H_{mi}} + \sigma_F M_{N2}} \times \frac{1000}{233} \tag{5.16}$$

The excess oxygen factor β is not directly given because, usually oxygen analyzers give measurements of mole fraction of oxygen $\%O_{2_{mole}}$ in dry flue gas. Fortunately, the quantities $\%O_{2_{mole}}$ and β are interchangeable through following formula:

$$\%O_{2_{mole}} = \frac{\beta}{\sum_{i=1}^{k} (a_i n_i) + \beta + \sigma} \tag{5.17}$$

Or,

$$\beta = \frac{\%O_{2_{mole}}}{1 - \%O_{2_{mole}}} \times \left(\sum_{i=1}^{k} (a_i n_i) + \sigma \right) \tag{5.18}$$

The equations (5.15) and (5.18) are solved to calculate β.

The equivalence ratio $'\phi'$ is defined as ratio of AFR to AFR_{st} and it is customary to relate amount of constituents with equivalence ratio. Given the oxygen percentage in flue gas it is possible to calculate equivalence ratio using equations (5.15)-(5.18).

5.7.3 AFR for Incomplete Combustion

Due to incomplete combustion, hydrocarbons in natural gas produce carbon monoxide which causes loss of energy and it is required to calculate amount of carbon monoxide to calculate energy loss by its formation. Moreover the amount of carbon monoxide is also required to calculate exact composition of combustion products. In literature many complicated models exist for predicting the carbon monoxide composition in combustion products. Mellor [63] developed a characteristic time model to predict the CO emissions based on combustion parameters and furnace geometry. The model used semi empirical modeling techniques accompanying kinetic and fluid mechanics times of all emissions. The model was verified and used in [64] for heavy duty dual fuel combustors to predict the emissions. Similarly various authors have tried to formulate carbon monoxide production using temperature and pressure of combustion zone [65][66][67].

The production of carbon monoxide is strongly correlated with air to fuel ratio. It is observed that carbon monoxide is maximum under fuel rich conditions when AFR is too low. This occurs because oxygen content is too low to form carbon dioxide or convert carbon monoxide to carbon dioxide. Also the temperature is too low to execute full oxidation of carbon monoxide. Even at stoichiometric amount of air supplied leads to improper mixing of oxygen and fuel consequently producing carbon monoxide. To avoid that more air is supplied than theoretical air which raises the flame temperature as well as proper mixing of oxygen and fuel both leading decreased carbon monoxide production rate. Based on these facts AFR is very empirical factor for the production of carbon monoxide and hence it must be intelligently operated to regulate the production of carbon monoxide.

The general trend of carbon monoxide with AFR can be characterized by an exponentially decreasing curve. This trend has been discussed several times in literature. With $AFR > AFR_{st}$ the the CO production is profoundly decelerated due to which AFR is kept higher than AFR_{st} to avoid CO emissions.

In [68] effects of variations of AFR on different fuels were presented. The results of that can be used to approximate a simple mathematical relation between CO and AFR. Following plot gives the digitized points (in blue) of the results presented in [68].

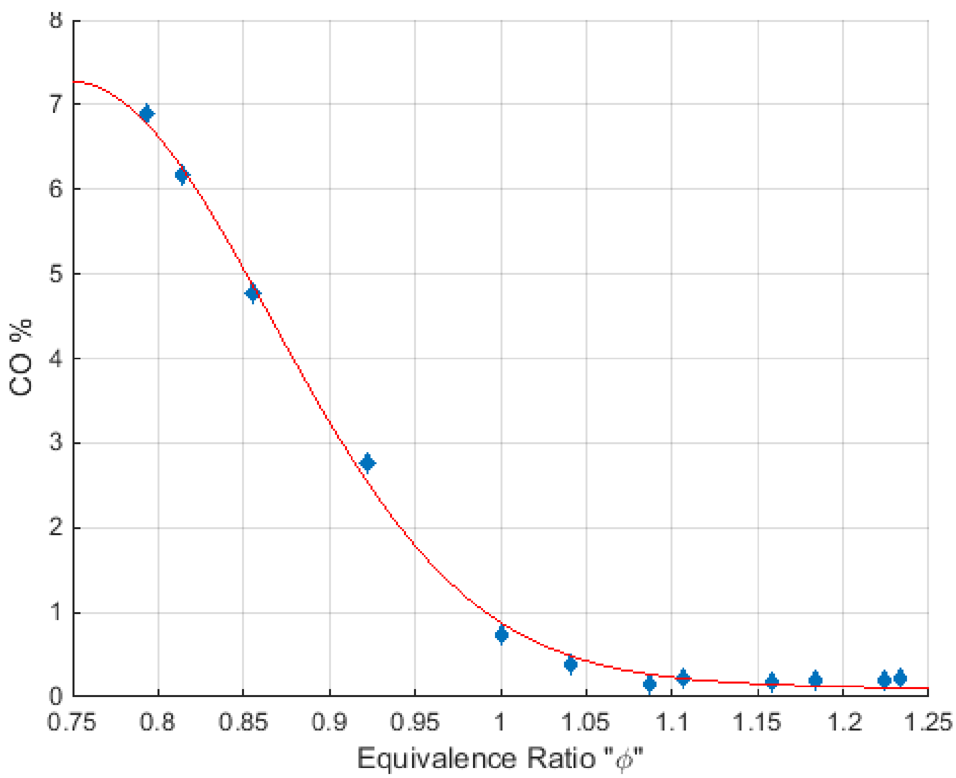

Figure 11 CO variations with equivalence ratio (ϕ)

The red curve represents approximate model of CO vs ϕ which is:

$$\%CO_{mol} = a1 \times exp\left(-\left(\frac{\phi - b1}{c1}\right)^2\right) + a2 \times exp(-\left(\frac{\phi - b2}{c2}\right)^2) \quad (5.19)$$

Where the coefficients are given in Table 3.

Table 3 Coefficient Values for CO Model

Coefficient	**Value**
a1	2.196e+14
b1	-19.07
c1	3.419
a2	6.716
b2	0.752
c2	0.162

The above formulation of CO vs AFR can be used to calculate products of combustions using following calculations.

5.7.4 Flue Gas Composition for Incomplete Combustion

In reality there is always some fraction of fuel with incomplete combustion. Given the data of $\%CO_{mol}$and $\%O_{2_{mole}}$, it is possible to calculate percentage of all components of flue gas as well as AFR for incomplete combustion. If measurements of $\%CO_{mole}$ are not available, equation (5.19) can be used to calculate the composition of flue gas. For this stoichiometric relations between components need to be formed to calculate exact mole fraction of each component based on combustion reaction equation. For this, first we form a generalized reaction equation for combustion process as following:

$$0.874\,CH_4 + 0.112\,C_2H_6 + 0.006\,C_3H_8 + 0.008\,N_2 + \gamma\left(O_2 + \frac{79}{21}\,N_2\right) \rightarrow$$

$$a\,CO_2 + bCO + \ c\,H_2O + (0.008 + \gamma\frac{79}{21})N_2 + \beta O_2 \qquad (5.20)$$

Where $'\gamma'$ represents moles of oxygen and $'\beta'$ represents moles of excess oxygen in flue gas. All molar values $a, b, c, \beta\ and\ \gamma$ are function of time. For incomplete combustion the above chemical equation needs to be solved to calculate flue gas composition. For calculation convenience we neglect the formation of nitric oxides as they constitute a very small fraction of flue gas hence neglecting them is not going to alter our results with significant extent.

Using balance of carbon atoms we have:

$$a + b = 0.874 + 2(0.112) + 3(0.006) = 1.116$$

$$a = 1.116 - b \qquad (5.21)$$

Using balance of hydrogen atoms we have:

$$2c = 4(0.874) + 6(0.112) + 8(0.006)$$

$$c = 2.108 \qquad (5.22)$$

Using balance of oxygen atoms:

$$2\gamma = 2a + b + c + 2\beta$$

Using equation (5.21) and equation (5.22), we have:

$$2\gamma = 2.232 - 2b + b + 2.108 + 2\beta$$

$$\gamma = 2.17 - 0.5b + \beta \tag{5.23}$$

$$b = 4.34 + 2\beta - 2\gamma \tag{5.24}$$

Using equation (5.16) the air to fuel ratio for equation (5.20) is given as:

$$AFR(t) = \frac{32\left(\frac{1000}{233}\right)\gamma}{0.874(16) + 0.112(30) + 0.006(44) + 0.008(28)} = 7.7\gamma \tag{5.25}$$

The equivalence ratio is given as:

$$\phi(t) = \frac{AFR(t)}{AFR_{st}} = \frac{7.7\gamma}{16.7111} = 0.46\gamma \tag{5.26}$$

The above relation gives equivalence ratio totally in terms of γ so we can state in generalized way that ϕ is a function of γ, i.e.

$$\phi = f_{\phi,\gamma}(\gamma) \tag{5.27}$$

As O_2 analyzers give readings in terms of $\%O_{2_{mole}}$ in dry flue gas, so we have to write β in terms of $\%O_{2_{mole}}$, where $\%O_{2_{mole}}$ is given as:

$$\%O_{2_{mole}}(t) = \frac{\beta}{\beta + a + b + (0.008 + \gamma\frac{79}{21})}$$

So β is given as:

$$\beta = \frac{\%O_{2_{mole}}(t)}{1 - \%O_{2_{mole}}(t)} \times \left(a + b + (0.008 + \gamma \frac{79}{21})\right) \tag{5.28}$$

With a, b,and c given as in equations (5.21), (5.24), (5.22) and known measurements of $\%(O_2)_{mole}$, we have β from equation (5.28) completely in terms of γ i.e

$$\beta = f_{\beta,\gamma}(\gamma) \tag{5.29}$$

Now the fraction of carbon monoxide i.e. $\%CO_{mole}$ from equation (5.20) is calculated as:

$$\%CO_{mole}(t) = \frac{b}{\beta + a + b + c + \left(0.008 + \gamma \frac{79}{21}\right)} \tag{5.30}$$

By using equations (5.21), (5.24), (5.22) and (5.29), the equation (5.30) is only a function of γ:

$$\%CO_{mole} = f_{CO,\gamma}(\gamma) \tag{5.31}$$

From equation (5.19), we can write as:

$$\%CO_{mole} = f_{CO,\phi}(\phi) \tag{5.32}$$

Or using equation (5.27):

$$\%CO_{mole} = f_{CO,\phi}(\phi) = f_{CO,\phi}\left(f_{\phi,\gamma}(\gamma)\right) \tag{5.33}$$

The equations (5.31) and (5.33) can be solved for the value of γ as they are equal:

$$f_{CO,\gamma}(\gamma) = f_{CO,\phi}\left(f_{\phi,\gamma}(\gamma)\right) \tag{5.34}$$

The calculated value of γ from above procedure exactly fits in the equation (5.20) maintaining the stoichiometric balance of equation. The other parameters $\beta, b\ and\ a$ are easily calculable from value of γ using the equations (5.28), (5.24) and (5.21).

Once $a, b\ , c\ and\ \beta$ are calculated, we can calculate time varying mass fractions of all the wet flue gas components as follows:

$$\%CO_{2_{mass}}(t) = \frac{44a}{44a + 28b + 18c + 32\beta + \left(0.008 + \gamma\frac{79}{21}\right)28} \tag{5.35}$$

$$\%CO_{mass}(t) = \frac{28b}{44a + 28b + 18c + 32\beta + \left(0.008 + \gamma\frac{79}{21}\right)28} \tag{5.36}$$

$$\%H_2O_{mass}(t) = \frac{18c}{44a + 28b + 18c + 32\beta + \left(0.008 + \gamma\frac{79}{21}\right)28} \tag{5.37}$$

$$\%N_{2_{mass}}(t) = \frac{\left(0.008 + \gamma\frac{79}{21}\right)28}{44a + 28b + 18c + 32\beta + \left(0.008 + \gamma\frac{79}{21}\right)28} \tag{5.38}$$

And the air to fuel ratio is determined from equation (5.25).

Note that for composition calculation only time data of $\%O_{2_{mole}}$ was required to be known. That implies if any of the excess oxygen, air to fuel ratio or equivalence ratio is known, all composition of flue gas can be determined using the same steps.

With the available data of $\%O_{2_{mole}}(t)$ as in Figure 16, we calculate mass fractions of all the flue gas constituents in Matlab and plot them as in Figure 12 and Figure 13.

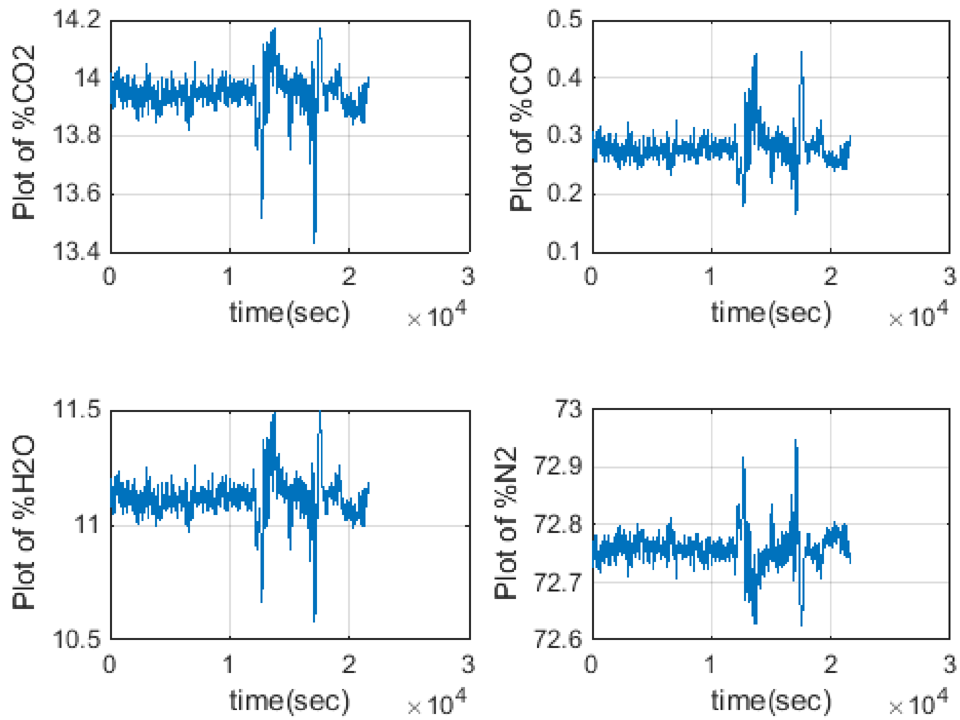

Figure 12 Time variations of flue gas constituents

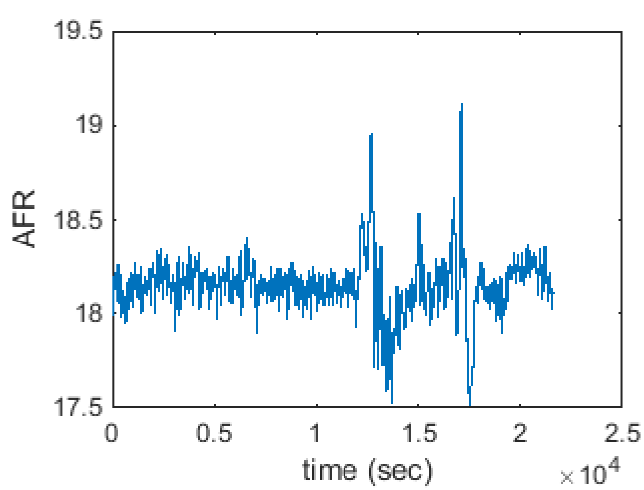

Figure 13 Time variations of AFR

5.8 Thermal properties of flue gas constituents

Thermal properties of flue gas like specific heat C_p and latent heat of vaporization of water play empirical role to determine various losses, it is therefore required to calculate them before the calculation of losses.

5.8.1 Specific Heat C_p

Specific heats of flue gas components play important role in calculating efficiency as they are used to determine amount of energy the components take away at certain temperature. Components having high C_p contribute more in losses as they have more capacity to carry away heat energy. Mathematically C_p's are monotonic increasing functions of temperature and time variations of temperature and composition can be used to calculate time variations of C_p.

For individual components, C_p can be approximated using following expressions:

$$C_{p,CO_2} = 0.108 + 0.39\frac{T}{1000} - 0.304(\frac{T}{1000})^2 + 0.0933(\frac{T}{1000})^3 \quad (5.39)$$

$$C_{p,H_2O} = 0.428 + 0.026\frac{T}{1000} + 0.14(\frac{T}{1000})^2 - 0.048(\frac{T}{1000})^3 \quad (5.40)$$

$$C_{p,N_2} = 0.266 - 0.115\frac{T}{1000} + 0.23(\frac{T}{1000})^2 - 0.1(\frac{T}{1000})^3 \quad (5.41)$$

$$C_{p,O_2} = 0.21 - 2.4(10^{-5})\frac{T}{1000} + 0.13(\frac{T}{1000})^2 - 0.079(\frac{T}{1000})^3 \quad (5.42)$$

$$C_{p,CO} = 0.23 + 0.066\frac{T}{1000} - 0.0161(\frac{T}{1000})^2 + 0.0013(\frac{T}{1000})^3 \quad (5.43)$$

Where these C_p's are given in kCal/kgC. The specific heat of flue gas $C_{p_{FG}}$ is calculated as:

$$C_{p_{FG}}(t) = \sum_{i=1}^{k} \%X_{i,mass}(t)C_{pi}(t) \quad (5.44)$$

Where $\%X_{i,mass}(t)$ represents mass percentage of flue gas component 'i' at instant 't'. Time variations of $C_{p_{FG}}(t)$ are calculated in MatLab and plotted as follows:

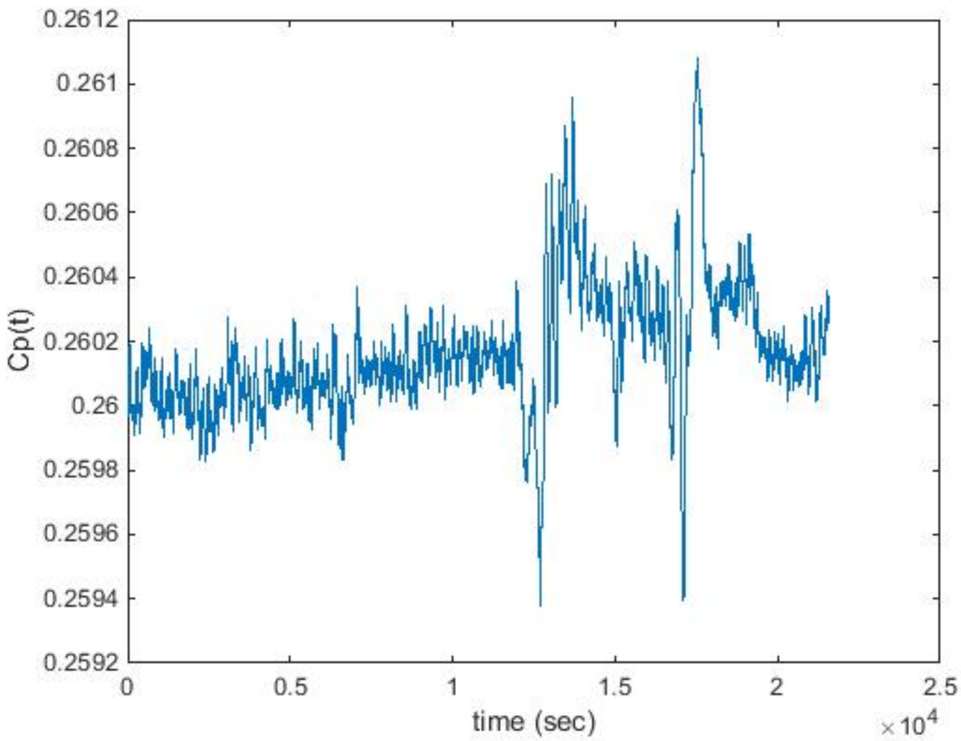

Figure 14 Time variations of specific heat of flue gas C_p (kCal/kgC)

5.8.2 Latent Heat of Vaporization of Water

Water takes up energy for evaporation that is determined by latent heat of vaporization of water. In combustion process water is formed and evaporated from hydrogen contained in the fuel. The moisture in fuel and air also evaporates and contributes in the loss of energy. To determine these losses, we need to calculate latent heat of vaporization of water based on its mole fraction in flue gas.

For a mixture of flue gas, latent heat of vaporization, h_{fg} is a function of partial pressure of water i.e.

$$h_{fg} = f(P_{H_2O}) \tag{5.45}$$

Where 'f' is determined using steam table and can be approximated using interpolation. The partial pressure of water is calculated as:

$$P_{H_2O}(t) = \%H_2O_{mole}(t) \times P_{atm}$$

Where P_{atm} is atmospheric pressure. $\%H_2O_{mole}$ is determined using following equation and is plotted in .

$$\%H_2O_{mole}(t) = \frac{c}{a + b + c + \beta + \left(0.008 + \gamma \frac{79}{21}\right)}$$

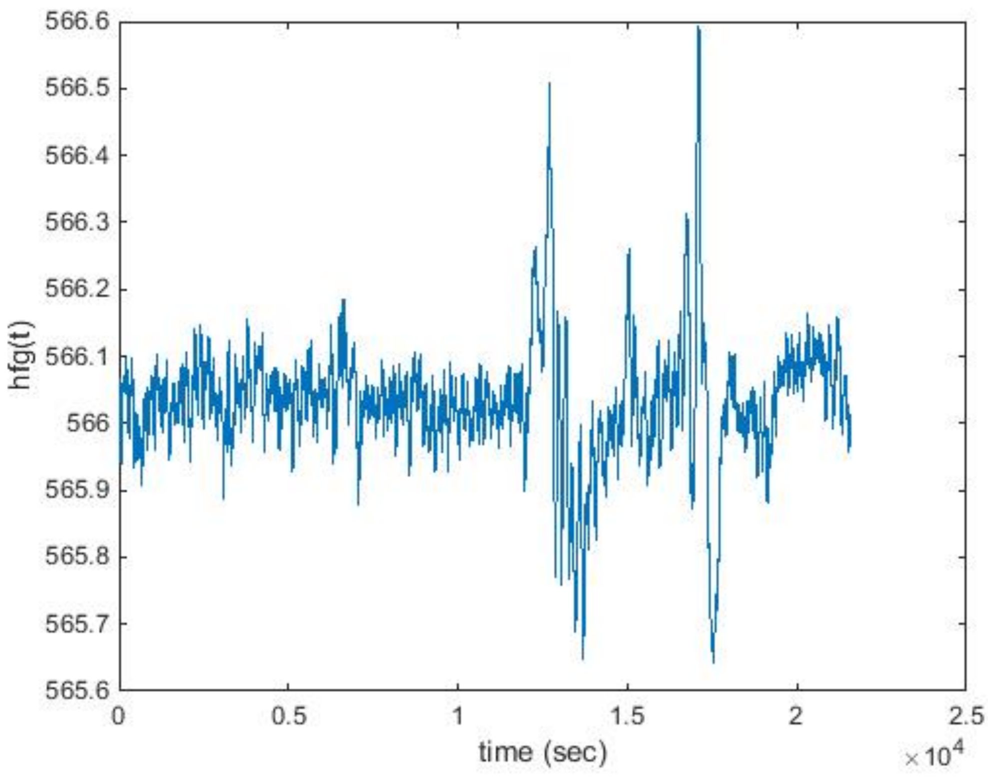

Figure 15 Time variations of h_{fg} (kCal/kgC) of water

5.9 Ambient Air Temperature, Pressure and Humidity:

Ambient conditions play important role in determining the efficiency of boiler. They are among those factors which are uncontrollable and hence loss caused by them is totally unavoidable. Usually they vary according on the climatic conditions of regions. For small time span, variations in ambient conditions are too slow to affect the dynamics of efficiency and other variables hence it is reasonable to consider average ambient conditions in efficiency analysis.

Ambient temperature gives the initial temperature of components and serves as reference temperature to calculate change in temperature of components. We take it as the average room temperature of 30 C.

The ambient pressure is required to calculate the partial pressure of water vapors in flue gas to determine its thermal properties. The flue gas is unpressurized and hence its ambient pressure is assumed to be same as atmospheric pressure i.e. 101.3 kPa.

Vaporization of water takes amount of energy and the humid air of combustion chamber contains vapors that get vaporized in combustion process and contributes in the loss of energy. We take the humidity factor to be 0.014% according to the local conditions.

5.10 Calculations for Losses and Efficiency:

The American Society of Mechanical Engineers (ASME) published a standard procedure of calculating losses in power test code (PTC 4.1). In [19] the same procedure has been applied elegantly and we follow the same mathematical framework for calculating the losses with some modifications. All losses are calculated in units of kCal per kg of fuel and. First formulation of losses is formed, afterwards real-time data is used to calculate and plot these losses.

5.10.1 Heat Loss Due to Dry Flue Gas (L1)

This loss is because of capability of flue gas constituents to absorb and take away some amount of heat from total energy produced in combustion. Flue gas temperature "T_{FG}" is the key variable that affects the dynamics of this loss.

$$L_1(t) = \frac{m_{FG} C_{p_{FG}} (T_{FG} - T_a)}{GCV} \times 100\% \tag{5.46}$$

Where m_{FG} represents mass of dry flue gas and is determined using AFR, $\lambda(t)$ as:

$m_{FG}(t) = (1 + \lambda(t))$ kg/kg of fuel

$C_{p_{FG}}$ is the specific heat of flue gas and is calculated using equation (5.44). Mass of flue gas represents sum total of masses of all individual components of flue gas.

5.10.2 Heat loss due to water formed from hydrogen in fuel (L2)

This loss, as evident from its name, is dependent on quantity of hydrogen in fuel. Whereas its dynamic behavior is most influenced by temperature of flue gas. This loss is caused firstly by evaporation of water and that is formed by oxidation of hydrogen. The evaporation of water occurs after absorbing certain amount of energy which is determined by latent heat of vaporization h_{fg}. Secondly the formed water vapoers carry away heat energy depending on their heat capacity. Mathematically this loss is given as:

$$L_2(t) = \frac{9 \times H_2\left(h_{fg}(t) + C_p(t)(T_{FG} - T_a\right)}{GCV} \times 100\ \% \qquad (5.47)$$

Where C_p is the specific heat of superheated steam which is determined by equation (5.40) , h_{fg} is the latent heat of vaporization given by equation (5.45).

