CHAPTER 1

INTRODUCTION

Electricity is the primary indicator of the economic growth and standard of living of the people in a nation. Generation of power is mainly dependent on coal-fired power plants throughout the world. Coal is known to be one of the most important natural resources in the world. The surplus availability, extensive distribution and versatility of coal makes it a significant source of electrical energy for all times. The major proportion of electricity is produced from coal rather than any other source of fuel. It is cheaper than other fossil fuels but it is hard to be burnt. For power units operating on fossil fuel, the sole, prime, operating cost is fuel. The fuel expenses account for about 50 - 60% of the cost of generating electricity. Hence, procuring fuel of lower price is often a major challenge. Despite this and other environmental issues, coal is still expected to hold a major share of the electrical energy consumption in future. Coal-fired power plants, also known as thermal power plants, provide over 48% of global electricity supply.

Coal has remained a major source of fuel for power generation. The key focus of power generation units has been to generate the load as demanded by the transmission centre. Very less attention has been given to the coal quality and to the amount of pollutants produced. However, new regulations imposing the reduction or almost elimination of NOx, SOx and CO2 led to new operational policies and strategies, novel burner designs and an intensive study
on coal composition and properties. Moreover, present day competitive market scenario demands an economic production of power for which the cost implications on fuel properties and the combustion strategy need to be seriously viewed. Therefore, the present operation of a Fossil Fuel Power Units (FFPU) is not bound by a single operating objective, but rather, quite a lot of objectives that need to be satisfied simultaneously; possibly with different hierarchy. Few of the most essential operational objectives include:

- Cyclic operation, which demands the operation of the power units in a wide-range and in a load-following method despite the fact that the units are originally designed for constant load operation.
- Extension of plant life to maximize the utility of capital resources, reduction of down time and decreasing operational and maintenance costs.
- Significant improvement in heating rate in order to reduce the economic impact due to the cost, quality and quantity of coal usage.
- Minimization of adverse impacts on the environment due to incomplete combustion of coal.

In summary, it is found that from the performance point of view, attaining an optimal process operation is considered essential.

### 1.1 THERMAL POWER PLANT

A thermal power plant produces electrical power from fossil fuel, namely coal through several energy conversion processes, using water as a working fluid. It comprises a boiler, turbine, electric generator and other
auxiliary equipments each of which serve a definite purpose. An aerial view of a thermal power plant with the coal yard is shown in Fig. 1.1.

Fig. 1.1 An Aerial View of a Thermal Power Plant
A schematic diagram of the thermal power plant is shown in Fig. 1.2.
Fig 1.2 Schematic Diagram of a Thermal Power Plant
In a conventional coal fired thermal power plant, chemical energy of coal is transformed into thermal energy by the boiler which in turn is transformed into rotational mechanical energy by the turbine. Finally, it is transformed into electric energy by the generator and fed to the power grid.

1.1.1 Boiler Description

The boiler, comprising the furnace, drum and super-heaters, generates steam at high pressure by transferring the heat generated due to combustion in several sections of heat transfer. The conversion of water to steam in the boiler takes place in three stages.

- Sensible heat addition that involves heating the cold water to its boiling point.
- Latent heat addition which converts the water boiling at saturation temperature to steam.
- Superheating in which the steam at saturation temperature is heated to high temperature to increase the output and efficiency of the power plant.

The water from the feed water tank is fed at high pressure into the boiler using the feed water pumps. The pre-heaters use the extracted steam from the turbine to add a part of the sensible heat even before the feed water enters the boiler. Major portion of the sensible heat is absorbed in the Economizer. The economizers are a group of coils made of steel tubes and are found in the back end of a boiler. The hot flue gases leaving the boiler furnace heat the water in the coils. The water from the economizer is fed to the boiler drum. The drum is a large cylindrical structure that is used as a vessel for feeding and storing water.
and to also to collect the water and steam mixture. It is the largest and heaviest component in a sub-critical boiler and weighs around 225 tons for a 500 MW boiler.

The water from the drum starts boiling in the water walls which are nothing but water filled tubes that form the furnace walls. The water walls receive the water from the down comers which are huge pipes connected to the drum. As the water begins to heat up in the furnace, a portion of the water in the water-wall tubes is converted into steam. This mixture of water and steam has a lesser density than the water in the down comers. This difference in density results in circulation of water from the drum, through the down comers, water walls and back to the drum. Steam gets collected in the upper half of the drum. The schematic diagram of circulation system is shown in Fig.1.3.