5.10.3 Heat loss due to evaporation of moisture in fuel (L3)

In our case the fuel was moisture free so we take this loss to be ‘0’.

$$L_3(t) = 0 \qquad (5.48)$$

5.10.4 Heat loss due to moisture present in air (L4)

The moisture in air absorb certain amount of energy as it gets evaporated under high temperatures of furnace. The moisture is determined by humidity in air which is a region dependent factor but as its variations are not significant we assume its average value. The product of AFR and humidity determines the amount of moisture coming in through air. Mathematically it is given as:

$$L_4(t) = \frac{AFR \times humidity \times C_p \times (T_{FG} - T_a)}{GCV} \times 100\ \% \qquad (5.49)$$

Where 'humidity' is assumed to be 0.014 kg/kg of air.

5.10.5 Heat loss due to incomplete combustion (L5)

The improper mixing of air to fuel leads to the inefficient oxidation of carbon in fuel generating CO instead of CO_2. The loss of energy occurs as heat of formation of CO is less as compared to CO_2. Mathematically it is given as:

$$L_5(t) = \frac{\%CO_{mole}}{\%CO_{mole} + \%CO_{2_{mole}}} \times \frac{\%C_{mass} \times 5744}{GCV} \times 100\% \qquad (5.50)$$

Where 5744 is heat loss (in kCal) due to partial combustion of carbon (C) into CO. $\%C_{mass}$ is mass fraction of carbon in fuel. $\%CO_{mole}$ and $\%CO_{2_{mole}}$ are mole fractions of carbon monoxide and carbondioxide respectively and are determined from calculations in Section (5.7.4.

5.10.6 Heat loss due to radiation and convection (L6)

This loss occurs due to heat transfer from boiler outer surface into atmosphere. Mainly it depends on surface temperature, ambient temperature and boiler surface area. The dynamics of surface temperature are strongly correlated with dynamics of fuel flow rate.

As we don’t have the full measurements of all variables that contribute in this loss hence we can calculate it based on some realistic assumptions or we can use its average value from literature. American Boiler Manufacturers’ Association (ABMA) developed a chart of this loss vs load for different capacity of boilers which can serve as standard tool to calculate this loss for different loads and boilers. Using that we get the average value of this loss to be 1%. The error caused by these assumptions is in affordable range as this loss contribute a relatively low fraction in calculation of efficiency compared to other losses especially L1 and L2.

$$L_6(t) = 1\% \tag{5.51}$$

5.11 Simulations and discussion

Having formulated all the losses, we calculate and plot them using equations (5.46), (5.47) , (5.48), (5.49), (5.50) and (5.51) in Figure 17 and Figure 18. Figure 16 shows the plot for available measurements.

The experimental data used for calculating flue gas constituents and losses was of $\%O_2$ and FGT. But practically AFR is the actual input that determines $O_2\%$ in flue gas, hence we discuss these losses based on the input of AFR along with FGT.

Clearly the rising and falling trends in L1, L2 and L4 are following the behavior of flue gas temperature. This similarity in trends is reasonable as FGT is the main determinant of efficiency. High FGT means more energy in the constituents of flue gas and more energy taken up by vapor formed from moisture in air and vapor formed from hydrogen content in fuel. Moreover this fact is also evident by mathematical relations of all losses.

L2 is highest of all losses. The reason being natural gas has very high percentage of hydrogen i.e. 25% whereas for other fuels like coal this loss is about 5% while for oil is about 7% due to their low hydrogen content.

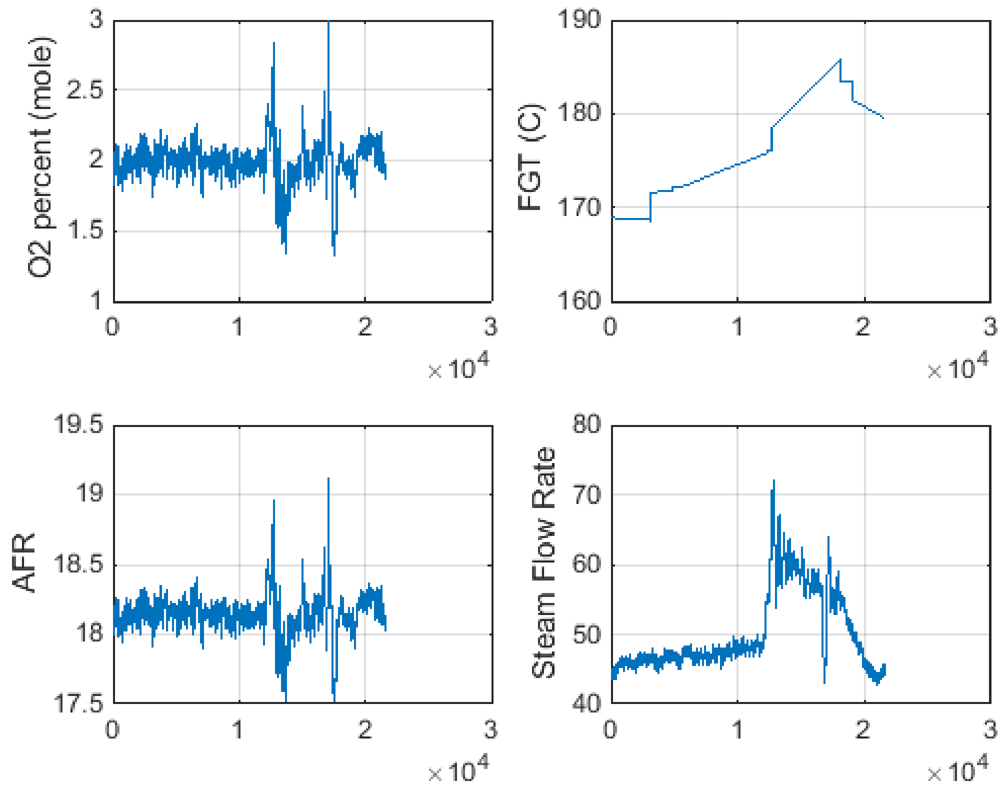

Figure 16 Plots of available data and AFR

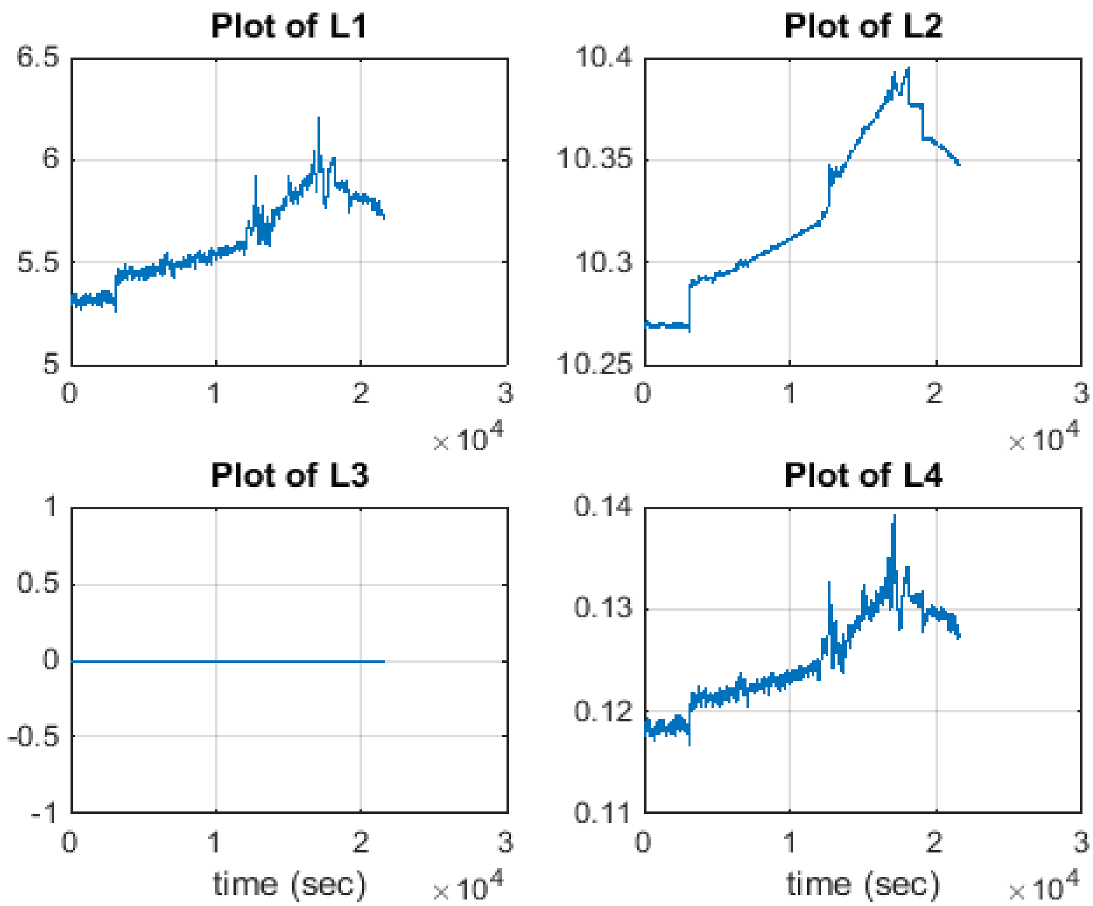

Figure 17 Time variations of losses L1-L4.

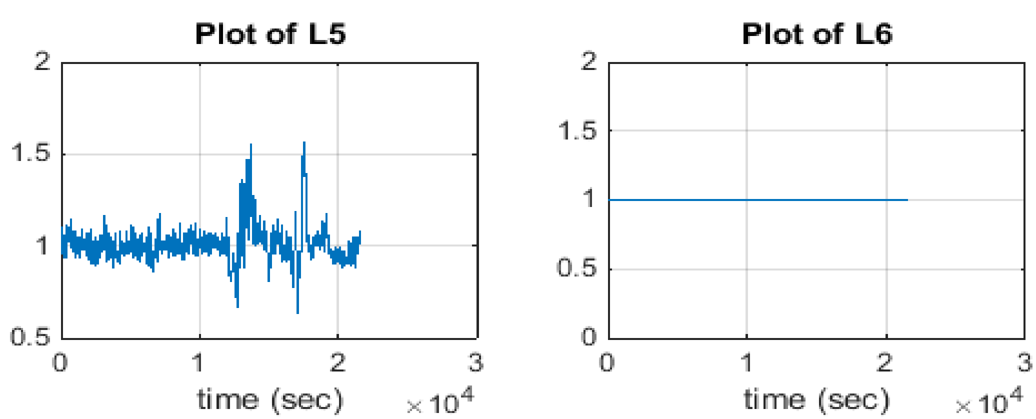

Figure 18 Time variations of losses L5,L6.

Besides being correlated with FGT, L1 and L4 also bears some correlation with AFR. Especially the high frequency content of graphs are because of AFR. In L1 magnitude of loss is influenced equally by both FGT and AFR. L2 is less influenced by AFR where it is only influencing thermal coefficients like C_p and h_{fg} in L2. L4 has relatively stronger dependence on AFR, although as humidity factor is low, this loss is minimum of all.

Dynamics of L5 are only correlated with AFR. This is because this loss is highly dependent on $\%CO_{mole}$ which is only determined by AFR. This loss is relatively higher (around 2%) for other fuels but in case of natural gas, the amount of CO is eclipsed by high value of GCV as given in equation (5.50).

After evaluating all the losses we calculate and plot the efficiency by subtracting all the losses from 100% as:

$$\eta = 100 - (L_1 + L_2 + L_3 + L_4 + L_5 + L_6) \tag{5.52}$$

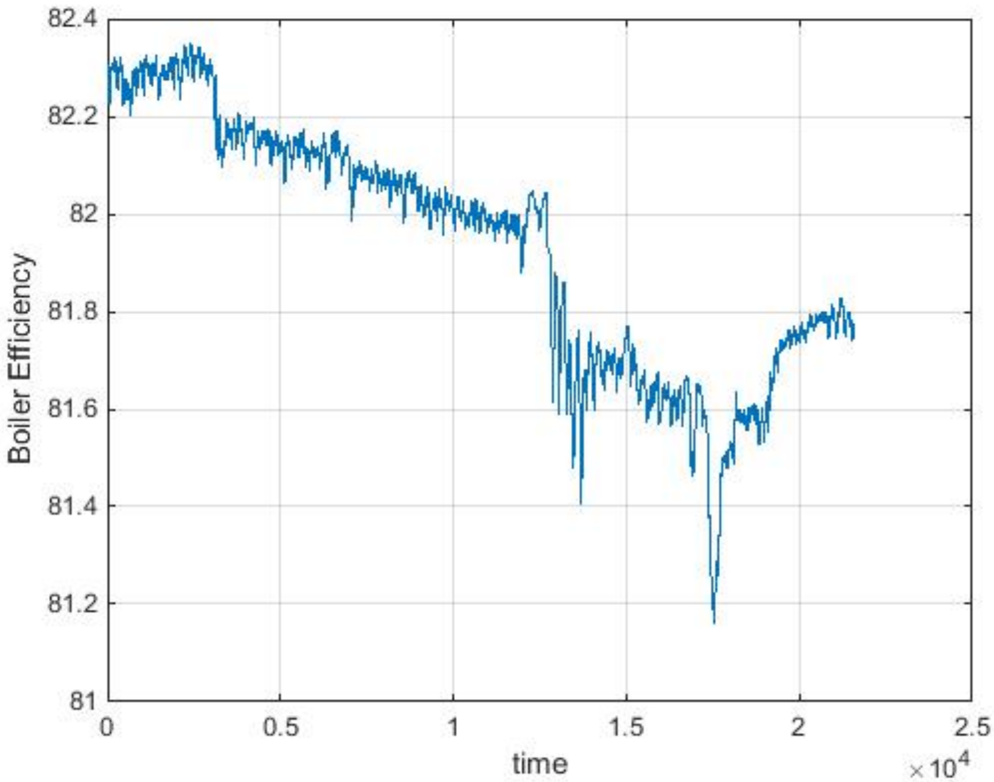

Figure 19 Time variations of efficiency

It is evident from Figure 19 that overall trend of efficiency has come out to be decreasing with time not to mention the high frequency harmonics it contains because of noisy AFR. As discussed earlier two variables FGT and AFR determine the dynamics of efficiency, we can discuss the influence of each variable on efficiency by using the correlation analysis. The general formula for cross correlation of two variables is given in Appendix. Using that formula, the correlation between efficiency and FGT, $r_{\eta,FGT}$, is coming out to be -0.9770. The figure of -0.9770 indicates a very strong correlation between the two variables. The negativity of correlation indicates an inverse relation between the two variables i.e. if one increases the other variable decreases and vice versa. The negative correlation is very intuitive because with increase in flue gas temperature more energy is lost through flue gas as evident in L1, L2 and L4 equations. The correlation of efficiency and AFR, $r_{\eta,AFR}$, comes out to be 0.2550. This is comparatively lower than $r_{\eta,FGT}$. The low correlation implies efficiency is showing both increasing and decreasing trends with increase in AFR. This type of behavior occurs typically when AFR is operated around optimum point where efficiency is maximum. The trend of efficiency with AFR is exclusively discussed in Section 5.13.

5.12 Input Output Based Model of Efficiency

The purpose of modeling is to provide input output relation for any system. For efficiency, modeling is essential as we don't have measurements available all the times to calculate efficiency. Similarly for different operating conditions efficiency varies differently with different dynamic behavior of inputs and outputs. Hence modeling is required to investigate how inputs interact directly with efficiency. More importantly if we augment efficiency model with dynamic model of boiler, we can predict all the states more precise as efficiency influences all the states at each instant. In the contest of control, we can achieve great level of improvements in overshoots and settling times of variables. We use heating rate, 'Q', to control dynamics of drum pressure, P, but in real-time operation we manipulate 'Q' through fuel flow rate (FFR) and the relation of Q and FFR is purely subject to efficiency $\eta(t)$. The Figure 20 shows the implementation of efficiency model with the controller of pressure using the heating rate.

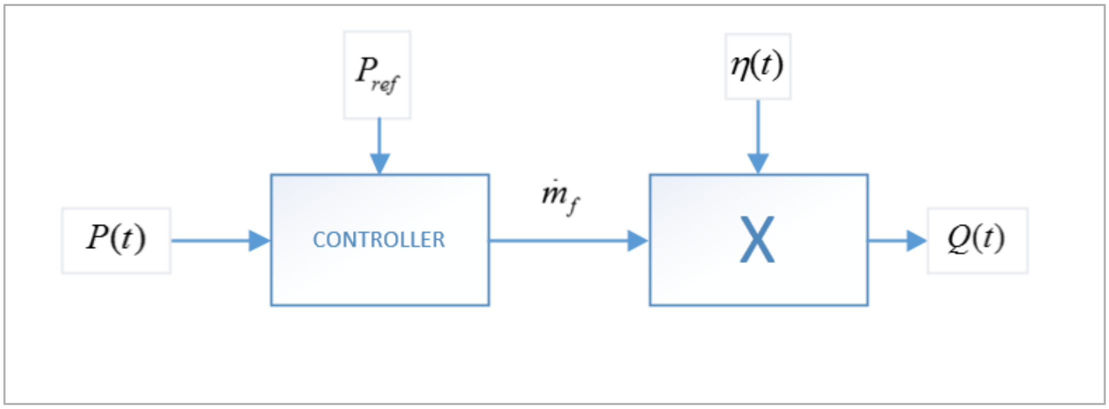

Figure 20 Control implementation with dynamic efficiency

In the context of optimization of efficiency with NOx, modeling can be very helpful because we require modeling equations for both quantities based on mutual inputs. Specifically for maximizing efficiency we can calculate online the best possible trajectories of inputs especially AFR on real time basis.

In the previous sections, we have made calculations to evaluate dynamic efficiency based on time varying data of FGT and AFR and other static variables like ambient temperature, fuel composition and humidity. Constructing a full input output model requires only modeling of FGT. The FGT is a dependent variable and if we figure out the relation between FGT and other inputs we are able to control the efficiency with the inputs as long as other design parameters and fuel composition remains constant. In real-time operation of boilers the main inputs that are used to control the dynamic behavior of boiler are FFR, feedwater rate and AFR. The feed water rate is dedicated to control the dynamics of boiler water level hence it is hardly related with controlling efficiency. FFR and AFR are the two main inputs that influence FGT directly hence dynamic behavior of FGT can be using these inputs. Once FGT is we can augment it with the efficiency equations and then we can investigate its behavior for different operating conditions.

5.12.1 Flue Gas Temperature Model:

Dynamic modeling of temperature of flue gas is very challenging. For full utilization of fuel energy, heat from the flue gas is extracted and further processed in economizer and super heater to recover more energy from it into steam. Exact model of FGT requires advanced mathematical equations using fluid dynamics of flue gas, heat transfer coefficients equations of economizer and superheater as well as thermal properties of metal surfaces. Due to unavailability of design parameters of super heater and economizer we refer to empirical schemes to investigate the influence of FFR and AFR on flue gas temperature. We have experimental data of flue gas temperature (as stated before) which will be used for this purpose.

The class of system identification deals with the empirical modeling techniques that use knowledge of measured data to form models that mimic actual behavior of dynamical system. The advantage of system identification is that we can use simple models to predict complicated systems with great accuracy. These techniques just require the knowledge of form of model and data set of input and output. With huge amount of experimental data set of 21600 samples we can easily construct a black box model of FGT using the inputs of AFR and FFR.

The Matlab toolbox of system identification also features process modelling based on available data of inputs and outputs of a system. Among variety of process models, we choose a simple transfer function model with one pole for each input as follows:

$$T_{FG}(t) = \frac{K_1}{1 + T_{p1}s}\,\lambda(t) + \frac{K_2}{1 + T_{p2}s}\,\dot{m}_f + \mathrm{e(t)} \qquad (5.53)$$

We use AFR and data set of FFR as in Figure 21 for calculating coefficients of above model:

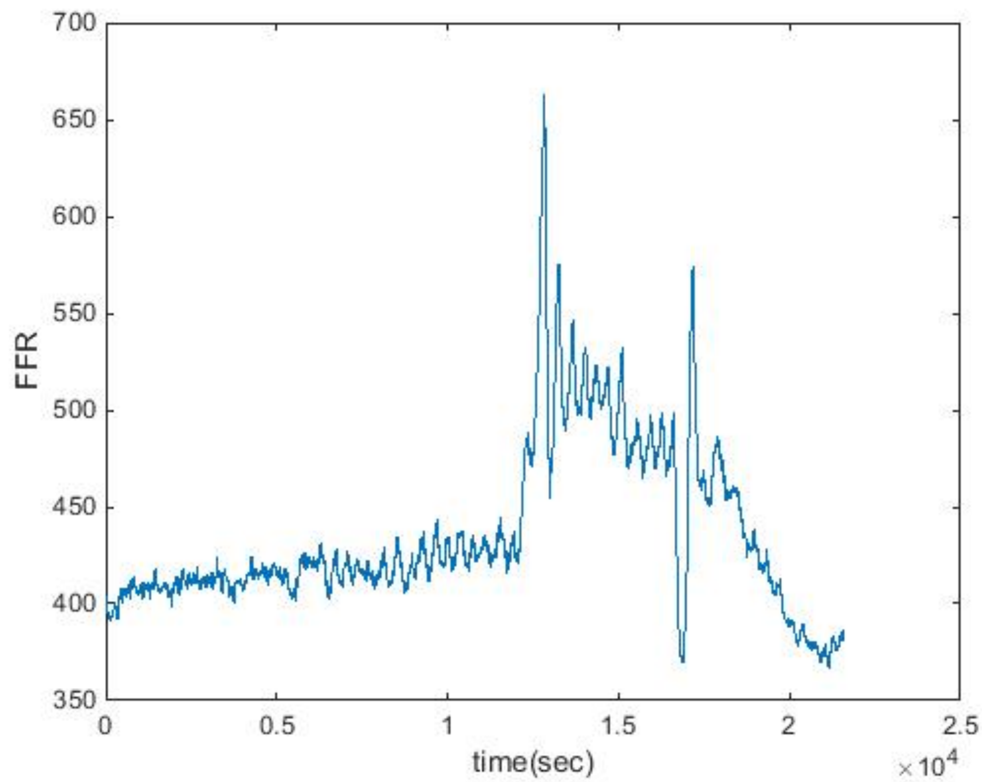

Figure 21 Plot of fuel flow rate (kSCFH) data

The first 85% of data was used for testing while last 15% was used for validating the result. With 20 iterations and letting toolbox choose automatically the most optimal search algorithm we got the parameters values as shown in Table 4. The plots for both and measured FGT is shown in Figure 22. The model was also validated for another boiler installed in parallel with our case study boiler. Figure 23 shows the validation plot which is showing a significant agreement between experimental and FGT for the given data of AFR and FFR.

Table 4 FGT Model Coefficients

Coefficient	**Value**
K_1	5.84
T_{p1}	5.31e03
K_2	0.168
T_{p2}	5.44e03
Variance e(t)	0.4656

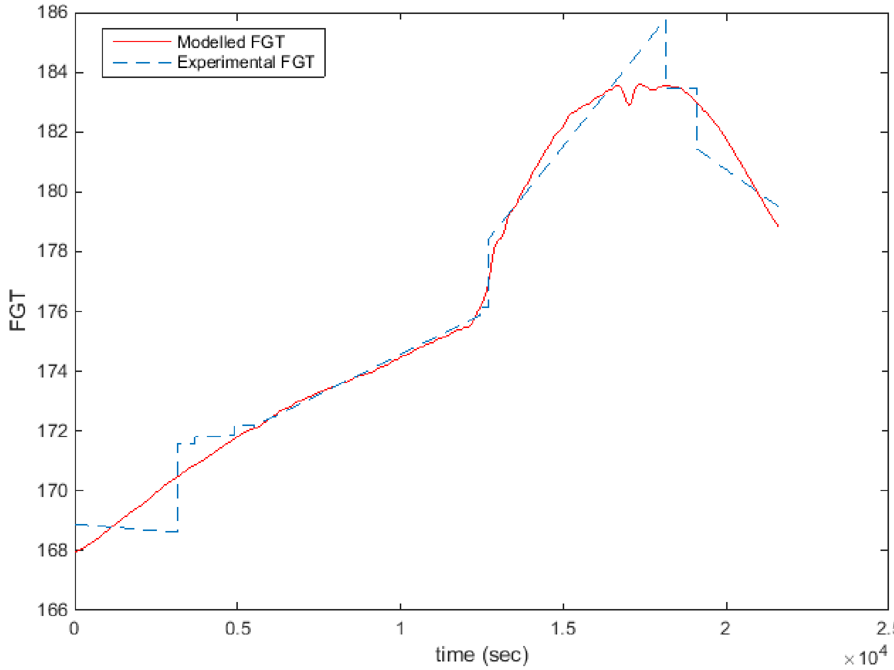

Figure 22 FGT plot of model and experimental Data

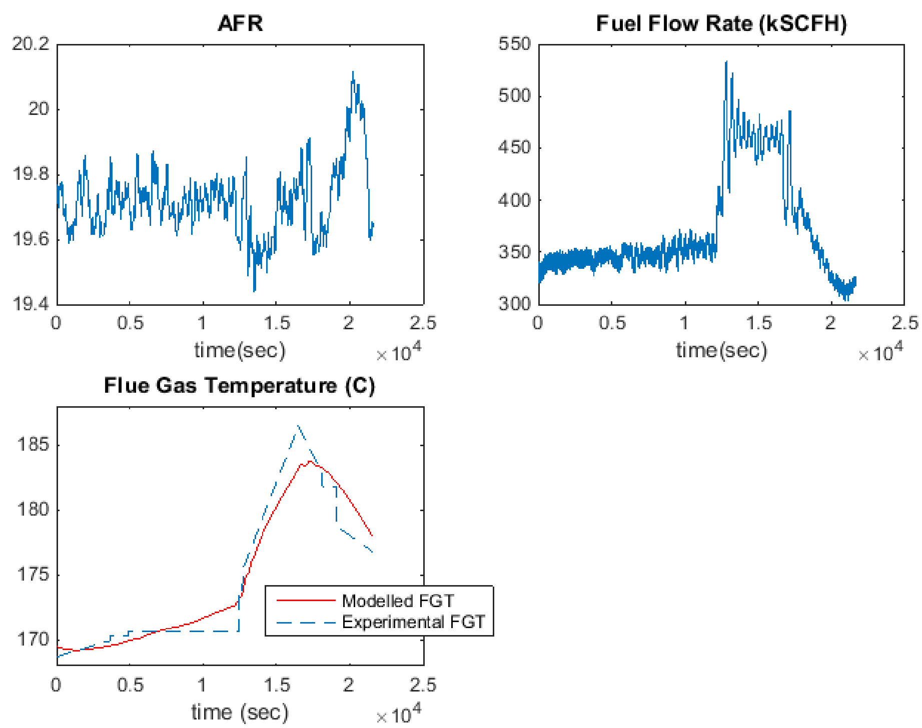

Figure 23 Validation plot of FGT using data of second boiler

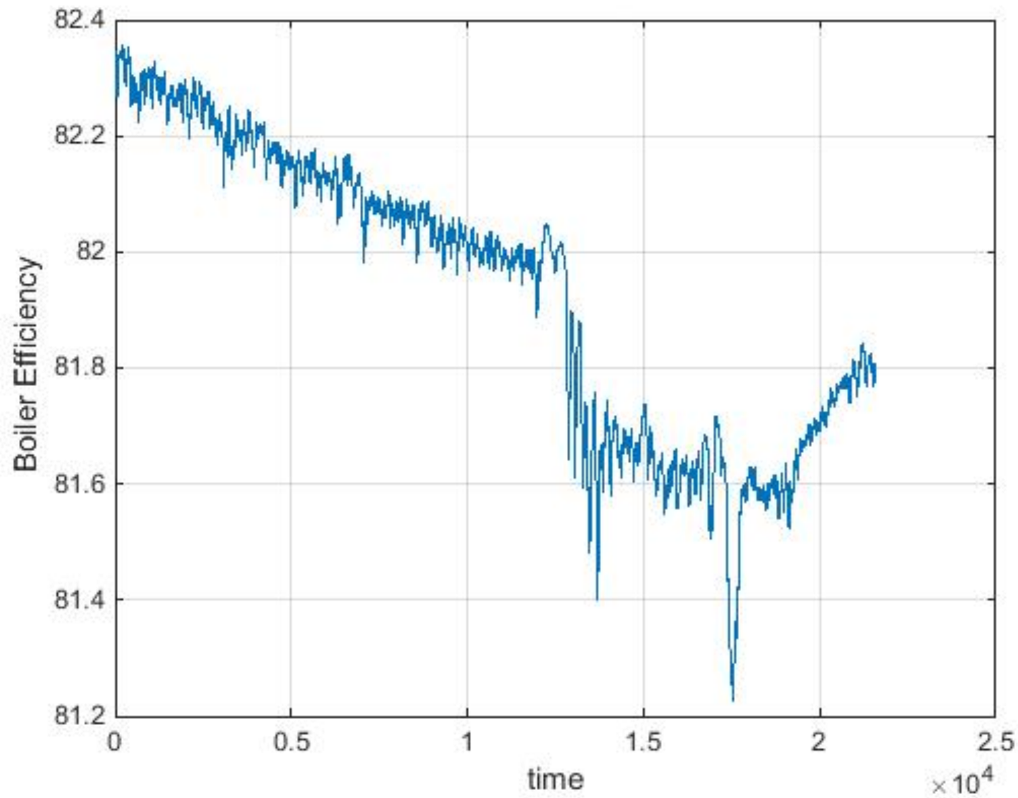

Figure 24 Time variations of efficiency using FGT model

With the augmentation of FGT model with efficiency equations (5.46)-(5.51) from section 5.10 we get the input output model for efficiency of following form.

$$\eta(t) = \eta(\lambda(t)\ ,\ \dot{m}_f, x) \tag{5.54}$$

Where $'x'$ represents vector of constant parameters given as:

$$x = [GCV, \%X_{mole}, T_a, humidity] \tag{5.55}$$

Figure 25 shows the block diagram of efficiency model. The model shows strong agreement with efficiency calculated from experimental data as evident from Figure 24 and Figure 19.

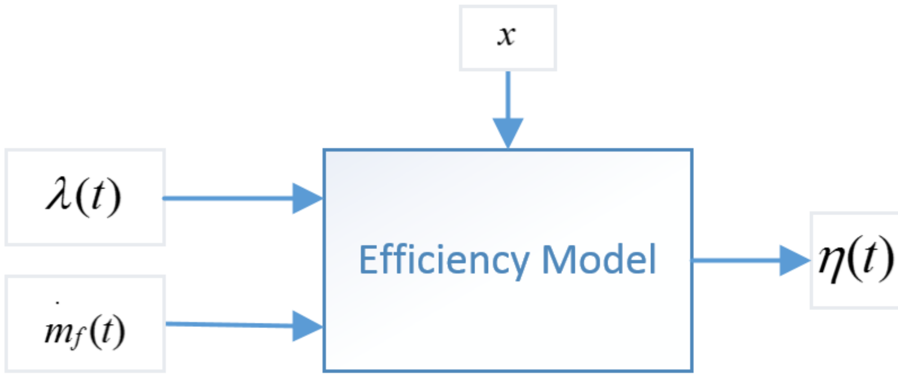

Figure 25 Efficiency model with inputs and output

5.13 Influence of AFR and FFR variations on Efficiency

The variable of steam is considered as a disturbance agent in whole boiler system, and a little variation in steam can cause all the boiler dynamics to go violent. This behavior of steam necessitates the use of controllers to control all the variables using the available inputs. The pressure control is implemented by using a control block which decides the variations in FFR based on measured output of pressure as well as the pressure set point. In this control process, under dynamic variations due to steam disturbance, efficiency is duly affected due to its strong dependence on FFR based on derived mathematical relations. Intricately this dependence on FFR is because FGT which is the main determinant of efficiency, is highly influenced by FFR. Based on the model we created, we can easily investigate the influence of FFR on efficiency. In other words dynamic behavior of pressure has an effect on efficiency which can be analyzed by our formulated efficiency and FFR mathematical relation. This can be done by demonstrating the variations in efficiency from maximum allowable swings in FFR. For this purpose we use the static model of efficiency which uses average, minimum, and maximum values of FFR. The maximum swings in FFR can be derived from [37] as it used the same boiler as ours.

Variations in FFR are analyzed in the context of swing rates. In [37] 4 different swing rates have been considered where the swing rates are determined by rate of change of steam flow rates. The swing rates ranged from 5 to 40 percent of maximum continuous rating (MCR) steam flow rate pet minute. Corresponding to each swing rate of steam it was observed a simultaneous swing in heating rate from its nominal value. The results of that can be summarized in following table.

Table 5 Swing Rates Effect on Min. And Max. Of Input Variables

Swing Rates	**Q_{max} (MW)**	**Q_{min} (MW)**	**FFR_{max} (kg/s)**	**FFR_{min} (kg/s)**
5%	118	85	2.78	1.9
40%	128	85	3.02	1.9

Where 'Q' refers to heating rate. FFR has been evaluated from 'Q' using following:

$$\dot{m}_f = \frac{Q}{GCV \times \eta} \tag{5.56}$$

The influence of AFR on efficiency is very important based on the context of optimization of efficiency. Several papers in the literature discuss the variations of efficiency with AFR based on a bell shaped curve with both increasing and decreasing trends. The air which is responsible for providing oxygen to execute combustion is also responsible for taking away the useful energy into waste. This is because decreased amount of air causes ineffective combustion and superfluous air causes more energy bagged by air. This gives rise to the need of finding optimum AFR where we have both these phenomenon operating at minimum level. We can generalize this important effect by using modeling equations to plot efficiency with AFR for minimum, average and maximum loads.

Our model gives us the opportunity to throw some light on the analytical relation of efficiency with FFR and AFR. This model can be used for both dynamic and static operating conditions. The AFR effect on efficiency for different loads is usually demonstrated by considering the average behavior of efficiency irrespective of time. By taking time based average of other variables, we use the same modeling equations to investigate behavior of efficiency in static operating conditions. The *Figure 26* gives the generalized behavior of efficiency with varying AFR and FFR where minimum and maximum loads correspond to FFR_{min} and FFR_{max} respectively.

The Figure 26 shows that the optimum point of efficiency lies at the equivalence ratio, $\phi = \phi_{optimum} = 1.07$. Before this point the air supplied is too insufficient for complete oxidation of fuel. Hence going leftwards from the optimum point there is an increase in CO production as well as CO losses. This effect is straightforwardly validated by equation (5.19) and equation (5.50). Hence efficiency gets highly suppressed when CO losses dominating.

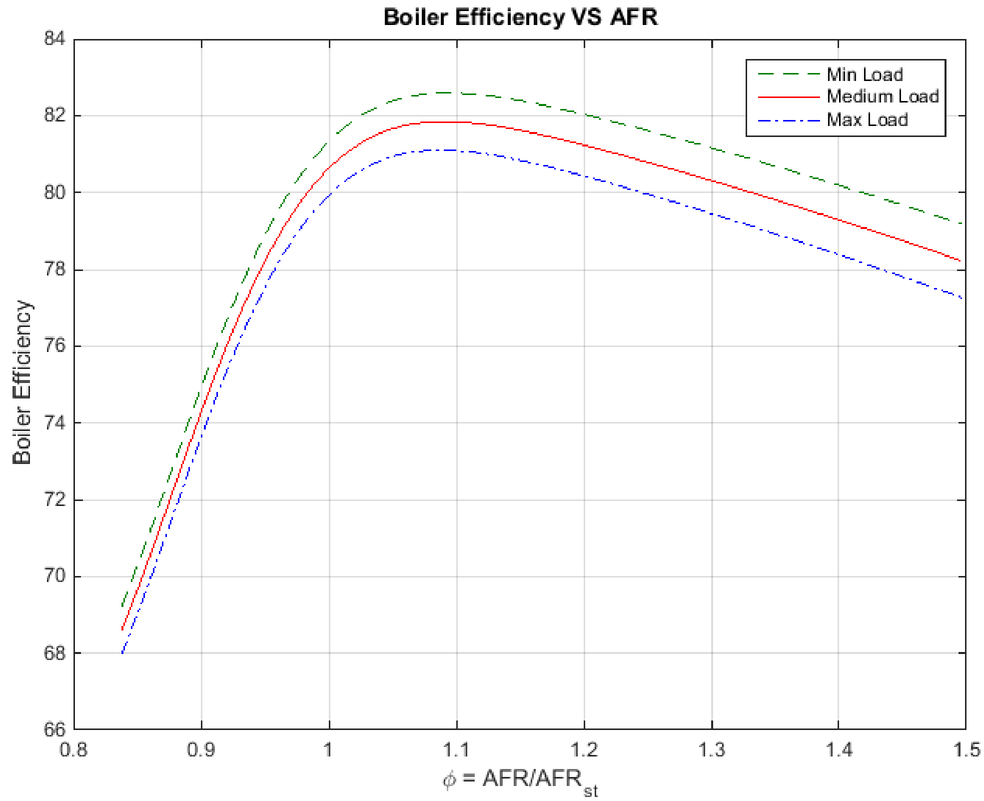

Figure 26 Efficiency variations with AFR for different Loads

After $\phi_{optimum}$, the CO losses decrease monotonically due to complete oxidation of fuel and low production of CO. However efficiency decreases rightwards as FGT as well as the content of air starts dominating giving rise to L1 and L2. Increase in air content increases the capacity of air to carry away more energy and increase in FGT occurs as fuel is combusted more properly giving rise to high temperatures. These effects are validated by modeling equations (5.46) and (5.53).

Fuel flow rate interact with efficiency based on their influence on FGT. The FGT is positively correlated with FFR. Hence increasing FFR increase the FGT thereby decreasing efficiency whereas decreasing FFR has an effect otherwise.

5.14 Summary

In this chapter we have discussed modeling of efficiency by two methods which are direct method and indirect method. The indirect method is then used to model time variations of efficiency using time varying data of operational variables of a typical package boiler. Later we formulate a second order dynamic model of FGT using system identification technique. This model is used to extend the indirect method of efficiency to calculate instantaneous efficiency in terms of operational inputs only. Finally the utility of novel input output based model has been discussed based on its usage in dynamic control and dynamic optimization of boiler variables especially NOx.

CHAPTER 6 CORRELATION ANALYSIS OF BOILER VARIABLES

In this chapter we perform the correlation analysis of all the operational variables of boiler including both input and output variables. The idea behind this analysis is to figure out how variables influence each other over different operational regimes. The available data of our industrial boiler has distinctively two regimes which are classified as steady state interval and dynamic interval. We discuss the correlation of variables individually for both these intervals and present the results in tabular form. Finally, we plot the correlation of all the variables over full range of time to illustrate how time shifting in variables influences the correlation coefficient.

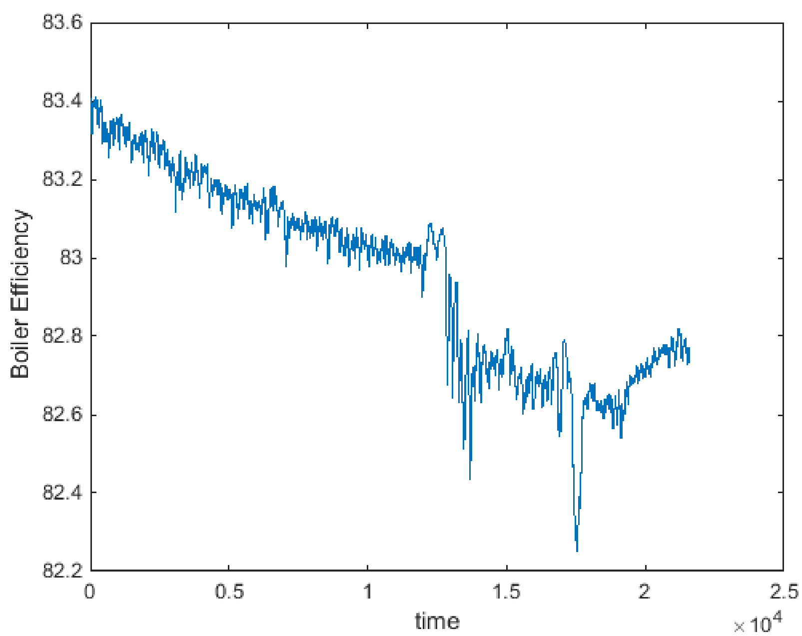

Figure 27 Boiler's efficiency with time

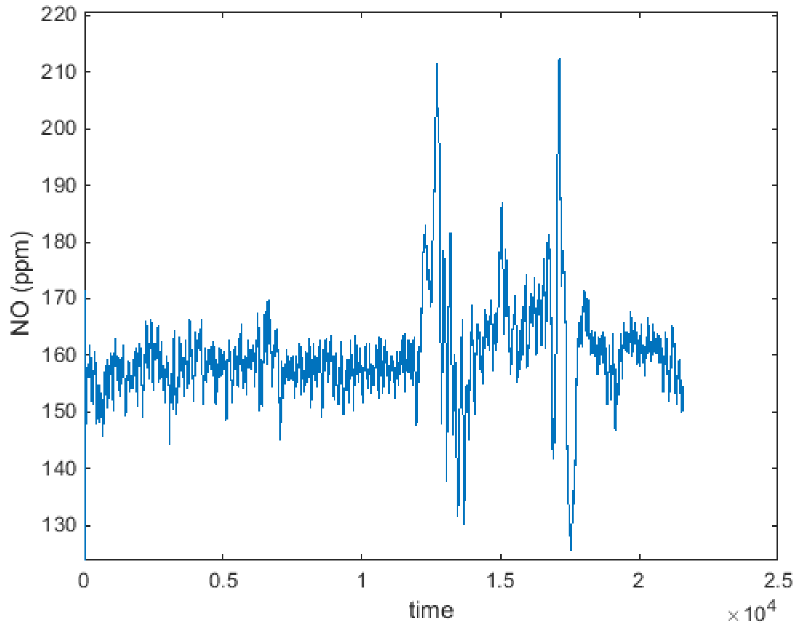

Figure 28 NOx variation with time

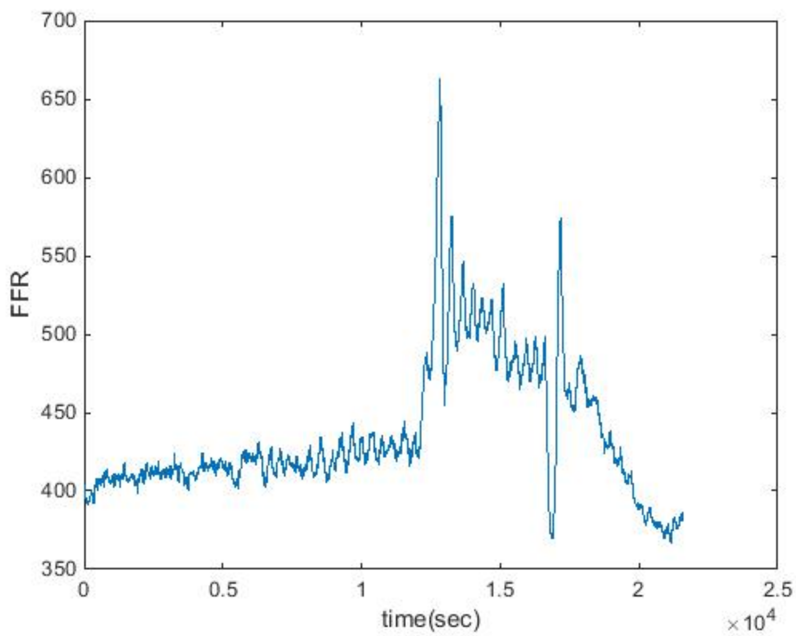

Figure 29 Fuel flow rate (kSCFH) with time

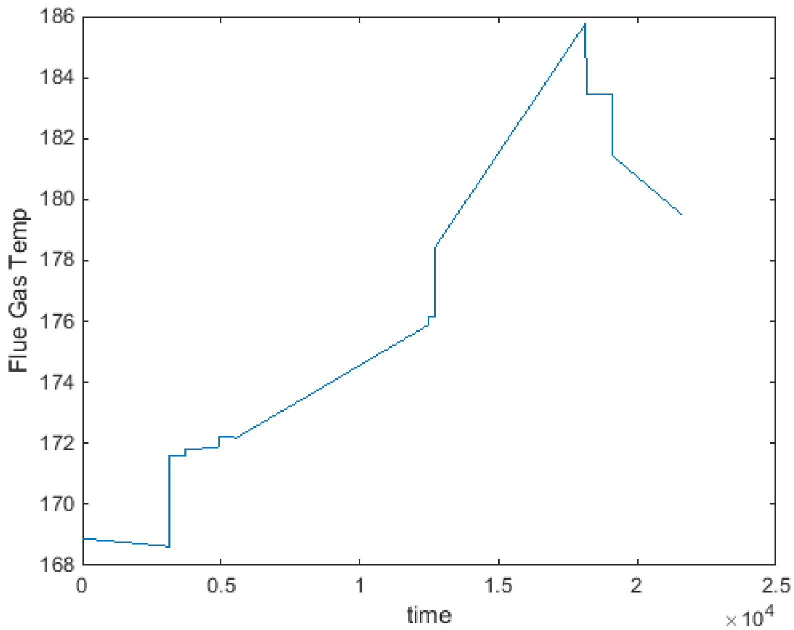

Figure 30 Flue gas temperature with time

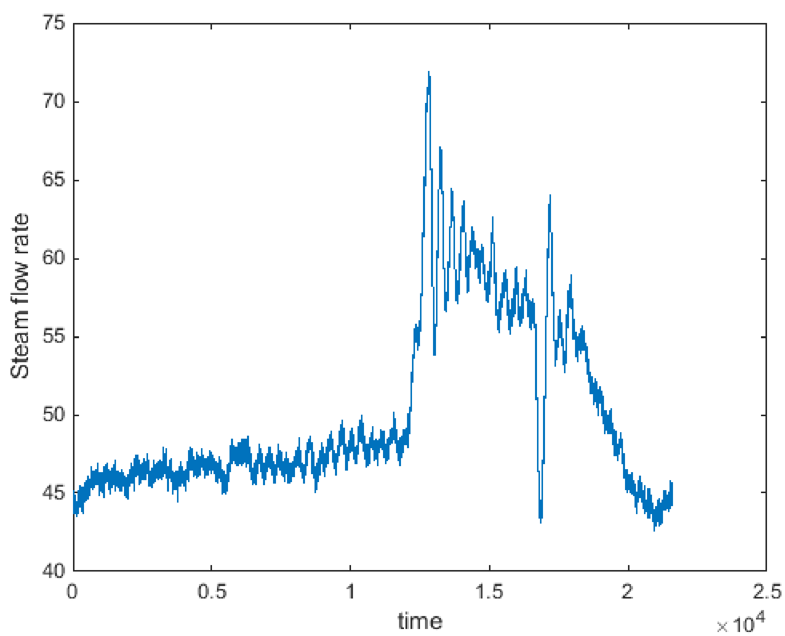

Figure 31 Steam flow rate with time

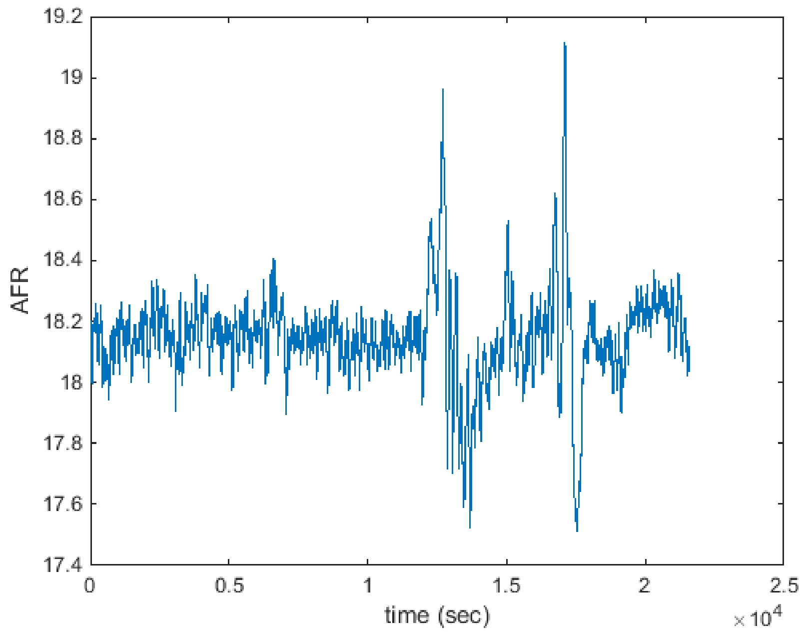

Figure 32 Air to fuel ratio variation with time

In Figure 27 to Figure 32 we replot all the important variables of boiler based on the available experimental data. With sampling time of 1 second we have 21600 data points covering the time length of 21600 seconds (6 hours). Considering this large time interval it is reasonable to divide this interval into two sub intervals so that we can perform the correlation analysis more efficiently.

The subintervals selected are $[\,0 \rightarrow 12000\mathrm{s}]$ and $[12000s \rightarrow 18200s]$ where each subinterval contains either dynamic variations or steady variations in data. The correlation is calculated using a correlation formula which has been discussed in the Appendix. Using correlation formula, the correlation analysis of both intervals is discussed hereafter:

6.1 Time Interval = $0 \rightarrow 12000s$

It will be more illustrative if we re-plot the variables for the desired interval as in Figure 33.

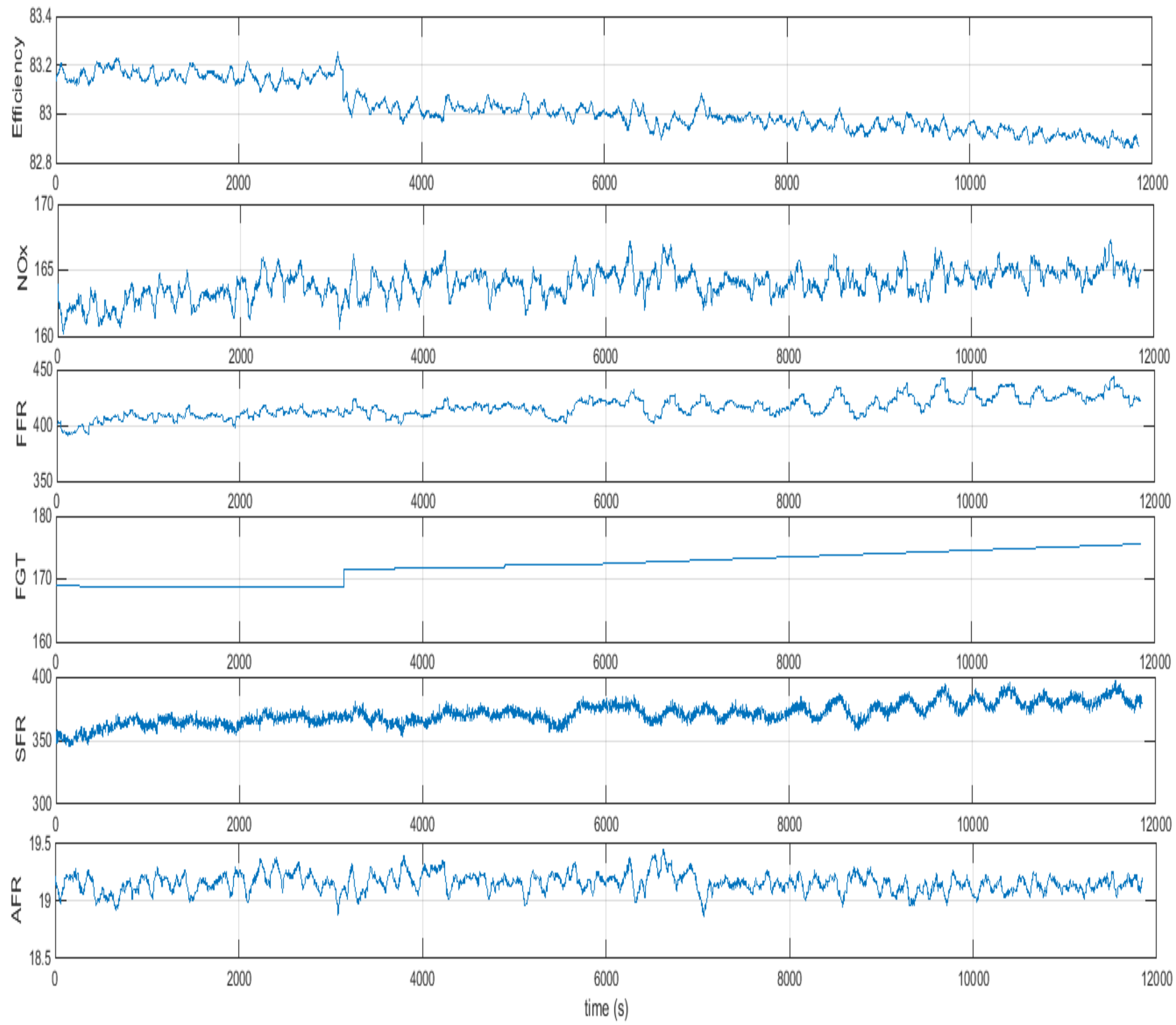

Figure 33 Steady state interval plot

Where the y-axis labels FFR, FGT, SFR, AFR refer to Fuel flow rate, Flue Gas Temperature, Steam Flow Rate and Air to Fuel ratio respectively.