The saturated steam from the drum passes to the super-heater coils placed in the flue gas path. The temperature of steam increases from the saturation temperature until it attains the superheated state. The superheated steam then finally goes to the High Pressure (HP) stage of the turbine. The exhaust steam from the High Pressure (HP) turbine flows back to the boiler for reheating and returns to the second stage. The steam that has returned from the HP turbine is reheated in the reheater coils that are located in the flue gas path. The pressure of the reheat steam is much lower than the super-heated steam but the temperature of the final reheater is the same as that of the superheated steam.
Reheating to high temperature is done to improve the output and efficiency of the power plant. In addition, a precise and sustained control of the steam generation system is also vital for increasing the boiler efficiency. In order to develop and analyze the control strategies, it is essential to develop an accurate and valid boiler model. A schematic diagram of the boiler and its subsystems is shown in Fig. 1.4.

1.2 COMBUSTION PROCESS

Coal that is conveyed from the coal storage yard is stored in bunkers and is pulverized in mills before entering into the combustion chamber. Coal is pulverized to improve its thermal use. The primary air carries the pulverized
coal to be fed into the burners located on the furnace walls. Then, secondary air is introduced into the burners to enable the coal to be dispersed inside the combustion chamber. In order to ensure complete combustion, air is normally fed in excess of the stoichiometric amount.

The combustion takes place in boiler furnace. The coal is kindled and burned in the “furnace chamber”. The oxygen required for combustion is provided by blowing ambient air into the furnace chamber. Even though the main components of coal are carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S) etc., carbon, hydrogen and sulfur are the combustible components. Owing to the extremely high temperatures produced during combustion, the carbon and hydrogen present in the coal are oxidized to carbon dioxide (CO$_2$) and water (H$_2$O) respectively. Similarly the sulfur is oxidized to SO$_2$. The nitrogen present in the combustion air and in the fuel react with oxygen to form NO$_x$. The entire oxygen in coal is considered to become water vapor by combining with hydrogen during the combustion. These combustion products that are at very high temperature are emitted from the furnace in a stream of gas called collectively as flue gas. The production of NO$_x$ increases with the increase in combustion temperature.

The amount of coal needed for combustion process depends on steam parameters at boiler output and they vary depending on electrical power at the output of turbine-generator system. The critical process parameters of the boiler are as shown in Table 1.1.
### Table 1.1 Critical Process parameters of the Boiler

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
<th>Controlled Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Coal Flow</td>
<td>• Main Steam</td>
<td>• Main Steam Temperature</td>
</tr>
<tr>
<td>• Primary Air Flow</td>
<td>• Hot Reheat Steam</td>
<td>• Main Steam Pressure</td>
</tr>
<tr>
<td>• Secondary Air Flow</td>
<td>• Flue Gas</td>
<td>• Drum Level</td>
</tr>
<tr>
<td>• Feed Water Flow</td>
<td>• Ash</td>
<td>• Furnace Pressure</td>
</tr>
<tr>
<td>• Spray Flow</td>
<td></td>
<td>• Reheat Steam</td>
</tr>
<tr>
<td>• Burner Tilt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Cold Reheat Steam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Schematic diagram of the boiler and its subsystems is shown in Fig. 1.4. The water from the Economizer (ECON) enters the drum. The water in the drum boils in the waterwalls (WW) which are long tubes that form the furnace walls. The waterwalls receive heat from the downcomers (DC). The water that boils in the drum is converted to steam that rises through the superheater tubes, namely LTSH (Low Temperature SuperHeater), Panal and Platen superheaters. The steam at high pressure and temperature at the outlet of the Platen Turbine is fed to the High Pressure Turbine (HPT). The remaining steam is reheated in the reheaters (RH1 and RH2) and fed to the Intermediate Pressure Turbine (IPT).
Fig. 1. Schematic diagram of Boiler and its Subsystems
1.3 MATHEMATICAL MODELING

A Mathematical Model creates a virtual plant in the computer through mathematical formulations. Since boilers are so common, there are many modeling efforts. There are complicated models in the form of large simulation codes based on finite element approximation to partial differential equations. Though such models are important for plant design and commissioning, they are of little interest for control system design due to their complexity. With the advent of high performance processors and advanced mathematical computations, it is possible to develop high performing simulators for complicated systems.