Considering above plots this interval is exhibiting vary low dynamics in fact it appears that the variables are either tending to remain constant or exhibiting a very small amount of rising behavior. The noise and small harmonics of data are very small and the maximum variation ($\Delta x/\Delta t$) these variables have exhibited is about 0.1. Moreover no significant disturbance has occurred in all the inputs (fuel flow rate, air to fuel ratio and steam flow rate) during this interval as shown in the plots. The outputs also follow the similar behavior exhibiting no significant disturbances. In general we can conclude from above plots that the variables of NOx, fuel flow rate, flue gas temperature and steam flow rate are rising slowly whereas efficiency is slowly decreasing while the air to fuel ratio almost remains the same i.e. is constant. Due to small scale variations in all the variables we can categorize this interval as steady state conditions for all the variables. In the same way the next interval due to violent variations will be categorized as dynamic conditions for the variables.

The correlation of all the variables for the time interval of $0 \rightarrow 12000$s is tabulated in Table 6 and Table 7.

Table 6 Values of Correlation Coefficient of input and output variables

Variables/Inputs	**Fuel Flow Rate**	**Air to Fuel Ratio**	**Steam Flow Rate**
Flue Gas Temperature	0.9407	-0.0327	0.9418
NOx	0.9224	0.3202	0.9017
Efficiency	-0.9260	-0.1076	-0.9287

Table 7 Values of Correlation Coefficient of output variables with each other

Variables/Inputs	Efficiency	Flue Gas Temperature
Flue Gas Temperature	-0.9901	1
NOx	-0.9156	0.8759
Efficiency	1	-0.9901

Analyzing the behavior of fuel flow rate in Figure 33, it can be observed that it is increasing with positive slope. The flue gas temperature and NOx follows i.e. both show similar increasing behavior. This similarity of behavior can be mathematically quantified using equation (8.3) for which the flue gas temperature and fuel flow rate correlation coefficient comes out to be $+0.947$. The big positive number of coefficient indicates that in current conditions fuel flow rate and flue gas temperature have shown a similar trend of increasing. And the same goes for NOx with correlation coefficient (with fuel flow) equal to $+0.922$. This high value of correlation coefficient is very plausible as NOx has been calculated based on modeling equation (4.10) instead of directly measured and the modeling equations show that NOx has direct proportional dependence on fuel flow rate. Besides that these values are very intuitive because high fuel rates are more conducive to high temperature of furnace where flue gas is created and hence it has high temperature in steady conditions and similarly low fuel rates cause low flue gas temperature. Likewise, NOx has also direct proportional dependence on furnace temperature and hence giving high positive correlation coefficient with fuel rate.

Efficiency and fuel flow rate are exhibiting negative correlation (-0.926) implying a strong inverse relation between them in steady conditions. This correlation value is a direct effect of the type of correlation between flue gas temperature and fuel flow rate. Efficiency, just like NOx, has been calculated instead of measured. The mathematical model used for calculating efficiency, as discussed in CHAPTER 5, shows a very strong dependence of efficiency on flue gas temperature. As the flue gas temperature is increasing, more energy gets wasted through all of the losses that are majorly dependent on flue gas temperature. That is why efficiency shows opposite behavior i.e. it decreases.

Flue gas temperature is giving very low correlation with air to fuel ratio (-0.0327). From the plots the air to fuel ratio is almost constant (disregarding the noise and low harmonics). This gives the notion of low dependency of flue gas temperature on air to fuel ratio. But as explained earlier the flue gas temperature has increased based on increasing behavior of fuel flow input which refutes that notion. However this behavior of flue gas temperature with air to fuel ratio can be analyzed more carefully by using more dynamic (non-constant) behavior of air to fuel ratio and then observing how flue gas temperature varies and correlates with it (as in the next interval). The same explanation goes for low correlation between efficiency and air to fuel ratio (-0.1076). NOx on the other hand gives small positive correlation (+0.32) which is, of-course, not small enough to neglect. NOx and air to fuel ratio are related based on modeling equations of NOx and from the plots it appears that air to fuel ratio is trying a little to drive the NOx along its direction i.e. its constant behavior but nevertheless NOx has increased with time. It seems better to compare correlations of NOx with both inputs of fuel flow rate and air to fuel ratio. The former is tending to increase NOx while the latter is trying to keep it constant. That just exhibits dual dependence of NOx on both variables in which fuel flow rate is more influencing and air to fuel ratio is less influencing NOx. Moreover, NOx behavior with air to fuel ratio can be examined more evidently by observing it with non-constant or more dynamic behavior of air to fuel ratio which will be in the next time interval.

The variable of steam is considered as a disturbance agent in whole boiler system, and a little variation in steam can cause all the dynamics to go violent. This behavior of steam necessitates the use of controllers to control all the variables that is why all the variables are somehow dependent on steam load. The correlation analysis of all variables validates this dependence by giving all correlation coefficients with steam close to 1 (in magnitude) in steady state interval like this. For instance flue gas temperature and NOx both gives correlation values of +0.9418 and +0.9017 respectively and exhibits similar rising behavior just like steam flow rate. Theoretically it suffices to say NOx and flue gas temperature are also correlated with steam flow but a reasonable explanation can be deduced by considering behavior of other variables as NOx and flue gas temperature are not directly related to steam flow rate. This can be done by examining the behavior of fuel flow rate. The fuel flow rate and steam flow rate have a high correlation coefficient of +0.97 because the behavior of fuel flow rate is majorly influenced by steam flow rate due to control action. And as discussed earlier NOx and flue gas temperature strongly depend on fuel flow rate so indirectly they are significantly correlated with steam flow rate.

Efficiency and steam flow are negatively correlated in the interval of our current interest (-0.9278). The explanation for this can again be deduced from fuel flow rate as fuel flow rate and steam flow almost goes in same direction (increase or decrease together). The increasing fuel flow causes more energy waste through the losses mentioned earlier and hence causes efficiency to go low in this interval.

Efficiency and NOx are correlated by factor of -0.9156. This cross correlation value signifies an inverse and strong relation between these two variables in steady conditions like this interval. In earlier discussion we mentioned that efficiency is highly correlated with fuel flow rate and steam flow rate. Likewise NOx is also correlated with these two variables as well as air to fuel ratio to some extent. Based on these correlations and mathematical model used for calculating efficiency, it is evident that the efficiency is dependent on all the parameters that affect NOx formation out of which major ones are fuel and steam flow rate. Intuitively a strong correlation should exist between NOx and efficiency hence bringing up large value of correlation coefficient in current steady state interval. The negativity of correlation simply signifies the inverse behavior of both variables with each other which can also be ascribed to the fuel flow rate. As explained earlier fuel flow rate and efficiency are negatively correlated i.e. high fuel rates are more conducive to low efficiency and vice versa and fuel flow rate is positively correlated with NOx that is why efficiency and NOx are negatively correlated.

6.2 Time Interval = $12000s \rightarrow 18200s$

This interval signifies the turbulent or dynamic behavior of all the variables. We replot all the variables for this interval as in Figure 34 to Figure 36.

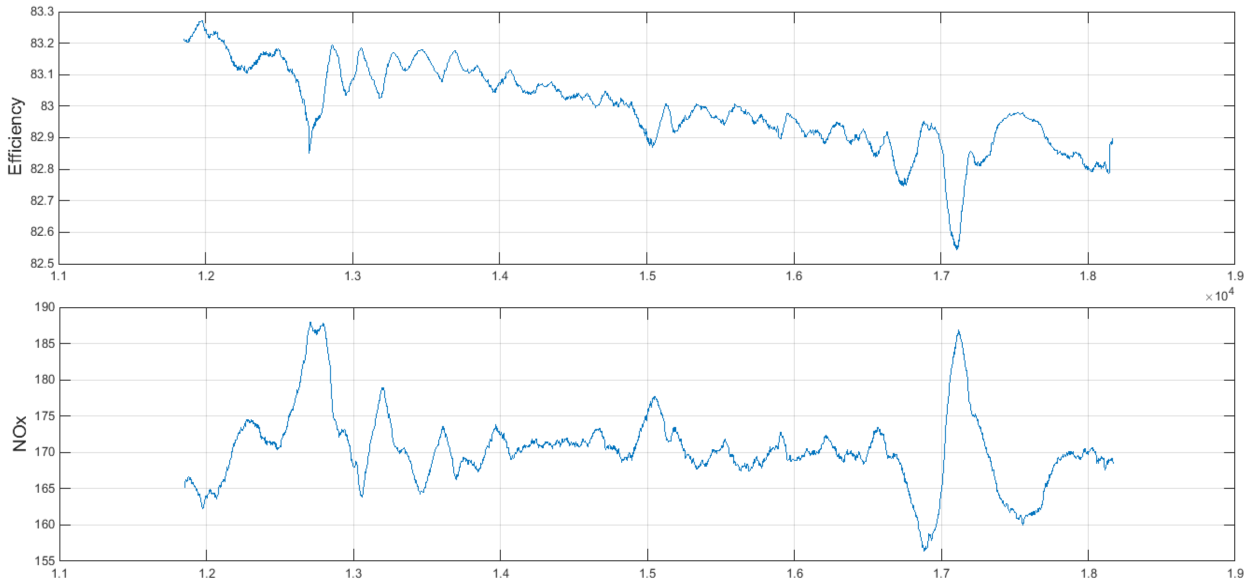

Figure 34 Dynamic interval plot of efficiency and NOx

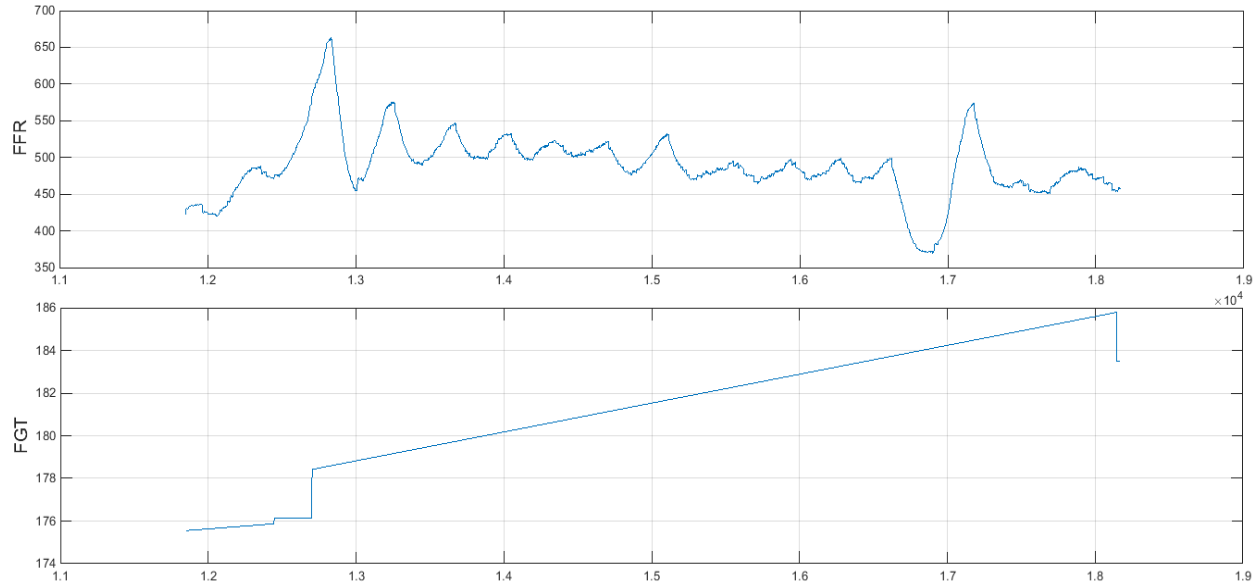

Figure 35 Dynamic interval plot of FGT and FFR

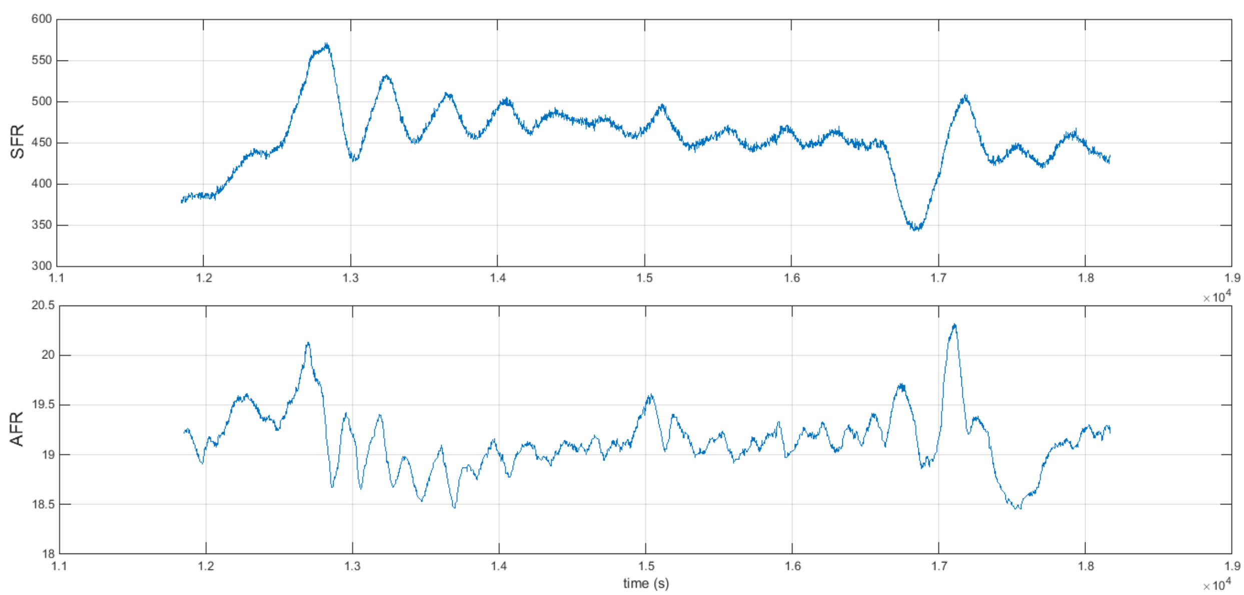

Figure 36 Dynamic interval plot of SFR and AFR

As shown in figures, none of the variables are constant i.e. all variables are showing violent variations and oscillate for the whole time interval. In fact this interval represents the most dynamic of all. There are two peaks in the interval representing maximum dynamic change that are identifiable in the plots of all the variables and after each peak the oscillations tend to decrease. The flue gas temperature, however goes as an exception showing very little variations compared to others, and appears to be almost noiseless and with no oscillations. The oscillatory behavior of other variables is because of slow control action that is pushing and pulling the variables in order to stabilize them at their respective set points in the presence of disturbance which in our case is associated with steam input. For correlating the variables it plausible to discuss the general trend of all the variables from beginning to the end of interval regardless of the noise and oscillations. For instance, the general trend of flue gas temperature is appearing increasing in the current interval. The air to fuel has also general behavior of increasing. The fuel flow rate, efficiency and steam flow rate have a general trend of decreasing. NOx, on contrary to all, oscillates around a constant value. The correlation coefficient values of all the variables for this interval is tabulated in Table 8 to Table 9.

Table 8 Values of Correlation Coefficient of input and output variables

Variables/Inputs	**Fuel Flow Rate**	**Air to Fuel Ratio**	**Steam Flow Rate**
Flue Gas Temperature	0.0672	-0.1657	0.6607
NOx	0.8235	0.6930	0.7515
Efficiency	-0.6293	-0.4313	-0.7090

Table 9 Values of Correlation Coefficient of output variables with each other

Variables/Inputs	**NOx**	**Flue Gas Temperature**
Flue Gas Temperature	0.4555	1
NOx	1	-0.4555
Efficiency	-0.5261	-0.8359

Analyzing the behavior of fuel flow rate as in Figure 34 to Figure 36, it can be observed that it is oscillating and its general behavior can be categorized as decreasing. Flue gas temperature has under gone a monotonic increase in this interval. Due to this vivid difference between the variations both variables have undergone, the correlation is coming to be very small i.e. 0.0672. This small value of correlation indicates that under violent dynamic variations the flue gas temperature doesn't follow the trend of fuel flow rate. Although in the first interval where variables were either in steady state or slowly changing, the trend in both variables was similar or correlation was very high. It follows that behavior of flue gas temperature differs a lot from the behavior of fuel flow rate in violent dynamic conditions.

NOx on the other hand has followed the trend of fuel flow rate with high correlation coefficient of 0.82. The trend is also very noticeable in plots i.e. like fuel flow rate, NOx has undergone same oscillations as well as same general decreasing behavior. So it can be inferred that in both steady state and violent conditions NOx dynamic behavior is similar to fuel flow rate i.e. both increase and decrease together. The conclusion is also justified by NOx modeling equation (4.10) that we have used which signifies the direct proportional behavior of NOx with fuel flow rate.

The correlation of efficiency with fuel flow rate has gone low compared to first interval. The figure of -0.6293 indicates that efficiency is moderately correlated with fuel flow rate in this interval. The negativity of correlation coefficient indicates an inversely proportional relation between the variables i.e. if one increases the other tends to decrease. This behavior is more evident at the localized region of interval where the two peaks have occurred. As has been mentioned earlier, these two peaks in their plots correspond to extreme disturbances the variables have undergone in this interval. It is observable from plots that in those localized regions of peaks the inverse relation between these two variables is more prominent. However in the remaining of interval, particularly after first peak, both efficiency and flue gas temperature have shown similar behavior characterized by their general trend i.e. the general trend in both variables is same decreasing. These two contradictory behavior of two variables are the reason for the correlation lessened (in magnitude) to a value of -0.6293. Moreover the decreasing behavior of efficiency can be ascribed to flue gas temperature which has direct influence on it based on the modeling equations of CHAPTER 5. As the flue gas increases, the losses mentioned earlier increase and efficiency decreases. The inverse proportional behavior (prominent around peaks) is also due to the fact that increasing fuel rate causes more energy losses and hence the efficiency should decrease based on this clue. So in conclusion both direct and inverse proportional behavior of these two variables are evident in this interval concluding a moderate value of correlation.

The air to fuel ratio and flue gas temperature have maintained their low value of correlation in both intervals. For this interval correlation coefficient of -0.1657 still signifies the random relation between both variables. Also this relation is evident from their plots in which flue gas temperature is monotonically increasing while air to fuel ratio is undergoing oscillations. Hence we can assume that flue gas temperature is majorly responsive to parameters or variables other than air to fuel ratio both in steady and dynamic conditions.

The correlation of NOx with air to fuel ratio in this interval is not extreme or just moderately strong as obvious from the correlation coefficient value of 0.6930. The dissimilarity in both variables is that the general trend of air to fuel ratio is increasing while that of NOx is oscillatory around a constant value. But specifically the trend of oscillations are similar that's why we have a positive value of correlation showing almost 70% of similarity between behavior of both variables. This un-extreme correlation of NOx is also because of its strong correlation with fuel flow rate under all conditions as being exhibited in both intervals. The fuel flow rate drives NOx more powerfully than air to fuel ratio that's why under both steady and dynamic trends NOx is less responsive to air to fuel ration compared to fuel flow rate.

The efficiency is mildly correlated with air to fuel ratio with correlation coefficient value of -0.4313. The negative sign confirms that efficiency is mostly inversely related with air to fuel ratio i.e. when air to fuel ratio increases, efficiency decreases. Intuitively this inverse relation seems sensible as increased value of air to fuel ratio implies more quantity of air and more quantity of air has more capacity to carry energy from fuel to atmosphere. The moderate value of correlation coefficient indicates that under dynamic trends efficiency is more responsive to inputs other than air to fuel ratio. Another point of perlustration is air to fuel ratio is undergoing variations from 18.6 to 20. The scale of these variations is quite small compared to other inputs like fuel flow rate which undergoes between 400 to 600 as shown in the plots for the current interval. This is another major cause that is rendering correlations of all the variables with air to fuel ratio to be very limited.

The variable of steam as stated earlier is the main disturbance agent in whole boiler system, and a little variation in steam can cause all the dynamics to go violent. In fact the dynamic variations in all the variables are outcome of disturbance in steam flow rate as all the variables are somehow dependent on steam flow. The steam flow rate and flue gas temperature are related by correlation coefficient of +0.66. Compared to the steady conditions in first interval this value is decreased indicating that under dynamic conditions both variables are not extremely correlated. The positivity of coefficient however holds because when steam flow has drastically increased after first interval, flue gas temperature has also risen in same fashion. But the correlation coefficient value is signifying the fact that both variables have not followed the same trend i.e. steam flow has undergone oscillations and a general trend of decreasing while flue gas temperature has monotonic increase in the current interval. Moreover this smooth behavior of flue gas temperature is rendering its correlation with all other inputs to be very limited in this interval.

NOx has tried to maintain its correlation with steam flow rate in both conditions as the correlation coefficient has decreased slightly from 0.902 in first interval to 0.752 in this interval. This is because NOx responds to variations in steam flow with same trends in all conditions because of its direct proportional dependence on fuel flow rate which is highly correlated with steam flow rate in both steady and dynamic conditions. The little decrease in correlation coefficient value can be ascribed to the correlation of NOx with air to fuel ratio which is trying to push it slightly in its direction as indicated by their correlation of 0.69.

Efficiency and flue gas temperature have maintained strong negative correlation in both intervals. The correlation of -0.836 in this interval has signified its strong and inverse proportional relation which is also in agreement with the indirect mathematical model used for calculating efficiency.

In both steady and dynamic conditions efficiency is negatively correlated with steam flow rate: in steady state correlation is strong and in dynamic state correlation is moderately strong. In this interval the correlation coefficient of both variables is -0.7090 which is, however, highest (in magnitude) compared to efficiency correlations with other inputs of air to fuel ratio and fuel flow rate. A better analysis of the correlation can be done by looking individually into the local maxima of oscillations of both variables. Corresponding to each local maximum of fuel flow rate efficiency has local minimum which is confirming to their inverse relation. But the general trend of both variables is similar i.e. decreasing. The decreasing behavior of efficiency may be attributed again to flue gas temperature which has continuously increased in this interval hence it is pulling down the efficiency more. That is why a small resemblance between efficiency and flue gas temperature has emerged due to their similar decreasing trend in this interval which is the cause of decrease in their negative correlation.

The correlation between efficiency and NOx has lessened to a value of -0.5261 which is smaller compared to their correlation in first interval. Many factors are responsible for this change but major of them can be highlighted in this analysis. One is the flue gas temperature which has shown a very limited correlation with all the variables and because of strong dependence of efficiency on flue gas temperature, its correlations with all other variables including NOx has been adversely affected. Another factor is efficiency and NOx are coupled with almost all of the inputs in different and complex ways based on their mathematical models of CHAPTER 4 and CHAPTER 5 and the trends in the inputs are not similar especially when comparing air to fuel ratio with other inputs. Another factor is NOx moves majorly in the direction of fuel flow rate while efficiency moves in the direction of flue gas temperature and the flue gas temperature is poorly correlated with fuel flow rate. However despite all the factors discussed above, if we combine the results of both intervals, we can conclude that the supporting factors for correlation between these variables are dominant and that's why the correlation is far from being zero. Also noticeable point is that the negativity of correlation is maintained in both intervals that is signifying the inverse relation between both variables.

6.3 Time Varying Cross Correlation

In Appendix we have extensively discussed how we can calculate time varying cross correlation or cross correlogram of two variables. In this thesis work, we have used a Matlab command to calculate the cross correlogram which uses the same framework highlighted in Appendix. The cross correlogram of input variables i.e. steam flow rate, fuel flow rate and air to fuel ratio is first calculated and plotted in Figure 37. Also, the correlogram have been performed at full length of period i.e. from 0 to 21600 second. From Figure 38 to Figure 40 cross correlogram of NOx, FGT and efficiency have been plotted with all the inputs. Finally cross correlogram of efficiency with FGT and NOx have been presented in Figure 41 and Figure 42 respectively.