A power plant simulator is a computer program that simulates the real plant environment for training and research. The completeness of training achieved using the simulator is much greater since operator is performing in an environment which is identical to the control room. Moreover, experienced operators can be effectively retrained on the simulator for advanced engineering analysis and optimization. Modeling and simulation therefore helps in

- Checking the performance in design stage
- Proper sizing of system components
- Design of optimal control systems
- On-line plant optimization
- On-line guidance on operational strategies
- On-line diagnostics of process parameter variations
- Providing the state-of-the art training
A typical power plant simulator located at a power plant at Vijayawada Andhra Pradesh, India is shown in Fig.1.5.

Fig. 1.5 A Typical Power Plant Simulator

Modeling power plant processes may be approached from different points of view, depending on the purpose for which the model is intended. A few methods to develop such models are available in literature, but these methods are often plant specific. The primary focus of this research work is to develop a complete boiler model based on a synergistic integration of heuristic approach evolved on operational experience and lower order modeling philosophies. The model thus developed is suitable for real time applications.
1.3.1 Heuristic Approach

The word “heuristic” comes from the Greek word “Eurisko”, which means “I find”. Heuristic approach refers to techniques based on experiential learning and helps in finding solutions to problems of diverse nature and intensity. A heuristic method helps one to arrive rapidly at solutions that are considered to be close to the best possible answer, or optimal solution. Heuristics are "rules of thumb", educated guesses, intuitive judgments or simply common sense. A heuristic is a general way of solving a problem. In more precise terms, heuristics stand for strategies using readily accessible, though loosely applicable, information to control problem solving in human beings and machines.

1.3.2 Lower Order Modeling

A mathematical model basically establishes the relationship between the input and output of a system. The relationship may be

- Linear or Non-linear Algebraic Equations
- Linear or Non-linear Differential/Partial Differential/Time Varying Equations
- Transfer functions
- State Space Models

Generally, there are two modeling approaches that are adopted in order to determine the dynamic model of a system, viz. First Principle or Physical model Approach and Black Box model Approach
In the physical model approach, the process is assumed to be well understood. The modeling philosophy is based on the laws of conservation of mass, energy and momentum as is applicable to the physical process under consideration. This approach usually results in non-linear model equations consisting of differential and algebraic terms. The coefficients that are derived from the model equations have a wide range of validity and are related to the physical process to a great extent. In the Black Box model approach, the process may not be completely known or may be too complicated to be modeled by physical laws. Hence, the system under study is modeled using its input – output relationship. This approach is useful for the overall study of various systems.

Reduced order or Lower Order Modeling (LoM) of the subsystems in a power plant is necessary because it leads to reduced memory requirements and easy implementation. It can be used to study the effect of controller settings on a system without having to study the detailed mathematical model. It also helps one to realize a hardware simulator that can be used for stability analysis of the power plant and various diagnostic studies.

1.4 MOTIVATION FOR RESEARCH

As a major utility system in the thermal power plant, boilers consume a large portion of the total energy and costs. Significant reduction of boiler operational cost can be gained through improvements in efficiency. A very effective means of enhancing boiler efficiency is to improve the steam generation control system. An indispensable tool for such an improvement is a valid boiler model. An adequate dynamic model that comprehensively reflects the dynamic characteristics of the boiler is therefore required. Towards this
purpose, the various subsystems of the boiler such as furnace, mills, fans, pumps, circulation system, super-heaters, de super-heater, re-heater, economizer and air heaters are modeled independently and integrated together.

While the detailed, accurate and complex models are available for various subsystems, a detailed but computationally simple model for furnace is not available. This is due to the fact that the furnace is a complex system wherein the surfaces of water walls and different radiant super-heaters and reheaters receive heat by direct radiation and the remaining sensible heat energy determines the flue gas temperature at the furnace outlet plane. The quantum of direct radiation to these surfaces is further affected by the tilting of burners in upward or downward direction. The proposed research, therefore, presents a simplified but still accurate procedure for the development of the model of the furnace of a utility boiler of high capacity based on operational experience, heuristic approach and lower order modeling philosophies.