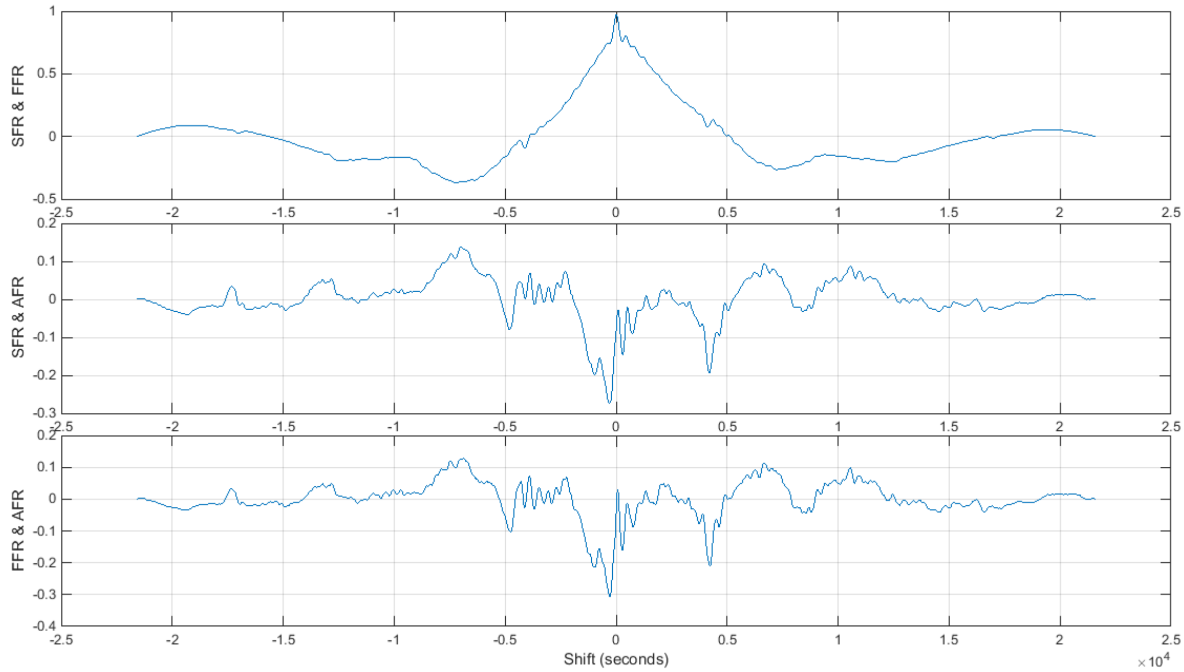

Figure 37 Cross correlogram of all inputs

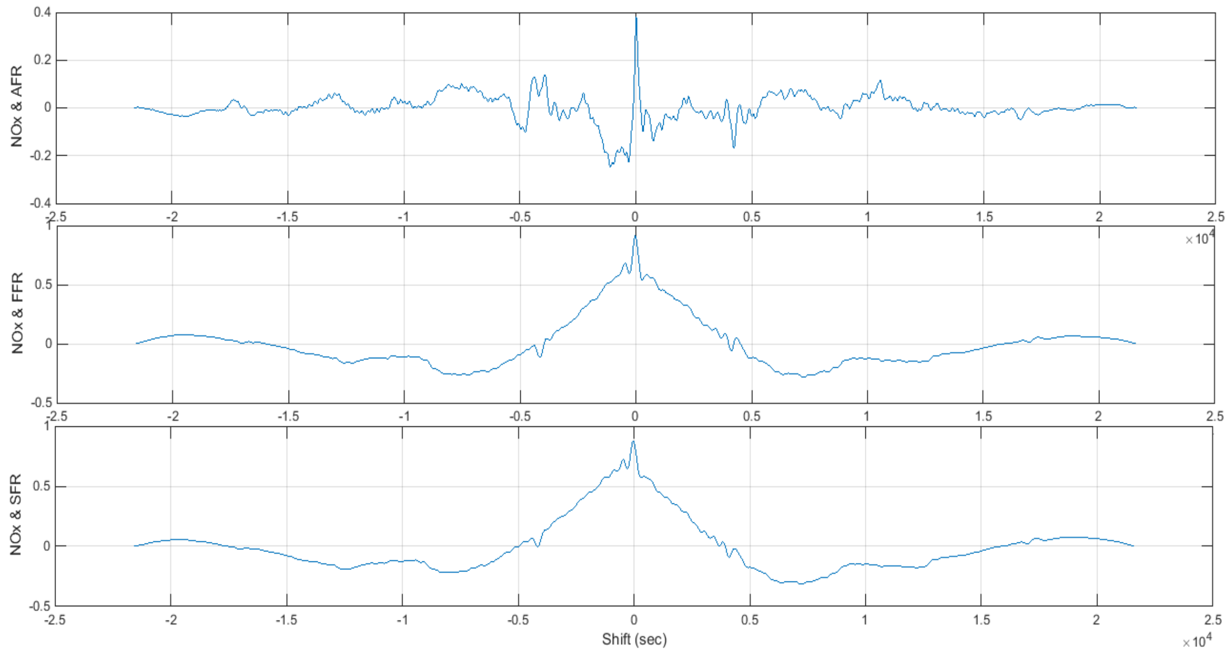

Figure 38 Cross correlogram of NOx with inputs

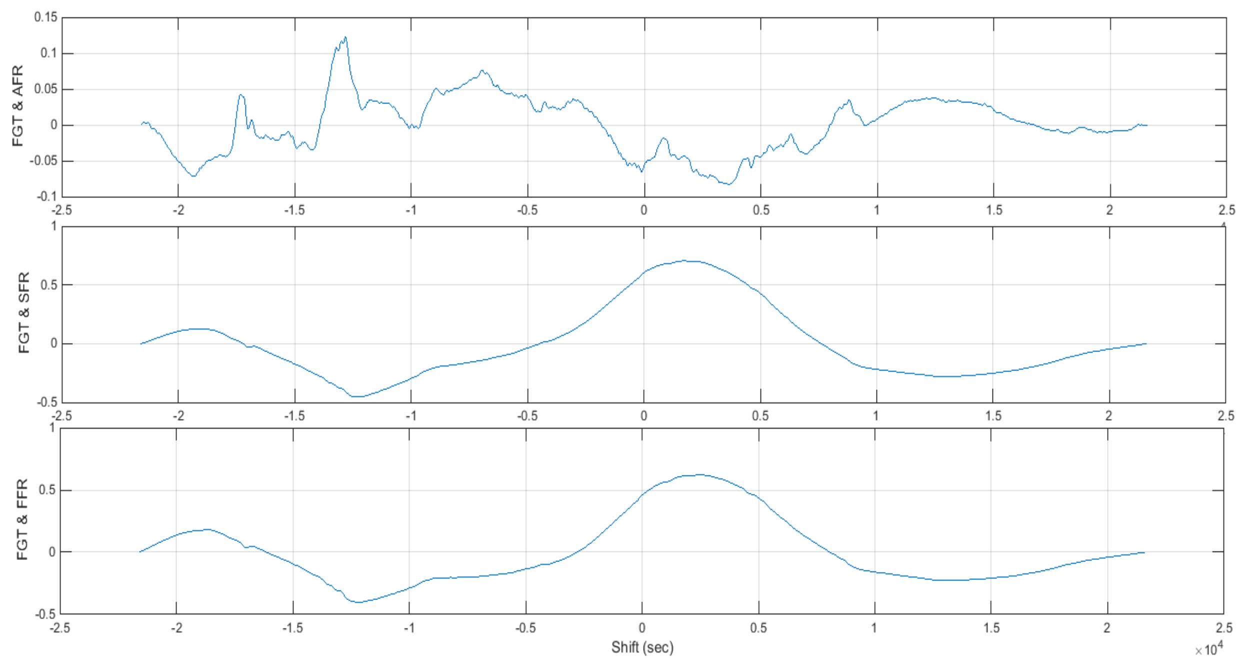

Figure 39 Cross correlogram of FGT with inputs

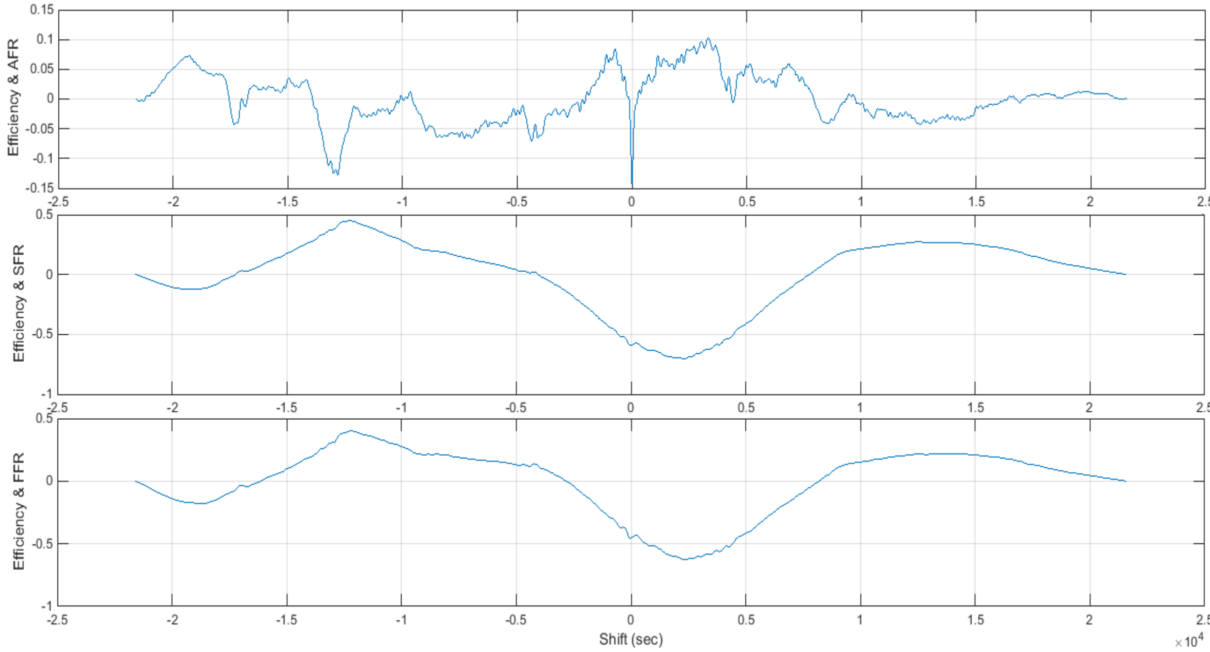

Figure 40 Cross correlogram of Efficiency with inputs

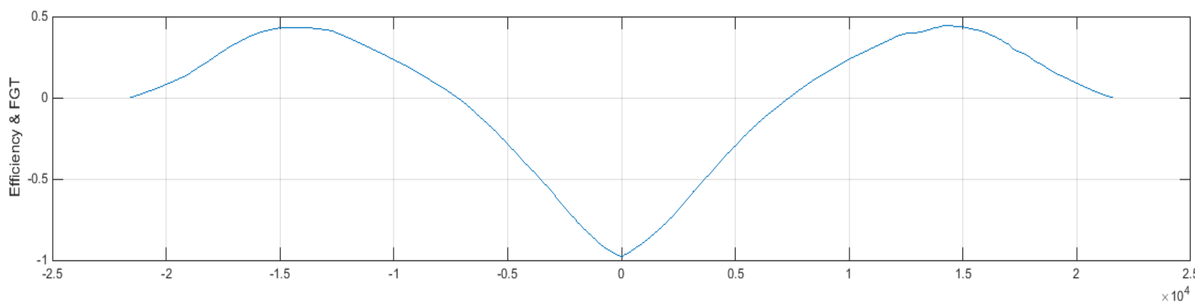

Figure 41 Cross correlogram of Efficiency and FGT

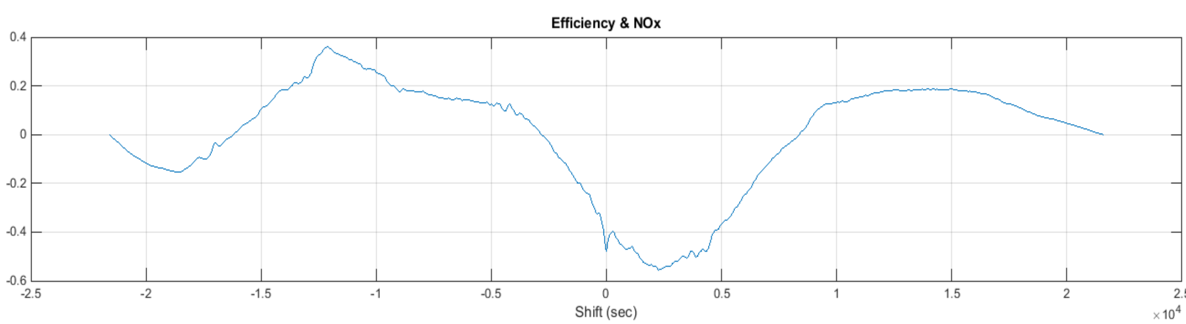

Figure 42 Cross correlogram of efficiency and NOx

6.4 Summary and Conclusion

In this chapter correlation of operational variables have been formed to investigate the influence of variables on each other under dynamic and static environments. From the tabulated results as in Table 6-Table 9, it is evident that the correlation is very distinctive in steady state condition i.e. the correlation is either highly positive or negative or almost zero. The trend however changes under dynamic environment as correlation values are neither extreme nor mild for almost all the variables. This signifies the fact that each variable is correlated with every other variable. In multivariable dynamic systems this correlation is translated as mathematical coupling between the variables which is also existent in boiler system. Furthermore cross correlogram of all the variables have also been plotted to show the time varying correlation between the variables. These plots can be used to determine how dynamic trends in one variable are shifted with respect to other variable. Regarding NOx and efficiency the correlation clearly reveals that both variables are in conflict with each other i.e. both increase and decrease at the same time. This key result highlights the importance of optimization based control system that can accomplish a certain tradeoff between the two by intelligently manipulating the inputs of the system.

CHAPTER 7 BOILER DYNAMIC CONTROL

In this chapter we discuss the control system that is necessary to control the dynamic behavior of boiler. First we highlight the importance of controller by discussing the essential issues of drum level's fluctuation, boiler MIMO system's instability and coupling of variables. Then we go through the controller mathematics by formulating a three term controller by modifying conventional PID controller. The controller is to be integrated with a unified dynamic model capable of modeling efficiency, NOx as well as efficiency. Finally we tune the controller parameters using genetic algorithm to maximize the controller's performance in terms of overshoots and settling times of boilers operational variables. An introductory discussion of genetic algorithm is also presented at the end of this chapter as it has been the core optimization technique of this thesis.

7.1 Necessity of Boiler's Control System

Boiler is one of the most dangerous equipment that is used in process industry due to its high pressures and temperatures. Inherently boiler system is an unstable system as small disturbances can lead the open loop boiler dynamics to go unstable. Hence boiler control is very important and in literature, as highlighted in CHAPTER 2, various control structures have been implemented to accomplish a safe operation of boilers. Specifically the purpose of the control action is to stabilize the boiler system, nullify disturbances in steam (or in other variables) and to achieve set point tracking of all the outputs. The set point tracking is done in order to confine the states to particular values. This is important because output variables may undergo different dynamic variations due to different reasons. This deviation from set points may cause the states to violate physical constraints or cause them to go violent. An efficient controller performs the disturbance rejection and set point tracking in all possible dynamic conditions. A controller's performance is judged by overshoots in both input and out variables as well as the settling times of output variables. Once the control structure has been identified, the controller parameters are tuned in order to optimize the settling times and overshoots in all the variables.

For a class of unstable MIMO systems like boiler, the multi control action is difficult to stabilize and control the states of system as the controllers clash with each other to perform their respective actions. This occurs due to mathematical coupling between the state equations of a systems. It is hence desired to locate the week couplings between the both the input set and the output set of variables. For boiler it is observed that feedwater rate bears a strong mathematical connection with the output level and heating rate with the output pressure so the control circuits are formed based on these strong connections between the input and output variables. With sensible tuning of controller it is possible to achieve weakly decoupled control action for both input output sets. Another issue with the boiler system is its non-minimum phase nature causing shrink swell phenomenon. This is because it is observed that a right hand zero is present in linearized form of boiler mathematical model [8]. Such systems offer hard time to the inputs while responding to the deviation in the outputs from their respective set-points. For simple control techniques, the shrink swell phenomenon becomes very difficult to control especially under fierce dynamic conditions. The steam flow rate is considered as a main disturbance agent and responsible for dynamic variations in all the variables. A change in steam flow cause an immediate effect on pressure which actuates the shrink/swell phenomenon causing a dynamic redistribution of steam water in drum. For example an increase in pressure causes the steam bubbles to shrink thereby lowering the drum level. The level sensor senses the lowering in the level and sends the signal to controller which commands an immediate increase in feedwater rate. The feed water with low enthalpy further imbalances the temperature and pressure of steam water mixture causing more collapse of steam bubbles. This double action misleads the controller which commands more overflow of feed water to counter the drop of level. Meanwhile, the pressure control loop tries to balance the sudden rise in pressure by manipulating the fuel flow causing the temperature and pressure to undergo a fall back to their set points. There is again a redistribution of steam water mixture where steam bubbles start to swell again owing to temperature and pressure falloff. This situation triggers a dramatic rise of level for which the level controller takes the action to slow the input flow. The controller struggles to contain rise and fall of drum level for a considerable amount of time until the level is either settled or completely goes off the limit. The same episode repeats when the pressure is decreased thereby causing steam bubbles to swell. The level controller takes an action by slowing down the input water flow which causing an increase in enthalpy of steam water mixture and level increases dramatically under the double action. The resultant effect of this tussle is immense oscillations of drum level owing to incapable control action. Moreover when the dynamic variations in steam demand are extreme, the resultant imbalance of steam water distribution may cause the level completely to go out of control causing shutdown of boiler. Such inefficacy is usually observed when simple control action like proportional controller or single element PI controller is used to control the boiler operation.

7.2 Control Problem Formulation

Boiler is one of the most dangerous equipment that is used in process industry due to its high pressures and temperatures [69]. Inherently boiler system is an unstable system as small disturbances can lead the open loop boiler dynamics to go violent. Hence boiler control is very important and in literature various control structures have been tried to accomplish a safe operation of boilers. Specifically the purpose of the control action is to stabilize the boiler system, nullify disturbances in steam (or in other variables) and to achieve set point tracking of all the outputs. The set point tracking is done in order to confine the states to particular values. This is important because output variables may undergo different dynamic variations due to different reasons. This deviation from set points may cause the states to violate physical constraints or cause them to go violent. An efficient controller performs the disturbance rejection and set point tracking in all possible dynamic conditions. A controller's performance is judged by overshoots in both input and out variables as well as the settling times of output variables. Once the control structure has been identified, the controller parameters are tuned in order to optimize the settling times and overshoots in all the variables.

For a class of unstable MIMO systems like boiler, the multi control action is difficult to stabilize and control the states of system as the controllers clash with each other to perform their respective actions. This occurs due to mathematical coupling between the state equations of a systems. It is hence desired to locate the week couplings between the both the input set and the output set of variables. For boiler it is observed that feedwater rate bears a strong mathematical connection with the output level and heating rate with the output pressure so the control circuits are formed based on these strong connections between the input and output variables. With sensible tuning of controller it is possible to achieve weakly decoupled control action for both input output sets. Another issue with the boiler system is its non-minimum phase nature causing shrink swell phenomenon. This is because it is observed that a right hand zero is present in linearized form of boiler mathematical model [8]. Such systems offer hard time to the inputs while responding to the deviation in the outputs from their respective set-points. For simple control techniques, the shrink swell phenomenon becomes very difficult to control especially under fierce dynamic conditions. The steam flow rate is considered as a main disturbance agent and responsible for dynamic variations in all the variables. A change in steam flow cause an immediate effect on pressure which actuates the shrink/swell phenomenon causing a dynamic redistribution of steam water in drum. For example an increase in pressure causes the steam bubbles to shrink thereby lowering the drum level. The level sensor senses the lowering in the level and sends the signal to controller which commands an immediate increase in feedwater rate. The feed water with low enthalpy further imbalances the temperature and pressure of steam water mixture causing more collapse of steam bubbles. This double action misleads the controller which commands more overflow of feed water to counter the drop of level. Meanwhile, the pressure control loop tries to balance the sudden rise in pressure by manipulating the fuel flow causing the temperature and pressure to undergo a fall back to their set points. There is again a redistribution of steam water mixture where steam bubbles start to swell again owing to temperature and pressure falloff. This situation triggers a dramatic rise of level for which the level controller takes the action to slow the input flow. The controller struggles to contain rise and fall of drum level for a considerable amount of time until the level is either settled or completely goes off the limit. The same episode repeats when the pressure is decreased thereby causing steam bubbles to swell. The level controller takes an action by slowing down the input water flow which causing an increase in enthalpy of steam water mixture and level increases dramatically under the double action. The resultant effect of this tussle is humungous oscillations of drum level owing to uncompetitive control action. Moreover when the dynamic variations in steam demand are extreme, the resultant imbalance of steam water distribution may cause the level completely out of control causing shutdown of boiler. Such inefficacy is usually observed when simple control action like proportional controller or single element PI controller is used to control the boiler operation.

So far PIDs are considered to be the most capable controllers for controlling boiler systems and they are vastly employed in the process industry for many equipment. The reason being that the modern control schemes implemented using sophisticated control techniques are usually of high order. They require complex hardware implementation and they are not as flexible as PID controllers with respect to online tuning ability. On the other hand PID control has a simple structure, a straight forward hardware implementation as well as a convenient real-time tuning. The control structure of PID is based on a feedback control loop in which the output is measured and a difference of set point and measured output is fedback as an input. Three control functions are employed in this respect based on the requirement: the proportional control (P), the proportional plus integral control (PI) and proportional-integral plus derivative control (PID). Each function penalizes the error by multiplication of a gain and produces a necessary control action to compensate for the error between set point and measured. The proportional controller is the simplest and it simply tries to reduce the error between the output and set point. The PI control action incorporates an additional integral action to remove steady state error. The PID adds a derivative action to PI in order to achieve quick response by predicting the error between outputs and set points.

For drum level control, the level is maintained using a three element controller. The structure of this controller is same as PI controller with the additional feedforward term of steam flow rate as shown in Figure 44. This is essential because it helps the controller to anticipate the variations in steam flow rate and provide the necessary counter variations in feed water rate. This control structure is immensely robust to steam disturbance because the mass balance of steam vs feedwater is achieved which counteracts the dominant portion of steam disturbance. The rest of the disturbance comprises only the weak portion of disturbance which is tackled out easily by PI control action. The effective disturbance counteraction immensely reduces the shrink/swell phenomenon causing a smooth and quick settling of level. Moreover it is observed that the derivative action is no longer necessary for water level control as the PI alone suffices to achieve the desired control in this form of three element control loop. The combination of feedforward and feedback performs very satisfactorily while maintaining the drum level at the desired point under wide range of dynamic conditions. The inner control loop dynamics of feedwater valve is very quick and hence for computational convenience we ignore its behavior as it has negligible interference with higher control loops. Given that the 'L' represents the drum level the mathematical formulation of level control loop is as following:

$$e_L(t) = L_d - L(t)$$

$$q_f(t) = q_s(t) + K_{pf} e_L(t) + K_{if} \int_0^t e_L\,(t) dt \tag{7.1}$$

Where 'q_s' is the feedforward term of steam flow rate, 'q_f' is the feed water rate and 'L_d' is the desired drum level.

Similarly the pressure control is implemented via manipulating fuel flow rate with full structure of PID as shown in Figure 44. The fuel flow rate is adjusted by controlling the speed of fuel feeders based on the error between the measured pressure and its set-point. Meanwhile a ratio control is in effect which ensures that air and fuel are injected according to a prescribed value of air to fuel ratio. This is done via controlling the speed of air supply fan. Mathematically the control is implemented as:

$$e_p(t) = P_d - P(t) \tag{7.2}$$

$$\dot{m}_f(t) = K_{pq} e_p(t) + K_{iq} \int_0^t e_p\,(t) dt + K_{dq} \frac{de_p(t)}{dt} \tag{7.3}$$

Where '$\dot{m}_f$' is the fuel flow rate, 'P' is the drum pressure and 'P_d' is the desired drum pressure.

7.3 Augmented Model of Boiler System

The equations (3.1)-(3.4), (4.10) and (5.54) are combined to give a composite model for boiler system as following:

$$\begin{bmatrix} a_{11} & a_{12} & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 & 0 \\ 0 & a_{32} & a_{33} & 0 & 0 \\ 0 & a_{42} & a_{43} & a_{44} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} dV_{wt}/dt \\ dp/dt \\ dx/dt \\ dV_{sd}/dt \\ d[NO]/dt \end{bmatrix} = \begin{bmatrix} \dot{m}_{fw} - \dot{m}_s \\ Q + \dot{m}_{fw} h_{fw} - \dot{m}_s h_s \\ Q - x h_{fg} \dot{m}_{\mathrm{dc}} \\ \rho_s / T_d \, (V_{\mathrm{sd}}^o - V_{\mathrm{sd}}) + (h_{fw} - h_w) \, \dot{m}_{fw} / h_{fg} \\ \alpha_0 \dot{m}_f^r (1 + \alpha_1 \dfrac{\xi - 55}{90})(\dfrac{1}{\lambda_{st}} - \dfrac{1}{\lambda})^{\frac{1}{2}} - [NO] \end{bmatrix} \tag{7.4}$$

Where, the heating rate 'Q' and FFR '$\dot{m}_f$' are related by following equation:

$$\dot{m}_f = \frac{Q}{GCV \times \eta(t)} \tag{7.5}$$

The GCV represents gross calorific value of fuel. For the current case of boiler the fuel used is natural gas and its GCV has been calculated to be 12982.96 kCal/kg.

$$\eta(t) = \eta(\lambda(t)\,,\, \dot{m}_f, x) \tag{7.6}$$

The pressure control scheme is shown in Figure 43 which shows that the heating rate is determined by both dynamics of efficiency as well as pressure.

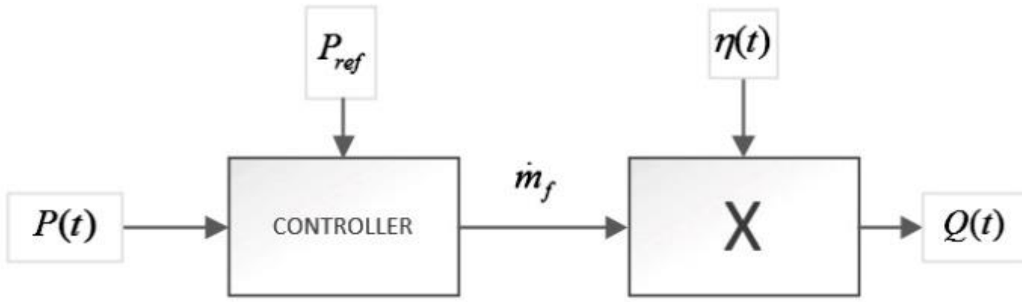

Figure 43 Pressure control block diagram

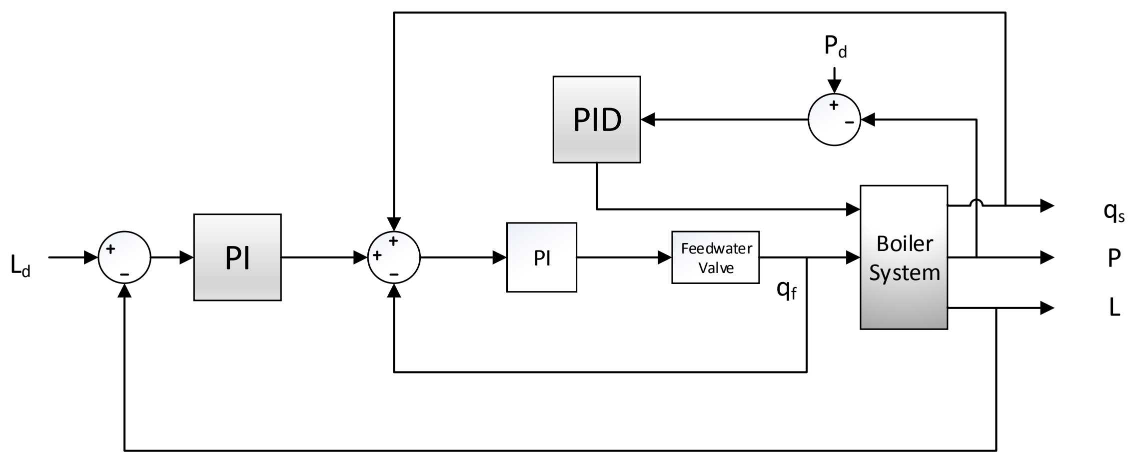

Figure 44 Control loops of boiler system

7.4 Control loop tuning

The control equations (7.1) and (7.3) cannot be implemented by some random values of proportional, integral and derivative gains. Rather they are selected to maximize the boilers performance by confining the feed rate, drum level and pressure within safe limit. For the current case we use the same strategy employed in [20] to achieve most favorable gains while optimizing the variables of feedwater rate, heating rate, drum level and drum pressure. Five objective functions are formed in this respect to acquire the best possible gains of pressure control loop and level control loop. The objective functions penalize the overshoots and deviations from the set points for the concerned input and output variables.

$$J_1 = \max_t \{ \text{abs}(\frac{q_f(t) - q_{fs}}{q_{fs}}) \} \tag{7.7}$$

$$J_2 = \max_t \{\text{abs} \left(\frac{Q(t)-Q_s}{Q_s}\right) \} \tag{7.8}$$

$$J_3 = \max_t \{\text{abs}(\frac{L(t) - L_d}{L_d})\} + \alpha_1 \sum_{t2}^{T} (\frac{L(t) - L_d}{L_d})^2 \tag{7.9}$$

$$J_4 = \max_t \{abs(\frac{P(t) - P_d}{P_d})\} + \alpha_2 \sum_{t2}^{T} (\frac{P(t) - P_d}{P_d})^2 \tag{7.10}$$

$$J_5 = \frac{1}{D_s} \tag{7.11}$$

$$J = J_i \sum_{i=1}^{5} w_i \tag{7.12}$$

Where D_s refers to percentage change in steam flow rate and α_i's and w_i's are penalizing factors. Other variables in the above equation are named as in list of abbreviations given at the start of this report. A ramp steam disturbance is applied with the swing rate of 41.6% as in [20] and the combined cost function 'J' is minimized with respect to the PID gains of pressure and level control loop. Different search algorithms can be implemented to minimize the cost function ‘J’. For our work we use Genetic Algorithm (GA) as done in [20]. A brief overview of GA is given following as we have used GA two times: for searching PID gains and for real time optimization of efficiency and NOx as discussed in CHAPTER 8.

7.5 Genetic Algorithm

GA’s are primarily used for finding an optimal solution for a given optimization problem using the idea of natural selection system and survival of the fittest individual. The most appealing advantage of GA is that it is able to locate multiple local optima even in the presence of noisy cost function. The basic operation of this algorithm involves specifying a cost function and a range of search space for the input variables. The search variables are symbolized as *chromosomes* and their combined set as *individual* which evolve through generations by reproduction from mating between the individual solutions. Each generation has a definite population of all the individuals and each individual has an attached evaluation index in the form of cost function value. The best individual leads the population and as the generation evolves the quality of individuals improves. The evolution of generation takes place at each iteration through three phenomena: selection, crossover and mutation. In selection the algorithm picks some individuals at random to bear next generation’s children. In crossover the selected individuals are mated using a specified crossover function to create offspring. The cross over is the dominant operation of GA and it leads to the betterment of elite individuals by suppressing the weaker ones. Mutation is applied with very low probability with the aim of altering the chromosomes of individual. It creates new individuals which expand the search operation for finding the best solution. All these operations contribute in progressive evolution of population and as the evolution proceeds the elite individuals converge to best possible solution. The fittest solution achieved after successive generations optimizes the controller in terms of performance criteria identified in cost function.

For control loop tuning, we use the built-in Matlab tool box of GA with same configuration of parameters as in [20]. The input variables to be searched are K_{pf}, K_{if}, K_{pq}, K_{iq} and K_{dq} and are given in Table 10.

Table 10 GA based optimal PID gains of control circuits

	Drum Level		**Drum Pressure**		
PID Gains	K_{pf}	K_{if}	K_{pq}	K_{iq}	K_{dq}
	159.497	0.092	0.0789	0.0198	0.0036

7.6 Summary

In this chapter a control scheme has been presented to control the dynamic behavior of boiler system. In this respect two control loops have been considered as in [20]; one loop regulates the fluctuations in drum level while other loop maintains the pressure at desired set point. The inputs used to control both variables are feedwater rate and fuel flow rate. To optimize the control loop parameters, genetic algorithm has been employed to enhance the system's performance by penalizing the overshoots and settling time of operational variables. The efficiency formulation from CHAPTER 5 as well as NOx formulation from CHAPTER 4 have been integrated with boiler's process model to formulate a unified dynamic model of boiler. In the subsequent chapters, we will simulate and discuss the dynamic response of the augmented model and control scheme as formulated in this chapter.

CHAPTER 8 EFFICIENCY AND NOx DYNAMIC OPTIMIZATION

In this chapter we carry out the optimization of NOx and efficiency under dynamic operating conditions. The optimization algorithm is implemented with boiler dynamic process model accompanied with control scheme as discussed in CHAPTER 7. First we discuss the requirement of optimization in the aura of contemporary issues of operational costs and pollution hazards associated with the boiler. Then we reproduce some essential literature results by simulating the dynamic response of variables without optimization using methodology of CHAPTER 7. Finally we discuss the optimization procedure as well as optimization results by simulating the unified dynamic model of efficiency, NOx and boiler's process model.

8.1 The Need of Optimization

Fuel economy and reduced emissions and are the major concerns among the serious issues of boiler operation. For the past few decades, efforts have been directed to solve the problem of costly fuel consumption alongside harmful emissions. Researchers have been trying to tackle these issues either individually or compositely. On one hand strategies are being made to enhance the efficiency while on the other hand a very hardcore research is being done to develop technologies to reduce emissions. The expense control of boiler is a daunting challenge for a process industry as the major portion of the bill comes from fuel consumption. With the passage of time the fuel economy degenerates due to poor maintenance, wear and tear and inferior combustion control. Efficient combustion control is such cardinal that a small improvement in efficiency improvement can translate into savings of millions per annum. Moreover finite natural resources must be utilized in extreme economic way as humanistic duty to prolong their utility. The other side of the coin is fuel based energy production is not a clean source of energy. Especially emission of nitric oxides (NOx) are dangerous in adversely affecting the atmosphere due to their capabilities of ozone depletion, acid rain and smog formation. For the past many decades research efforts are being strictly carried out to develop technologies and efficient combustion control to reduce NOx emissions. Strict environmental regulations are being imposed in several parts of the worlds to tackle the issue of NOx problem. Researchers seek out solution of the problem by either primary measures or secondary measures. Primary measures are based upon limiting the formation of NOx in combustion phase whereas secondary measures rely on reducing NOx after its formation. Secondary measures involve considerable human and material resources as they rely on design and technology based modifications. In terms of capital primary measures have considerable edge over secondary measures. One of the most economical primary measure is to minimize NOx by manipulating operational variables of boiler intelligently that are involved in the production of NOx. This can be carried out by using analytical model that relates operational variables of combustion process to NOx formation process. But based on operational variables of boiler NOx and efficiency poses a mutual conflict i.e. when the operational variables are regulated to contain NOx, the efficiency starts decreasing. Hence this dilemma is very confusing and strong mathematical formulation is required to fully address the issue or to seek out an analytical tradeoff between the two important quantities

The operational variables that are involved in optimizing efficiency and NOx are same inputs of boiler that affect its dynamic process on real time basis. Hence the optimization process must be augmented with real time control process and combined mathematical solution should be sought out that is fitting for both control and optimization. For this mathematical modeling of boiler dynamics along with efficiency and NOx must be brought together.

8.2 Unoptimized AFR Simulations

We start from the results of [61], [20] and [37] to have a composite summary of concerned literature results. All these works including ours are based on a commonly acquired data that comes from an industrial boiler installed in eastern province in Saudi Arabia. It is a water tube boiler that uses natural gas as fuel input. The data contains 21600 samples of SFR with sampling rate of 1 sec. We use the Astrom's model of boiler [8] to simulate the behavior of all the other variables. The results of that are validated against experimental data and extensively discussed in [61] and [20] but using our PID gains we simulate again the input output data set as shown in the Figure 45 and Figure 46 to provide a modest overview of available results in the literatures. It is apparent in the plots that the all variables have two distinct behaviors: one is the non-dynamic with very little variations and hence it can be regarded as steady state behavior. This behavior is identifiable in interval [0,12500s]. Second is the dynamic which shows violent variations as evident in the interval [12500s, 21600s]. The dynamic trends in the boiler variables are triggered by steam which is considered as main disturbance agent in boiler system. Inspecting the boiler model as in equation (7.4) we observe that the steam variable is appearing in the input channel hence a little variation in steam cause variations in all the states of boiler system. In fact the dynamic variations in all the variables are outcome of disturbance in steam flow rate as all the variables are somehow mathematically dependent on steam flow. The oscillatory behavior of variables is because of control action that is pushing and pulling the variables in order to stabilize them at their respective set points against the action of disturbance. It is evident from the plot that all variables have been stabilized efficiently by the controller in response to upset in steam variable. The level variations are almost confined within ± 1cm whereas pressure variations are contained within ± 1 kPa. The feed water rate mostly follows the trend of steam flow rate. The nominal difference between feed water rate and steam flow rate is caused by PI control action described in equation (7.1). The heating rate and fuel flow rate also follow the trend of steam flow rate this is because the variable heating rate confronts the steam disturbance in the input channel as evident in equation (7.4). Hence the steam plays an additive disturbance effect which is compensated by heating rate in order to stabilize the drum pressure. All the input and output variables are obeying the physical constraints as well as a stable behavior in terms of disturbance rejection.

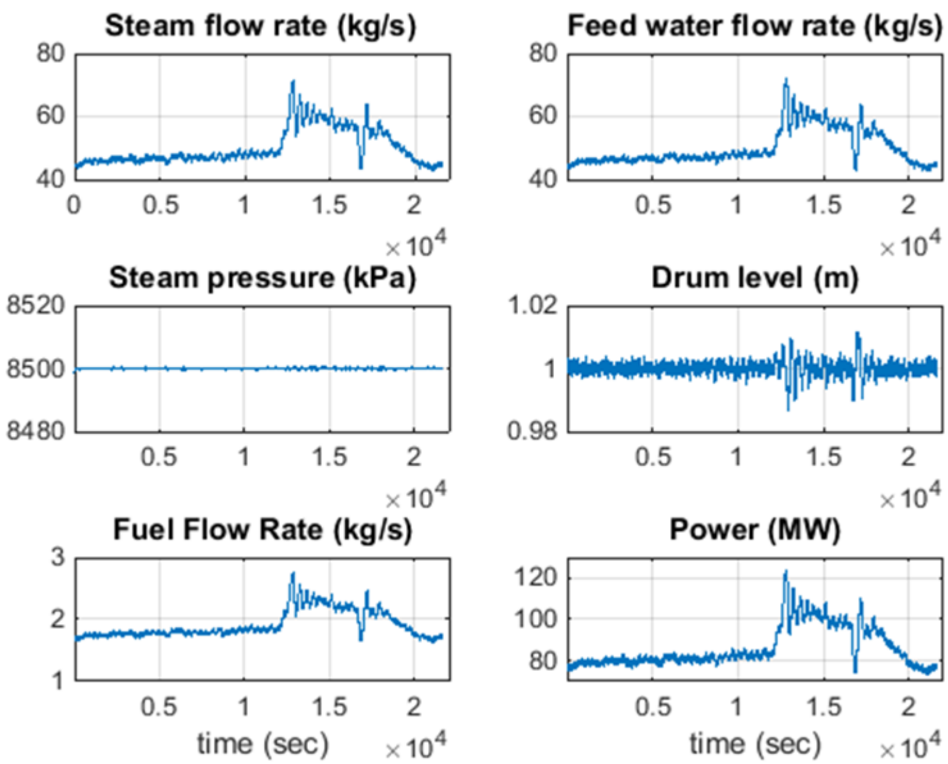

Figure 45 Boiler variable's response with experimental AFR

The AFR for this simulation is un-optimized and comes directly from experimental data as shown in the Figure 46. Based on this AFR, the variables of NOx and efficiency are calculated using equation (7.4) and are plotted in the Figure 46. The dynamics of efficiency as shown in the plot are determined by second order model and have been extensively discussed in CHAPTER 5 using the same experimental data we use for this work. The dynamics of NOx are dependent on both FFR and AFR. As there is no regulatory control used for NOx hence it comes as high as 180 ppm essentially violating the constraint of 100 ppm under current dynamic conditions.

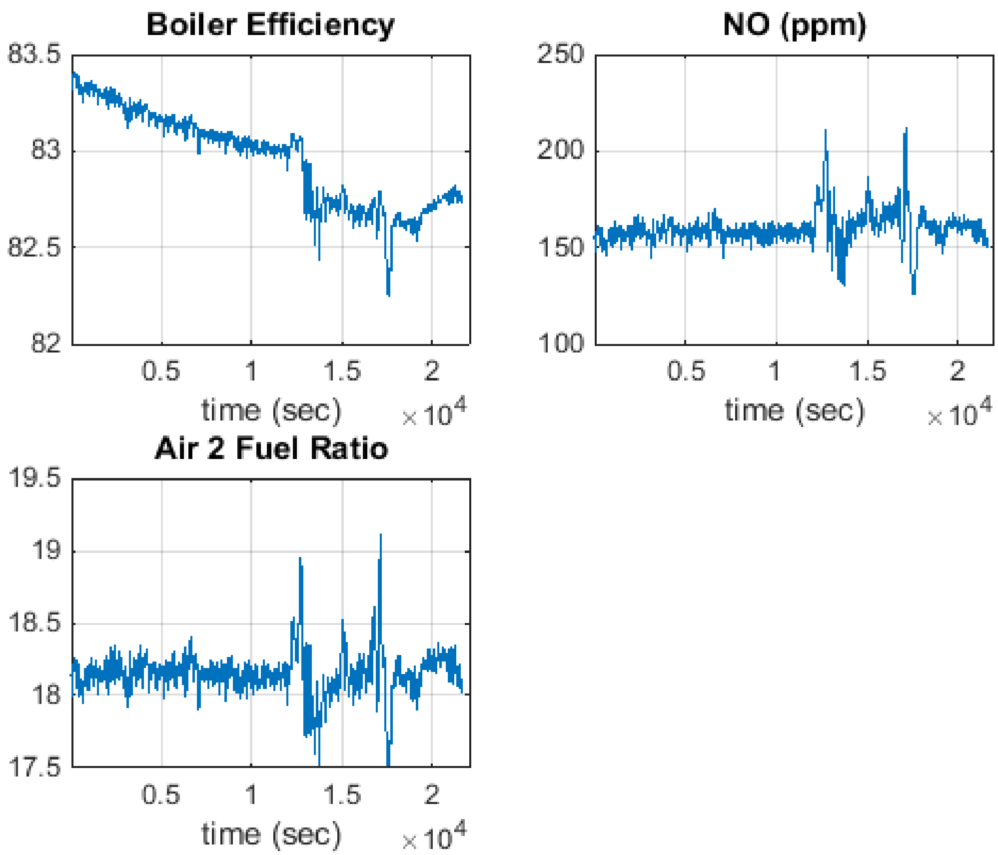

Figure 46 Efficiency and NOx response with experimental AFR

8.3 Optimization Based on AFR and Simulations

The modeling equations of NOx and efficiency can be used to achieve tradeoff between both variables by intelligently manipulating the available inputs. Inspecting the equation (7.4), it is noticeable that both NOx and efficiency depends on two input variables: FFR and AFR. For the type of control circuitry we have used, the FFR is fully dedicated to regulate the pressure and hence it cannot take part in optimization of NOx vs efficiency.

However the dynamic variations of FFR certainly affect the behavior of NOx and efficiency because of mathematical nexus between these two variables and FFR. This is practically very intuitive due to the fact that thermal NOx is highly correlated with the temperature of combustion chamber which in turn is proportional to the FFR. Efficiency is also affected by dynamic variations of FFR. Particularly at high loads when FFR is very high the losses as mentioned in CHAPTER 5 are high as well leading to reduced efficiency. Hence in normal operation of boiler when steam exhibits fluctuations due to change in demand, the variables of NOx and efficiency are consequently affected owing to the FFR-Pressure control element in the process.

With the input of AFR, both NOx and efficiency exhibit a similar trend i.e. both rise with increasing AFR from stoichiometric point, after certain and distinct values of AFR both decrease. The availability of NOx at stoichiometric AFR is practically zero. This is because no free oxygen radicals are available as all the air is used up for combustion of fuel. The NOx concentration begin to grow as AFR is increased beyond AFR_{st}. Hence a highest point of NOx curve is observed at some lean air fuel mixture after which a decreasing trend is observed. This is because the concentration ceases to rise while on the other hand more supply of air dilutes the flue gas mixture. Hence all the constituents of flue gas including NOx get to decrease with more increase in air supply. This behavior is very well captured by Li and Thompson's model [38]. Similarly the efficiency also has an optimum point at AFR slightly greater than AFR_{st}. In terms of equivalence ratio we have an optimum range from 1.05 to 1.2 depending upon the fuel used. Increasing and decreasing the equivalence ratio from this point decreases the efficiency. Under fuel rich conditions when AFR is too low, it is observed that carbon monoxide production is very high causing a decreasing trend for efficiency against decreasing AFR. This occurs because oxygen content is too low to form carbon dioxide or convert carbon monoxide to carbon dioxide. Also the temperature is too low to execute full oxidation of carbon monoxide. Even at stoichiometric amount of air supplied leads to improper mixing of oxygen and fuel consequently producing carbon monoxide. To avoid that more air is supplied than theoretical air which raises the flame temperature as well as proper mixing of oxygen and fuel both leading decreased carbon monoxide production rate. In air rich conditions we have again low efficiency because the flue gas content gets heavier with more supply of air ensuing in more energy loss from flue gas. This behavior is exhibited by equations (5.46) to (5.51) and have been fairly elaborated in CHAPTER 5. Hence for maximizing efficiency a balance is sought between wasting energy through air rich and fuel rich supply.

Mathematically we can formulate the optimization problem of NOx and efficiency using the equation (7.4) to (7.6). The first step is to design an objective function that penalizes high values of NOx and low values of efficiency. For this we use simple quadratic form of objective function as following:

$$J_\lambda = w_1(\eta - \eta_{max})^2 + w_2(NO - NO_{min})^2 \tag{8.1}$$

Where w_1 and w_2 are the penalizing factors for efficiency and NOx. For minimizing NOx we try to reduce it as low as $NO_{min} = 40$ppm. With the aim of maximizing the efficiency, η_{max} is set at 100. To get a general overview of optimization we use an average values of FFR and flue gas temperature and use the equations (4.10) and (7.6) in steady state to plot the J_λ for different values of equivalence ratio ϕ. Two different choices of penalizing factors w_1 and w_2 are used and the plot is as shown in Figure 47:

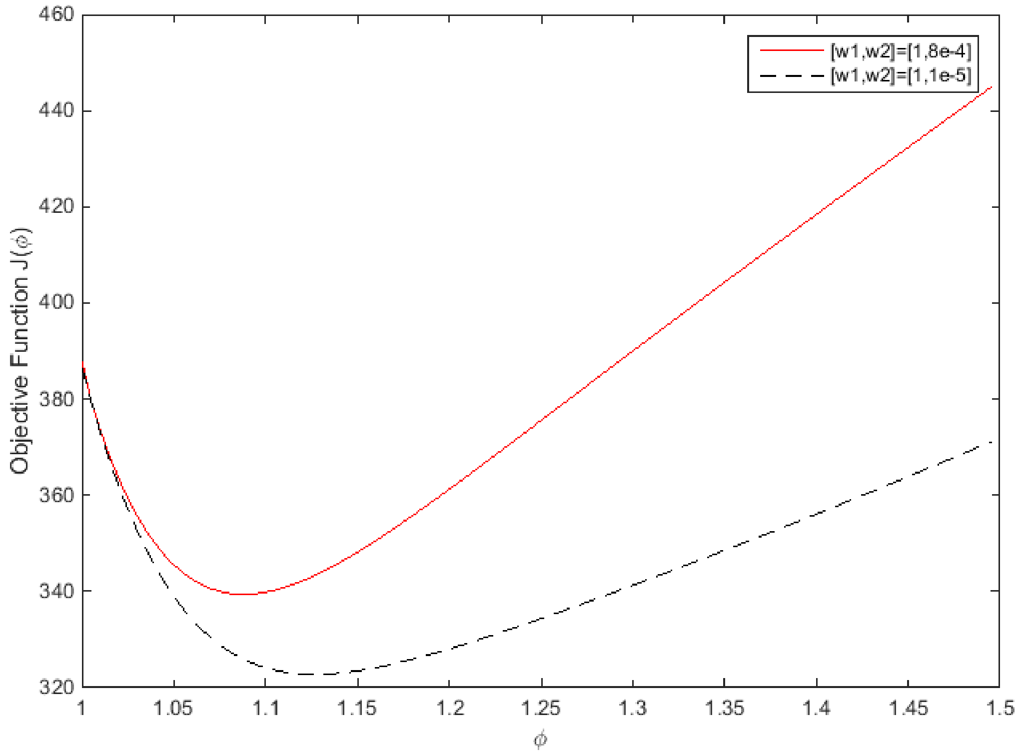

Figure 47 Plot of objective function against equivalence ratio

It is evident from the plot that minimum of objective function is subject to penalizing factors w_1 and w_2 i.e. the minimum point is shifted with different values of w_1 and w_2. We can choose high w_1 compared to w_2 to penalize efficiency more and maximize it at the cost of high NOx or we can do this otherwise. However it depends on the need of hour which variable to be optimized and which to be not. Another noteworthy point is that when the cost is minimized for different FFR's the minimum point certainly shifts again as both efficiency and NOx are correlated with FFR. Hence under dynamic conditions the AFR_{min} that corresponds to the minimum point varies dynamically under the action of steam disturbance and the imposed cost function minimization. Keeping that in mind we extend the methodology for time varying conditions by searching for AFR in such a way that the objective function in equation (8.1) is minimum with respect to AFR 'λ'. We implement this optimization algorithm online i.e. at each time step of simulation we minimize J_λ with respect to AFR and uses the corresponding AFR to be used in current time step. The state space model (7.4) is discretized using Euler's method and simulated using the same time step of 1 sec. Total time steps are based on the amount of SFR data which is 21600 samples with 1 sec of time step. For search algorithm we employ genetic algorithm again under the constraints of AFR =[AFR_{st}, 1.2AFR_{st}]. The population size is 500, number of generations are 5, mutation probability is 0.001, and crossover probability used is 0.9.

We consider three cases based on our preference regarding whether to maximize efficiency or minimize NOx or achieve a tradeoff between the two:

Case 1: w_1=1, w_2=0

Case 2: w_1=0, w_2=1

Case 3: w_1=1, w_2=0.005

All the plots corresponding to these cases are presented in Figure 48 to Figure 53 while Table 11 shows the average values of NOx and efficiency corresponding to each case. The weighting values determine the weightage that is given to each quantity. For example case 1 gives 100% preference to efficiency as compared to NOx. This means that the optimizing algorithm is going to bring out that trajectory of AFR for which the efficiency remains closed to its maximum value 100 at the expense of high NOx. The result of that is shown in Figure 49. The average efficiency is calculated to be 82.92%. This is the highest efficiency that the current algorithm can afford based on the input variable of AFR under current dynamic variations of steam variable. This is because some losses that contribute in lowering the efficiency are inevitable like loss due to evaporation of moisture in fuel and loss due to radiation and convection. Moreover the efficiency modeling equations (7.4)-(7.6) show that other losses cannot be made zero just on the basis of controlling AFR as there are many other contributing factors besides AFR. The plot also shows that the dynamic trends of efficiency is highly correlated with AFR. The NOx plot on the other hand shows high correlation with FFR i.e. NOx highly follows the trends of fuel flow rate as evident from the Figure 49. As stated earlier FFR is entirely dedicated to regulate the drum pressure hence as FFR varies in response to steam variations the NOx is varying in the same fashion for the case 1. It is also evident that NOx is extremely sacrificed for efficiency in this case as at each instant it is violating the NOx limit of 100 ppm. The average value of NOx for this case is 196ppm while the maximum overshoot it undergoes is 215ppm.

The efficiency for case 2 reduces by almost 1% as compared to case 1 while NOx shows a significant improvement from an average 196 ppm to 40 ppm. This shows that modelling equations have substantial leverage on NOx as compared to efficiency when the optimizer is manipulating only AFR. Considering NOx, the algorithm has performed very well as it has almost regulated NOx to the prescribed NO_{min} far away from the upper limit of 100 ppm. The AFR has gone quite dynamic as compared to case 1 while efficiency has shown the same trends. It is also evident from cases 1 and 2 that both NOx and efficiency goes in same direction i.e. both either decrease simultaneously or increase simultaneously.

The case 3 gains gives an optimal tradeoff between both variables where both are appearing in an acceptable ranges. The average efficiency comes to be 82.31% while average NOx is 91.74% which are in between the corresponding values of case 1 and 2. The dynamic trends of efficiency are same as in case 1 and 2 while dynamic variations of AFR appear to be inverse of steam flow rate as evident from Figure 53. Despite the vigorous fluctuations NOx has remained satisfactorily within regulatory level of 100 ppm under current behavior of steam disturbance. Fierce dynamic conditions with high swing rates may cause NOx to violate the limit but with the optimization the average behavior of NOx will certainly remain within safe bounds for this case. This case signifies the importance of a compromise between both variables where neither of the two is maximum or minimum.