The opportunity to access the data generated using the detailed and validated model of a 500 MW utility boiler that exists at BHEL, one of the pioneers in India for thermal power generation, is the steering force of the current research work. A large amount of input-output data of a 500 MW utility boiler for load variations as well as coal quality variations obtained from the detailed model as well as the Predicted Performance Datasheet of the Simhadri Unit of BHEL at Vishakapatnam is greatly exploited in this research work. The availability of the quantum of data facilitated the researcher to arrive at empirical relations between various input and output quantities of the boiler. The development of such a model enables the researchers in this field to use it
as a benchmark model to carry out advanced control system studies and stability analysis of a boiler, before it can be tested on the real plant.

1.5 RESEARCH OBJECTIVES

The main objective in doing the current research work is to develop a simple but accurate model of a highly complex system such as a boiler which involves a sequence of reactions like combustion, radiative heat transfer, convective heat transfer and so on. These reactions are normally represented using numerous equations and some of them are hard to represented using a well-defined equation. In this scenario, it is useful to develop a simple, yet computationally accurate model of such a system that is represented using empirical relations that can be easily implemented and require less hardware. An intuitive approach and operational experience is combined in this research work to develop simple and reduced order model of the utility boiler of a 500 MW capacity in a coal fired thermal power plant. The modeling approach is done in different stages that involves modeling the furnace, circulation system and the super-heaters separately and integrating them to analyze the overall response of the boiler for step changes in its input parameters. The objectives of the current research work, therefore can be summarized as given below.

- Model the furnace based on heuristic approach.
- Develop Lower Order Model of the Circulation System
- Develop Lower Order Model of Super-heaters
- Integrate the Circulation System with Super-heaters and simulate model.
- Validation of the developed model with the detailed mathematical model by determining the critical process parameters of the boiler as mentioned in Table 1.1.
1.6 GRAPHICAL ABSTRACT

The graphical representation of a concept conveys the information better. The research objectives presented in section 1.5 has been graphically portrayed in Fig 1.6. The entire research work has been presented in three modules.

Module I: This module adopts a heuristic approach to model the furnace of a utility boiler. Having determined the heat gained by the boiler sub systems, through the heuristic approach, the research further proceeds to the second module.

Module II: In this module, system identification techniques have been used to derive the lower order model of the circulation system of a boiler.

Module III: The lower order modeling of the super-heaters is dealt in the third module. The lower order models of the super-heaters are integrated with the lower order model of the circulation system derived in the second module.
Fig. 1.6 Graphical Abstract of Research
The simulation results obtained from the entire system is analyzed and validated based on relevant figures of merit that are chosen based on the critical process parameters of the boiler. In this research work, the process parameters that are used for validation of the model are the temperature of the flue gas at the furnace outlet plane, main steam temperature and main steam pressure.

1.7 ORGANIZATION OF THE THESIS

The thesis has been organized as chapters. The first section of every chapter makes a short introduction to the subject of the chapter. The last section of every chapter sums up the most important conclusions inferred from the chapter.

Chapter 1 gives a brief introduction to the thermal power plants, boilers and mathematical modeling philosophies. A detailed description of the major components of a thermal power plant, the boiler subsystems has been presented in this chapter. The concepts of mathematical modeling and an explanation about the heuristic approach and lower order modeling philosophies has also been given.

Chapter 2 summarizes the conclusions derived from the review of a number of literature on boiler modeling. The specifications of the power plant under study and its detailed mathematical model are also described in this chapter.

The current research is exhaustively discussed in Chapters 3, 4 and 5. Chapter 3 deals with the modeling of boiler furnace based on heuristic
approach. The mathematical procedures and intuitive assumptions that led to the development of heuristic equations that characterize the steady state behavior of the furnace of a boiler is discussed.

Chapter 4 presents the lower order modeling of the circulation system of a boiler based on system identification techniques. The need for lower order modeling, the methodology and the findings are summarized in this chapter.

Chapter 5 presents an elaborate discussion on the lower order modeling of boiler sub systems like the super-heaters, reheaters and their integration with the circulation system.

The novel techniques adopted and the results obtained are presented in this chapter. The results obtained from all the modules are analyzed and validated in Chapter 6. The validation of model based on heuristic approach and lower order modeling has been presented.

The overall conclusion of the research and scope for further research is presented in Chapter 7.