The case 1 and 2 are just for demonstration of model extent and are discredited for practical implementation. Violation of the limits of emissions is not just illegal but also unethical and inhuman. With the growing abundance of fuel based machinery, the emissions have not just become a concern but a threat with their far reaching consequences in terms of health diseases and ozone depletion. Hence regulatory authorities are getting stricter with this issue and the imposed upper limits for the emissions are being brought down further as the time is passing. In contrast to that the cost of operating plant mainly comes from the fuel consumption where the fuel bill runs with the figure of billion dollars annually. Hence the choice of operating the boiler at low efficiency is also out of question. In this scenario the best strategy is to achieve a tradeoff between NOx and efficiency. Hence for normal operation of boiler case 3 can be regarded as the best way to satisfy the demand of high boiler performance and low NOx emission by employing the current optimization technique.

Another noteworthy point is that the PID controller is robust enough to absorb the variations of efficiency and keeping all the variables under control. This is also because the dynamic variations of efficiency are confined within 1% bound and hence are easily nullified by the control action. The output variables of boiler i.e. pressure and Level have retained almost the same behavior as evident in Figure 46, Figure 48, Figure 50, and Figure 52. Apart from little noisy fluctuations, pressure is almost stable at 8500 kPa for all the cases. Feedwater rate almost follows the trends of steam flow rate as discussed earlier. Drum level oscillates within $\pm$1cm bound. Power and FFR are also similar for all the cases and are purely under the satisfactory limits.

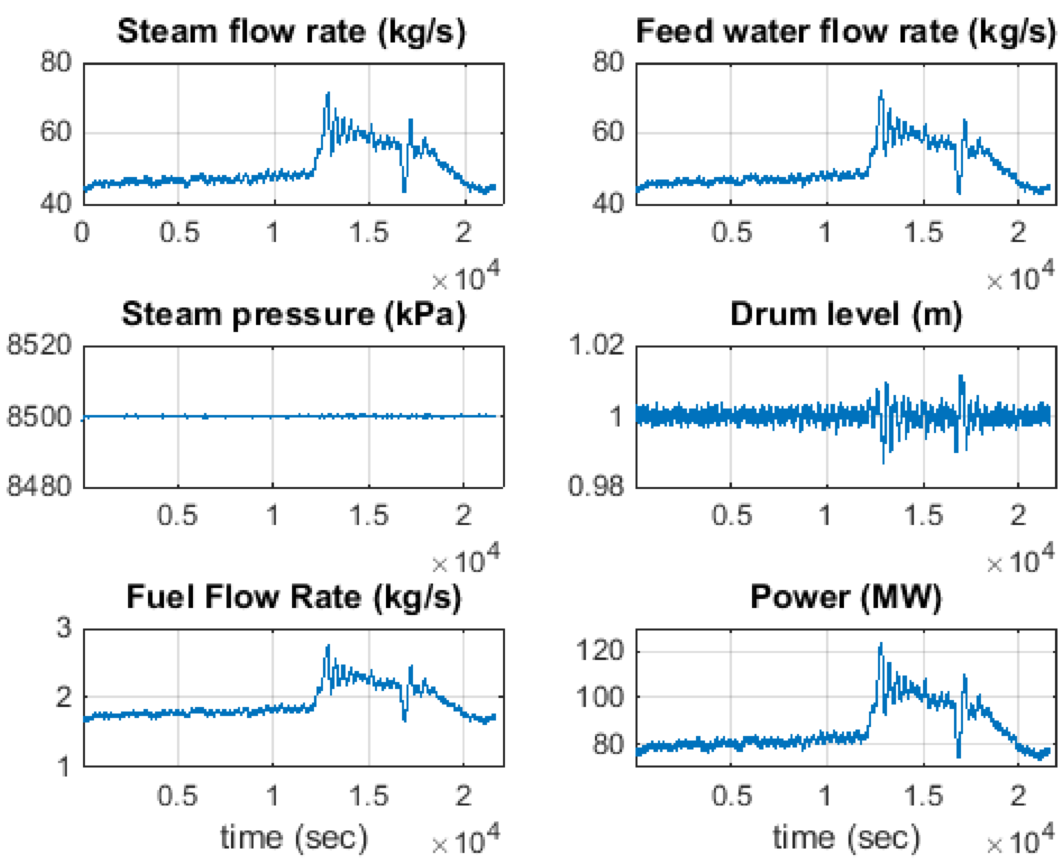

Figure 48 Boiler variable's response with optimized AFR of case 1

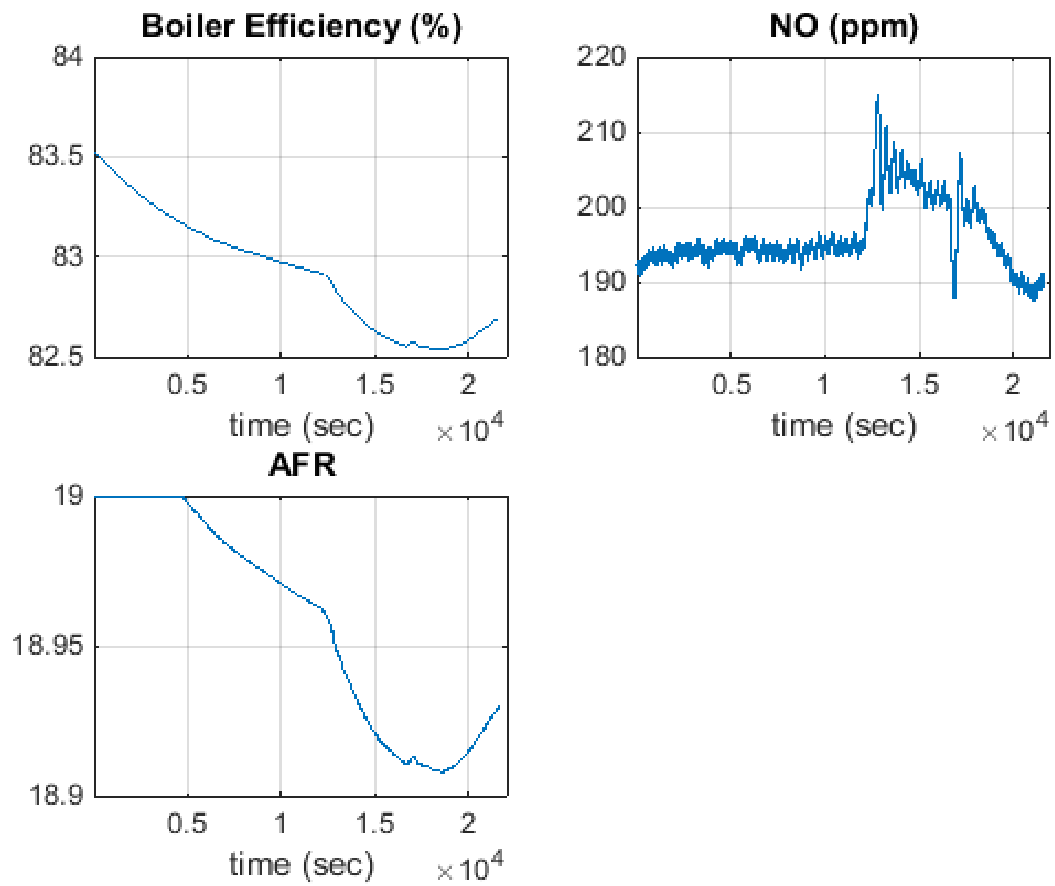

Figure 49 Efficiency and NOx response with optimized AFR of case 1

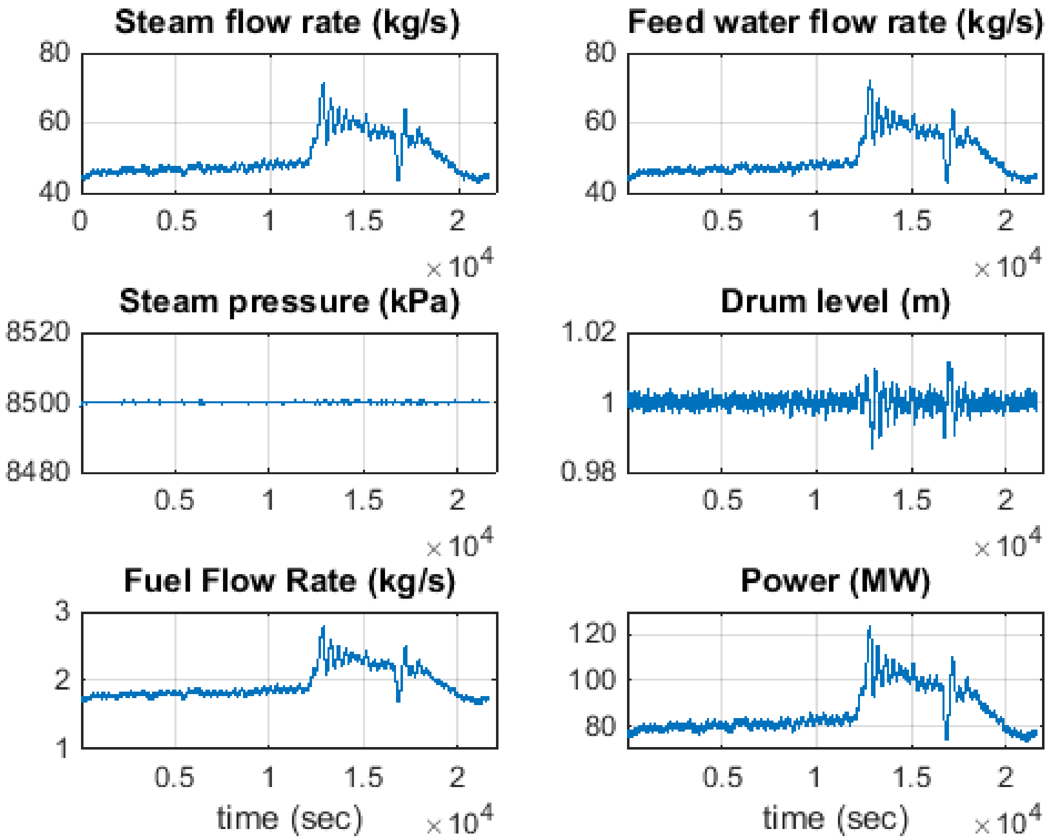

Figure 50 Boiler variable's response with optimized AFR of case 2

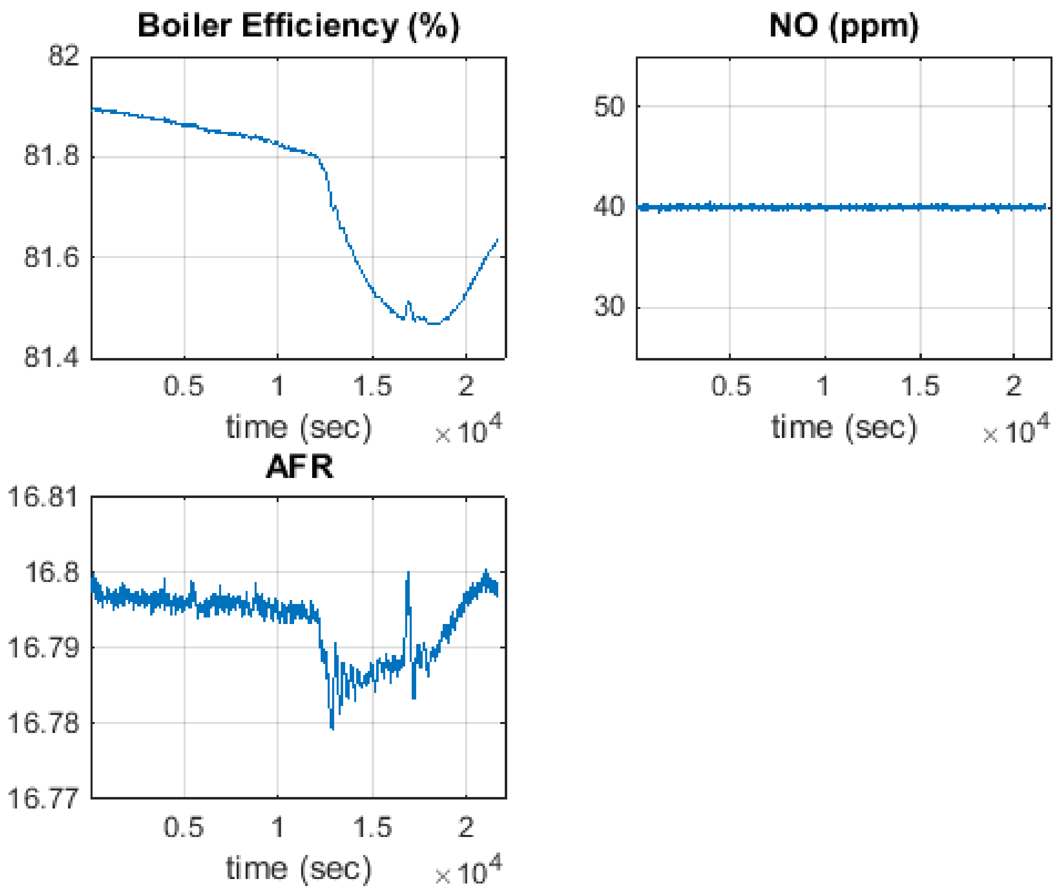

Figure 51 Efficiency and NOx response with optimized AFR of case 2

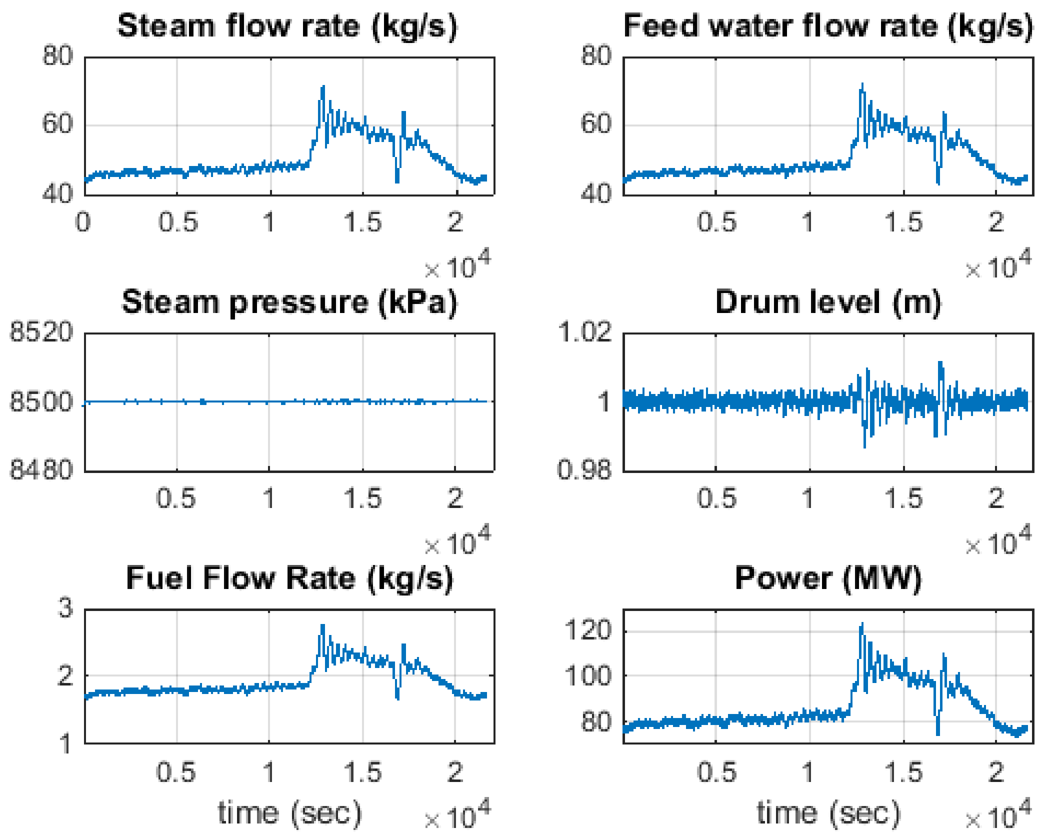

Figure 52 Boiler variable's response with optimized AFR of case 3

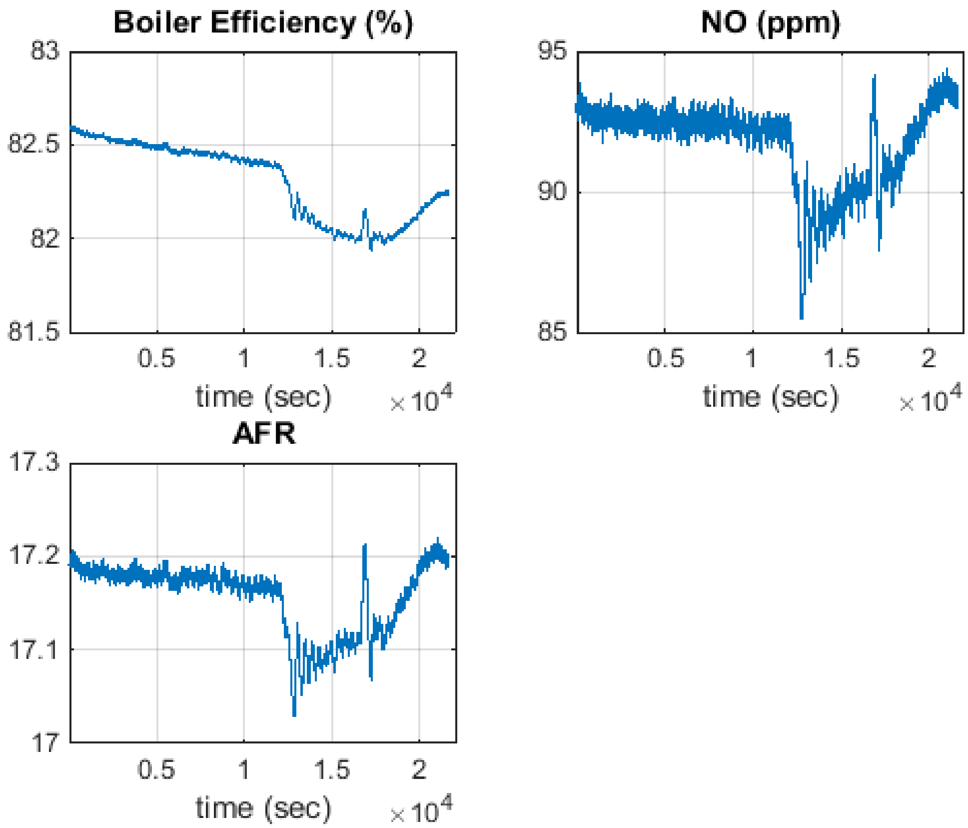

Figure 53 Efficiency and NOx response with optimized AFR of case 3

Table 11 Average efficiency and NOx values for all Cases

Case	Description	Weights	Average Efficiency (%)	Average NOx (ppm)
1	Efficiency is highly weighted against NOx	w_1=1,w_2=0	82.9213	196.1022
2	NOx is highly weighted against efficiency	w_1=0,w_2=1	81.7234	39.9956
3	Efficiency and NOx are weighted to achieve an evenly trade-off	w_1=1,w_2=0.005	82.3096	91.7357

8.4 Summary

In this chapter, dynamic optimization of efficiency and NOx has been carried out using the operational input of AFR. This has been achieved by formulating a quadratic cost function that penalizes low efficiency and high NOx. The minimum of this cost function is calculated at each discrete time step of simulation and the resulting optimal AFR is used as input for the efficiency and NOx model. The optimization process has been integrated with dynamic control process. The response of all boiler operational variables have been generated based on methodology as discussed in CHAPTER 7. Simulation and tabular results have been provided to illustrate the behavior of all the variables.

CHAPTER 9 CONCLUSION AND FUTURE WORK DIRECTIONS

In this thesis, optimization of NOx and efficiency along with dynamic control of boiler has been carried out using analytical models of all variables. Prior to optimization, dynamic models of NOx and boiler process variables have been investigated using existing models in the literature. Special focus has been given to dynamic modelling of boiler's efficiency as novel formulation of dynamic efficiency has been one of the core objectives of the thesis. First we have calculated time variations of boiler efficiency from real-time experimental data of boiler using indirect method. After calculating efficiency an input output based efficiency model has been formulated using fuel flow rate and air to fuel ratio. This has been specifically derived by augmenting the indirect method equations of efficiency with an empirical model of flue gas temperature. It has been shown and validated that flue gas temperature can be effectively modelled using available inputs based on system identification technique. The efficiency calculations from both data based flue gas temperature and input output based flue gas temperature validates the applicability of model. After this, the utility of model has been discussed from two aspects: one is how efficiency is influenced by varying air to fuel ratio and fuel flow rate and it has been successfully derived that based on the modelling equations, optimal point of efficiency exists and is calculable with respect to air to fuel ratio. Second is how combustion process interacts with boiler operating variables via instantaneous efficiency as the variations in efficiency affect the dynamics of all the boiler variables. In this respect it has been investigated through modelling equations that the heating rate is dynamically related to the fuel flow rate based on dynamic efficiency and boiler operating variables of level and pressure can be effectively controlled by augmenting dynamic efficiency model with control model. With these results, a paper titled "*Modeling Time Variations of Boiler Efficiency*" has been produced which has been submitted to a reputable journal.

After formulating the models of efficiency, NOx and boiler's process variables, a correlation analysis has been carried out in order to determine the relation of efficiency, NOx and boiler's process variables. For this, time varying experimental data of input variables have been used in a cross correlation formula and results have been tabulated. The results of the correlation have clearly demonstrated how important variables of boiler are statistically related to each other in different operating conditions.

As another part of thesis, the models of boiler response variables, efficiency and NOx have been integrated to produce a compact unified model. This has been a novel contribution in the literature of boiler in which the combustion process has been augmented with boiler's operational process where combustion process is being symbolized by dynamic efficiency along with NOx emissions and boiler's operational process is symbolized by boiler's response variables of drum level, drum pressure etc. This unified model is capable to realize the optimization of NOx and efficiency in real time dynamic operation of boiler. The optimization has been carried out by formulating a quadratic cost function which has been minimized using genetic algorithm at each time instant of discretized boiler model. It has been shown that different choice of penalizing factors of cost function produce different trajectories of NOx and efficiency. Based on requirement, one can have NOx minimized at the expense of low efficiency or efficiency maximized at the expense of high NOx or an optimal tradeoff between the two can be acquired. The optimized model is compatible with real time operation of boiler as the steam data of a practically working boiler has been used to test and validate the proposed techniques.

Finally the model was integrated with a three term controller to control boiler dynamics and genetic algorithm has been used to optimize PID gains of control loops of drum level and drum pressure. The controller performance and optimization algorithm has been tested by applying steam disturbance that match with the actual scenario of operating conditions of a typical package boiler. Simulation response of all variables have guaranteed that the optimized controller is successful in regulating the variables within practical constraints and safe limits. As well, the optimized responses of NOx and efficiency have been very encouraging regardless of violent disturbances generated by steam variable. With these results, another paper titled "*Boiler Dynamic Control with Optimized NOx and Efficiency*" has been produced which has been submitted to a reputable journal.

This thesis work can be extended through following directions:

- The control technique used in this work is a PID based three term controller that is used to control drum level and drum pressure. PIDs, in general, are used to control single input and single output (SISO) systems. For MIMO systems we have to determine the input-output pairs for using individual PIDs for each input-output pair. MPCs are one of the controllers that are dedicated to control MIMO systems and the issue of input-output pairing is capably handled by MPCs. The augmented model derived in this thesis work can be integrated with MPC to achieve both optimization and control of all the important variables of boilers. In this respect, the cost function that includes efficiency and NOx, will have to be extended to include output variables of pressure and level.

- Sliding model control is among the class of controllers that are robust and hence immune to the parametric uncertainties of the model. For boiler system, lot of parameters are measured and hence the uncertainties in the measurements can be troublesome for modelling and control purpose. The augmented model derived in this work can also be integrated with sliding model controller to accomplish a robust controlled response of the system. In this respect, PID based three term controller will have to be replaced with sliding mode controller without any change in cost function.
- From the dynamic models of both efficiency and NOx, a mathematical relation between NOx and efficiency can be sought out. This can be done by simultaneously solving the modelling equations of NOx and efficiency which shall yield a single equation relating NOx with efficiency and other operational variables of boiler. This relation will have the ability to generate graphical contours of efficiency and NOx in two dimensional form with different values of other operational variables. The contours can be very illustrative to investigate how efficiency and NOx are correlated with each other and also they can be specifically used to locate optimized regions where efficiency is high enough and NOx is also within regulatory limit.
- The NOx dynamic model used in this work was based on simplified model of Li and Thompson [38], that related thermal NOx with the operational inputs of AFR and FFR. The work of this thesis can be extended by using more sophisticated models of NOx that may relate all types of NOx with operational inputs. Also, the formation of NOx varies with different boilers hence the model also varies under different operating

environments. In this respect online tunable empirical model of NOx is also usable for carrying out the control and optimization purpose. In this regard, only NOx modeling equation will need to be modified and rest of modeling, control and optimization equations will remain the same.

- The FGT model used in this thesis work was based on empirical model that was derived by using system identification technique. The model can be made better by creating the capability of online adaptability so that the model parameters can be modified with time during real time operation of boiler.
- The cost function included in the optimization process of this thesis work only comprised of NOx and efficiency. The cost function can be extended by additional component of drum pressure. In this thesis work, the drum pressure has been controlled by PID control using the input of FFR. This control of pressure can be replaced by optimization of pressure in which pressure can be sacrificed in order to achieve increased efficiency and decreased NOx in a better way. This addition will result into increased degree of freedom for the optimization process i.e. the input of FFR will also be used to optimize three variables of NOx, efficiency and drum pressure.

APPENDIX

A.1 Unit Conversion

One important aspect to discuss while considering units of NOx is that the equation (4.10) gives rate of NOx measured as parts per million, while government regulations give maximum acceptable limit of NOx as nano gram (ng) of NOx produced per joule of fuel energy expended. In Saudi Arabia Royal Commission of Jubail and Yanbu (RCJY) is responsible for imposing these regulations and for upper limit emissions it uses the same unit of ng/joule. The unit conversion factor can be done by using following expression:

$$[\mathrm{NOx}]_{\mathrm{ppm}} = [\mathrm{NOx}]_{\frac{\mathrm{ng}}{\mathrm{J}}} \times 10^{6} \times \frac{\mathrm{GCV_{mole}}}{(1 + \mathrm{AFR_{mole}}) \times \mathrm{M_{NOx}}} \times 10^{-9} \qquad (8.2)$$

Where $\mathrm{AFR_{mole}}$ is air to fuel ratio by molar basis. 10^{6} and 10^{-9} are conversion factors for mol/mol to ppm and ng to gram respectively. $\mathrm{M_{NOx}}$ is molecular weight of NOx and $\mathrm{GCV_{mole}}$ is gross calorific value of natural gas by molar basis which is calculated based on the given composition of gas. For the thesis we use the same composition as in Figure 10. Different countries have different upper limit for NOx but for current work we assume the limit to be 36.66 ng/J. Using this conversion factor the upper limit of NOx is calculated to be 100 ppm.

$$[\mathrm{NOx}]_{\mathrm{ppm}} = 36.66 \times 10^{6} \times \frac{890310}{(1 + 9.88) \times 30} \times 10^{-9} = 100\ ppm$$

It is also noteworthy that this value is dependent on AFR which varies under dynamic conditions and so does the upper limit of NOx in ppm. To be on safe side we use the lowest value of AFR being equal to AFR_{st} which gives the minimum upper limit of NOx in ppm with reference to regulatory value of 36.66 ng/J.

A.2 Cross Correlation

The dynamic behavior of all variables can be mathematically formulated by using Correlation Coefficient 'r_{xy}' which is given by the following formula:

$$r_{xy} = \frac{\sum_{i=1}^{T}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{T}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{T}(y_i - \bar{y})^2}} \tag{8.3}$$

Where $\bar{x}$ and $\bar{y}$ represents average of vectors x and y.

The value of r_{xy} is interpreted by its sign and its absolute value from which we can deduce the direction and the magnitude of the relationship that exists between two variables. The correlation coefficient bears following properties:

- The value of a correlation coefficient ranges between -1 and 1.
- The greater the absolute value of a correlation coefficient, the stronger the linear relationship.
- The strongest linear relationship is indicated by a correlation coefficient close to -1 or 1.

- The weakest linear or totally random relationship is indicated by a correlation coefficient equal to 0. This usually occurs either because the two variables are either not related or they are nonlinearly related.
- A positive correlation means that if one variable gets increased, the other variable also increases.
- A negative correlation means that if one variable gets increased, the other variable decreases.

As the above formula is only sensitive to linear relationship between variables, it also necessitates to divide the data set into subintervals where each interval has either dynamic variations or steady variations in data variables.

A.3 Cross Correlogram

The time dependent cross correlation or cross-correlogram of two variables have been formed by using Matlab command which uses another algorithm of correlation function similar to equation (8.3) using following expression:

$$R_{xy} = \begin{cases} \sum_{n=0}^{N-m-1} x_{n+m} y_n, & m \geq 0 \\ R_{yx}(-m), & m < 0 \end{cases} \tag{8.4}$$

The output vector, $c(m)$ having almost double elements than 'x' or 'y' stores all the cross correlation values and is given by:

$$c(m) = R_{xy}(m - N), \quad m = 1, 2, 3, \dots, 2N - 1. \tag{8.5}$$

In the literature various expressions are available for calculating cross correlogram. Though all give similar results, they operate differently to implement the same basic algorithm. Hence, it is imperative to discuss in more detail how the above expression operates for achieving better insight of cross-correlogram analysis.

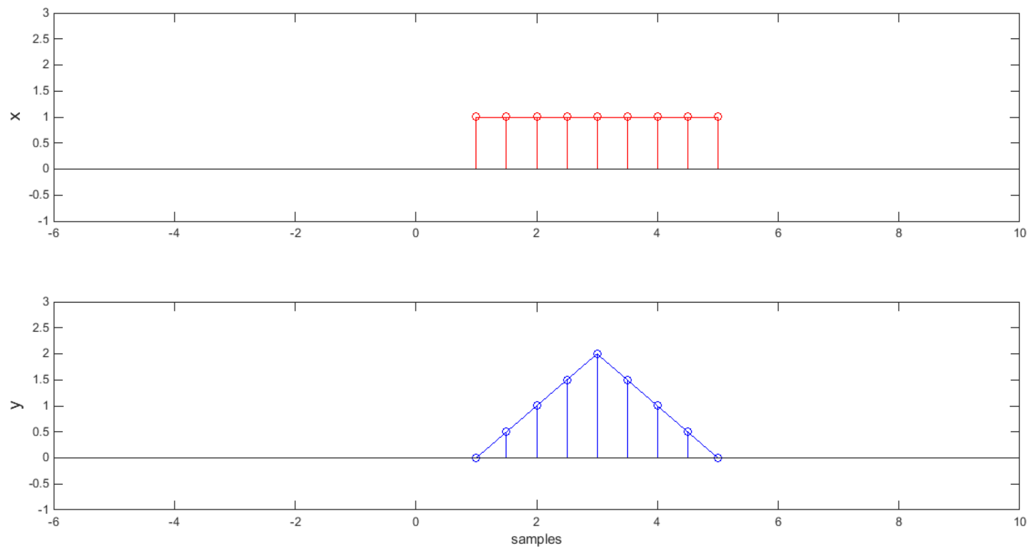

Figure 54 'x' and 'y' hypothetical variables

The above expression (8.4) calculates the correlation by multiplying, integrating and adding the two vectors and it does it repeatedly by shifting or delaying one of the variables (which is ‘y’ according to the above formula) by one sample at a time. Consider, for example two variables of same length ‘N’ as shown in Figure 54. At the start, the correlation algorithm shifts all the ‘y’ values –N times leftwards such that the last sample of ‘y’ coincides with first sample of ‘x’. It then performs the correlation of the variables and store them as first value in a vector $c(m)$. In the next iteration the variable ‘y’ is shifted rightwards with single sample delay and the correlation is again computed as stored in $c(m)$. The procedure iterates itself in this way '2N-1' times until the first value of 'y' gets correlated with last value of 'x' which is stored as last value on vector c (m). The argument of maximum of magnitude of cross correlation plot represents the amount of delay between the respective signals. Care needs to be taken to interpret the delay based upon its sign and the order of variables in matlab command 'xcorr'. For instance, if the variable 'x' is first and 'y' is second i.e. xcorr(x, y), then following rules are followed to interpret the delay:

- The two variables 'x' and 'y' are exactly synchronized if the argument of maximum of absolute of cross-correlogram occurs at zero.
- The variable 'y' is delayed compared to 'x' if the maximum of absolute of cross-correlogram occurs at some negative value of its argument.
- The variable 'y' is ahead compared to 'x' if the maximum of absolute of cross-correlogram occurs at some positive value of its argument.
- The argument of maximum of absolute of cross-correlogram determines the amount of delay between 'x' and 'y'.

This shifting procedure is demonstrated in Figure 55 to have better illustration of coinciding values of two vectors in each correlation turn.

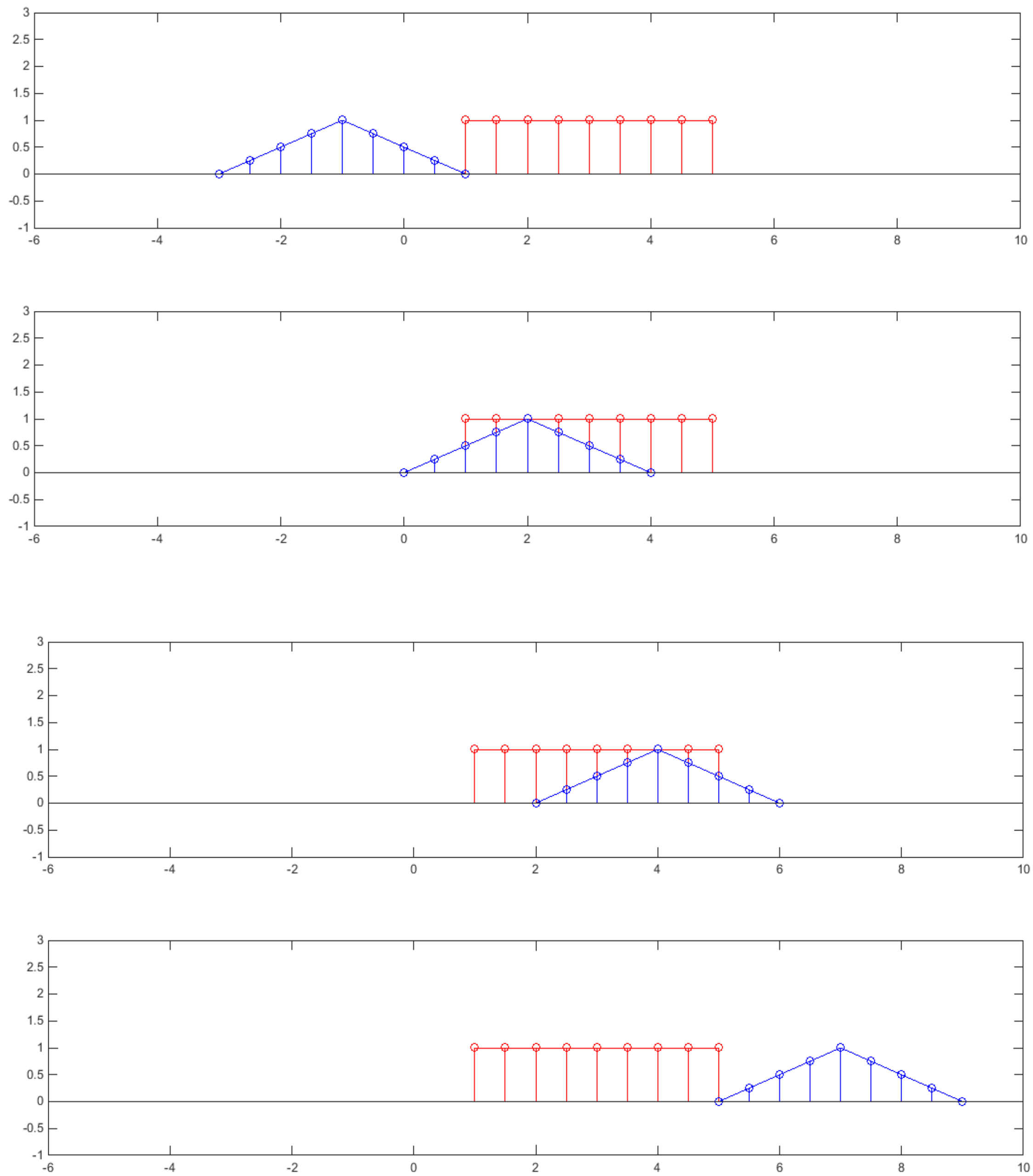

Figure 55 Cross correlation algorithm illustration

REFERENCES

[1] K. Yao and K. F. V. Wong, “Boiler combustion performance comparing different fuels,” in *American Society of Mechanical Engineers, Advanced Energy Systems Division (Publication) AES*, 1994, vol. 33, pp. 7–14.

[2] J. Feng, “Achievements in pollutant emission control from coal combustion in China,” in *Proceedings of the International Conference on Energy and Environment, ICEE*, 1996, pp. 6–10.

[3] M. L. Davis and W. J. Mikucki, “Choosing a technology for simultaneous control of NOx/SOx from industrial boilers,” in *Proceedings - A&WMA Annual Meeting*, 1989, vol. 2.

[4] K. Annamalai and I. K. Puri, *Combustion science and engineering*, 1st ed. Boca Raton: CRC Press/Taylor & Francis, 2007.

[5] H. Zhao and P.-H. Wang, “Modeling and Optimization of Efficiency and NOx Emission at a Coal-Fired Utility Boiler,” in *2009 Asia-Pacific Power and Energy Engineering Conference*, 2009, pp. 1–4.

[6] V. Ganapathy, *Steam Generators and Waste Heat Boilers*. Berlin, Heidelberg: CRC Press, 2014.

[7] Bureau of Energy Efficiency. Energy performance assessment of boilers. [Online]. pp. 1-5. Available: http://www.em-ea.org.

[8] K. Astrom and R. Bell, “Drum-boiler dynamics,” *Automatica*, vol. 36, no. 3, pp. 363–378, 2000.

[9] J. Barroso, F. Barreras, J. Ballester, and N. Fueyo, “Industrial Steam Boilers,” in *Handbook of Combustion*, Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA, 2010.

[10] G. P. Giacoia, “Nitric oxide: an environmental pollutant as a therapeutic agent.,” *Journal - Oklahoma State Medical Association*, vol. 88, no. 1. pp. 17–23, 1995.

[11] A. Agarwal and D. N. Assanis, “Multi-Dimensional Modeling of Ignition, Combustion and Nitric Oxide Formation in Direct Injection Natural Gas Engines,” in *SAE Technical Papers*, 2000.

[12] S. A. Iliyas, M. Elshafei, M. A. Habib, and A. A. Adeniran, “RBF neural network inferential sensor for process emission monitoring,” *Control Eng. Pract.*, vol. 21, no. 7, pp. 962–970, Jul. 2013.

[13] T. K. Sai and K. a. Reddy, “Measurement and control of NOx emissions using soft computing in a thermal power plant,” *2014 Recent Adv. Eng. Comput. Sci.*, pp. 1–6, Mar. 2014.

[14] S. . Hill and L. Douglas Smoot, “Modeling of nitrogen oxides formation and destruction in combustion systems,” *Prog. Energy Combust. Sci.*, vol. 26, no. 4–6, pp. 417–458, Aug. 2000.

[15] S. Minhajullah and S. Ferik, “MPC-based controller for augmented boiler-NO x model,” *Syst. Signals …*, vol. 35, no. 4, pp. 578–586, Jul. 2012.

[16] J. L. Toof, “MODEL FOR THE PREDICTION OF THERMAL, PROMPT, AND FUEL NO//x EMISSIONS FROM COMBUSTION TURBINES.,” *J. Eng. Gas*

Turbines Power, vol. 108, no. 2, pp. 340–347, 1986.

[17] "NOx," *Wikipedia*, 2016. [Online]. Available: https://en.wikipedia.org/wiki/NOx. [Accessed: 17-May-2016].

[18] W. S. Robertson, *Boiler Efficiency and Safety*, 1st ed. London: Macmillan Education UK, 1981.

[19] V. Nagar, "Boiler Efficiency Improvement through Analysis of Losses," *Int. J. Sci. Res. Dev.*, vol. 1, no. 3, pp. 1–5, 2013.

[20] M. Elshafei, M. A. Habib, I. Al-Zaharnah, and M. A. Nemitallah, "Boilers Optimal Control for Maximum Load Change Rate," *J. Energy Resour. Technol.*, vol. 136, no. 3, p. 031301, May 2014.

[21] A. Wienese, "Boilers, boiler fuel and boiler efficiency," in *Proc. S. Afr. Sug. Technol. Ass*, 2001, vol. 75, pp. 275–281.

[22] A. N. Aziz and Y. Y. Nazaruddin, "Structured Mathematical Modeling of Industrial Boiler," vol. 46, no. 1, pp. 102–122, 2014.

[23] T. Hong, H. Ni, and G. Cheng, "Full-scale Mathematical Model and Simulation of Marine Natural Recirculation Drum-boiler," *Procedia Eng.*, vol. 31, pp. 834–843, Jan. 2012.

[24] A. Kouadri, A. Namoun, and M. Zelmat, "Modelling the nonlinear dynamic behaviour of a boiler-turbine system using a radial basis function neural network," *Int. J. Robust Nonlinear Control*, vol. 24, no. 13, pp. 1873–1886, 2014.

[25] E. J. Adam and J. L. Marchetti, "Dynamic simulation of large boilers with natural

recirculation," *Comput. Chem. Eng.*, vol. 23, no. 8, pp. 1031–1040, Aug. 1999.

[26] M. Elshafei, M. a. Habib, I. Al-Zaharnah, and M. a. Nemitallah, "Boilers Optimal Control for Maximum Load Change Rate," *J. Energy Resour. Technol.*, vol. 136, no. 3, p. 031301, May 2014.

[27] T. S. Pedersen, T. Hansen, and M. Hangstrup, "Process-optimizing multivariable control of a boiler system," in *UKACC International Conference on Control '96,* 1996, no. 427 /2, pp. 787–792.

[28] R. Horalek and L. Imsland, "Nonlinear model predictive control of a benchmark nonlinear boiler," in *2011 XXIII International Symposium on Information, Communication and Automation Technologies*, 2011, pp. 1–6.

[29] G. Pellegrinetti and J. Bentsman, "Nonlinear control oriented boiler modeling-a benchmark problem for controller design," *IEEE Trans. Control Syst. Technol.*, vol. 4, no. 1, pp. 57–64, 1996.

[30] A. W. O'Brien and M. H. Melksham, "THERMAL SHOCK AND THERMAL FATIGUE CRACKING OF MEMBRANE BOILER WALLS FROM WATER BLOWER OPERATIONS.," in *American Society of Mechanical Engineers (Paper)*, 1984.

[31] J. Ginsztler, "ASSESSMENT OF THERMAL FATIGUE RESISTANCE OF SOME BOILER STEELS.," 1980, pp. 335–338.

[32] M. A. Habib, I. Alzaharnah, M. El-Shafei, N. Merah, S. Al-Anizi, M. Y. Al-Awwad, and M. Hajji, "Influence of Heat Flux and Friction Coefficient on Thermal Stresses

in Risers of Drum Boilers under Dynamic Conditions of Steam Demand," *Adv. Mech. Eng.*, vol. 2013, pp. 1–12, 2013.

[33] W.-J. Chang, Y.-C. Chang, and C.-C. Ku, "Passive Fuzzy Control via Fuzzy Integral Lyapunov Function for Nonlinear Ship Drum-Boiler Systems," *J. Dyn. Syst. Meas. Control*, vol. 137, no. 4, p. 041008, Apr. 2015.

[34] Y. Daren and X. Zhiqiang, "Nonlinear Coordinated Control of Drum Boiler Power Unit Based on Feedback Linearization," *IEEE Trans. Energy Convers.*, vol. 20, no. 1, pp. 204–210, Mar. 2005.

[35] P. Yang, D. G. Peng, Y. H. Yang, and Z. P. Wang, "Neural networks internal model control for water level of boiler drum in power station," in *Proceedings of 2004 International Conference on Machine Learning and Cybernetics*, 2004, vol. 5, pp. 3300–3303.

[36] M. Elshafei and M. a. Habib, "Softsensor for estimation of steam quality in riser tubes of boilers," *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.*, vol. 227, no. 10, pp. 2337–2347, Dec. 2012.

[37] I. Alzaharnah, M. a. Habib, M. Elshafei, and P. Ahmed, "Control of the Boiler Swing Rate for NO Emission Minimization," *Energy & Fuels*, vol. 27, no. 10, pp. 6079–6086, Oct. 2013.

[38] N. Li and S. Thompson, "A simplified non-linear model of NOx emissions in a power station boiler," in *UKACC International Conference on Control. Control '96*, 1996, vol. 2, pp. 1016–1021.

[39] S. Minhajullah, S. El Ferik, M. Elshafei, and M. A. Habib, “MPC-based controller for augmented boiler-NO x model,” in *9th International Multi-Conference on Systems, Signals & Devices (SSD)*, 2012, pp. 1–6.

[40] P. Ilamathi, V. Selladurai, K. Balamurugan, and V. T. Sathyanathan, “ANN–GA approach for predictive modeling and optimization of NOx emission in a tangentially fired boiler,” *Clean Technol. Environ. Policy*, vol. 15, no. 1, pp. 125–131, May 2012.

[41] H. Zhou, K. Cen, and J. Fan, “Modeling and optimization of the NOx emission characteristics of a tangentially fired boiler with artificial neural networks,” *Energy*, vol. 29, no. 1, pp. 167–183, Jan. 2004.

[42] V. Ganapathy, *Industrial Boilers and Heat Recovery Steam Generators*, vol. 149. CRC Press, 2002.

[43] S. Shah and D. M. Adhyaru, “Boiler efficiency analysis using direct method,” in *2011 Nirma University International Conference on Engineering: Current Trends in Technology, NUiCONE 2011 - Conference Proceedings*, 2011.

[44] L. Y. Huang, J. X. Wen, T. G. Karayiannis, and R. D. Matthews, “Numerical prediction of high efficiency boiler heat exchanger performance,” *Appl. Therm. Eng.*, vol. 18, no. 11, pp. 1089–1099, Nov. 1998.

[45] E. Carlon, M. Schwarz, L. Golicza, V. K. Verma, A. Prada, M. Baratieri, W. Haslinger, and C. Schmidl, “Efficiency and operational behaviour of small-scale pellet boilers installed in residential buildings,” *Appl. Energy*, vol. 155, pp. 854–865, Oct. 2015.

[46] V. Tanetsakunvatana and V. I. Kuprianov, “Experimental study on effects of operating conditions and fuel quality on thermal efficiency and emission performance of a 300-MW boiler unit firing Thai lignite,” *Fuel Process. Technol.*, vol. 88, no. 2, pp. 199–206, Feb. 2007.

[47] Y. Li and H. Gao, “On-line calculation for thermal efficiency of boiler,” in *Asia-Pacific Power and Energy Engineering Conference, APPEEC*, 2010.

[48] Y. Shi, J. Wang, B. Wang, and Y. Zhang, “On-line calculation model for thermal efficiency of coal-fired utility boiler based on heating value identification,” in *Proceedings of 2011 International Conference on Modelling, Identification and Control, ICMIC 2011*, 2011, pp. 203–207.

[49] G. Li, P. Niu, C. Liu, and W. Zhang, “Enhanced combination modeling method for combustion efficiency in coal-fired boilers,” *Appl. Soft Comput.*, vol. 12, no. 10, pp. 3132–3140, Oct. 2012.

[50] D. S. Jangamshetti and S. Sonoli, “Boiler efficiency estimation from hydrogen content in fuel,” in *2015 International Conference on Advances in Computing, Communications and Informatics (ICACCI)*, 2015, pp. 1107–1110.

[51] P. Li and C. W. Zhang, “The Analysis between Two Different Methods of Power Plant Boiler Thermal Efficiency,” *Appl. Mech. Mater.*, vol. 536–537, pp. 1578–1582, Apr. 2014.

[52] N. Dedovic, S. Igic, T. Janic, S. Matic-Kekic, O. Ponjican, M. Tomic, and L. Savin, “Efficiency of Small Scale Manually Fed Boilers —Mathematical Models,” *Energies*, vol. 5, no. 12, pp. 1470–1489, May 2012.

[53] J. Barroso, F. Barreras, H. Amaveda, and A. Lozano, “On the optimization of boiler efficiency using bagasse as fuel☆,” *Fuel*, vol. 82, no. 12, pp. 1451–1463, Aug. 2003.

[54] Z. Song and A. Kusiak, “Constraint-based control of boiler efficiency: A data-mining approach,” *Ind. Informatics, IEEE Trans.*, vol. 3, no. 1, pp. 73–83, 2007.

[55] W. Treedet and R. Suntivarakorn, “Use of Fuzzy Logic to Control Air Intake for Increase in Boiler Efficiency,” *Appl. Mech. Mater.*, vol. 564, pp. 275–280, Jun. 2014.

[56] A. Žandeckis, L. Timma, D. Blumberga, C. Rochas, and M. Rošā, “Solar and pellet combisystem for apartment buildings: Heat losses and efficiency improvements of the pellet boiler,” *Appl. Energy*, vol. 101, pp. 244–252, Jan. 2013.

[57] S. Li, T. Xu, S. Hui, and X. Wei, “NOx emission and thermal efficiency of a 300MWe utility boiler retrofitted by air staging,” *Appl. Energy*, vol. 86, no. 9, pp. 1797–1803, Sep. 2009.

[58] W. Weiqing, “Multi-objective Optimization of Coal-Fired Boiler Efficiency and NOx Emission under Different Ecological Environment,” in *Future Communication, Computing, Control and Management SE - 58*, vol. 141, Y. Zhang, Ed. Springer Berlin Heidelberg, 2012, pp. 433–439.

[59] B. T. Zhang, C. Y. Wang, Q. Qin, and L. Li, “Influence of Boiler Combustion Adjustment on NOx Emission and Boiler Efficiency,” *Adv. Mater. Res.*, vol. 732–733, pp. 234–237, Aug. 2013.

[60] X. Yuhua, Z. Jiayuan, Z. Xiaohui, L. Yongqing, and G. Ting, “Simulation of

Efficiency and Low NOx Combustion-Supporting Technology by Local Oxygen-Enrichment in Pulverized Coal Boiler," in *2012 Third International Conference on Digital Manufacturing & Automation*, 2012, pp. 771–775.

[61] M. Habib, "Influence of Boiler Load Swing Rates on Response of Drum Water Level," *J. Energy Resour. Technol.*, vol. 135, no. 2, p. 022904, 2013.

[62] G. Dolanc, S. Strmčnik, and J. Petrovčič, "NOX selective catalytic reduction control based on simple models," *J. Process Control*, vol. 11, no. 1, pp. 35–51, Feb. 2001.

[63] A. M. Mellor, "Semi-empirical correlations for gas turbine emissions, ignition, and flame stabilization," *Prog. Energy Combust. Sci.*, vol. 6, no. 4, pp. 347–358, Jan. 1980.

[64] C. S. Connors, J. C. Barnes, and A. M. Mellor, "Semiempirical predictions and correlations of CO emissions from utility combustion turbines," *J. Propuls. Power*, vol. 12, no. 5, pp. 926–932, Sep. 1996.

[65] W. S. Y. Hung and D. D. Agan, "The Control of NOx and CO Emissions from 7-MW Gas Turbines with Water Injection as Influenced by Ambient Conditions," *Am. Soc. Mech. Eng.*, 1985.

[66] A. H. Lefebvre, "Fuel effects on gas turbine combustion-liner temperature, pattern factor, and pollutant emissions," *J. Aircr.*, vol. 21, no. 11, pp. 887–898, 1984.

[67] N. Rizk and H. Mongia, "Emissions predictions of different gas turbine combustors," *AIAA, Aerosp. Sci. Meet. Exhib. 32 nd, Aerosp. Sci. Meet.*, vol. 94, no. 0118, 1994.

[68] J. A. Harrington and R. C. Shishu, “A Single-Cylinder Engine Study of the Effects of Fuel Type, Fuel Stoichiometry, and Hydrogen-to-Carbon Ratio on CO, NO, and HC Exhaust Emissions,” *SAE Tech. Pap.*, no. 730476, 1973.

[69] “BOILERS | Energy-Models.com,” 2016. [Online]. Available: http://energy-models.com/boilers. [Accessed: 08-May-2016].

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