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Development of Detailed Mathematical Model of a 500 MW Utility Boiler Based on Chemical and Thermodynamic Equations

Rajalakshmy[1]*, Subha Hency Jims[2], S. Dharmalingam[3], J. Jayakumar[4]

[1,2]Department of Electronics and Instrumentation Engineering, Karunya University, Coimbatore, India.
[3]Department of Instrumentation and Control Engineering, National Institute of Technology, Trichy, India.
[4]Department of Electrical and Electronics Engineering, Karunya University, Coimbatore, India.

Abstract : Environmental impact of pollutant emission and increased efficiency are the most important challenges faced by the industries in the modern world. In a power sector industry, the environmental impact of boilers may be due to air emissions from fuel combustion, untreated water and disposal of ash. Therefore, it is essential to adopt strategies that achieve better combustion efficiency with the least amount of pollutant emissions. One of the effective means of efficiency enhancement in boilers is an improvement of the steam generation control system. An essential tool for such an improvement is to develop a valid boiler model. This paper describes the chemical reactions and procedures involved in developing the detailed mathematical model of a pulverized, fossil fuel fired 500 MW utility boiler.

Keywords : Boiler, Mathematical Model, Thermal Power Plant, Boiler Efficiency.

Introduction

The enormous impact of fossil fuel heating systems on the environment continually draws a lot of global attention. The current global scenario faced by fossil fuel power units is characterized by many challenges like minimizing the cost of power generation, responding instantaneously to electrical grid demands, demands for a high degree of availability and reliability, meeting stringent government regulations on environmental impact, conservation of natural resources etc.[1] Excess air ratio is one of the operating variables affecting both thermal and environmental performances of a boiler. The rate of NOx emissions in the boiler is found to drastically reduce with a decrease in excess air ratio[2]. The thermal efficiency and operational reliability of boilers is affected by the excess air.[3]

An increase in the amount of the excess of air in the boiler furnace leads to a reduction in the adiabatic flame temperature, which in turn will prompt an increase in the heat transfer coefficients of the boiler components like superheaters and reheaters, causing a reduction in the flue gas temperature. The O_2 concentration in the furnace increases with an increase in the excess air ratio that results in the rise of the flame temperature in the boiler. This further leads to a drop of the temperature in the superheater sections, and eventually affects the boiler efficiency.[4,5] In order to ensure complete combustion and safe operation, a boiler should always be supplied with additional combustion air than is theoretically required. If the combustion air is not sufficient, there will be a rapid buildup of carbon monoxide in the flue gas and, in extreme cases, smoke will be produced.[6]

In recent times, there has been a drastic increase in activities for operator training and boiler efficiency enhancement through improved control strategies[7,8]. These efforts essentially require the development of an adequate mathematical model. But, it has been observed that the number of detailed, well-documented mathematical boiler models available in the current literature is rather limited. The models available in the open literature are essentially those presented by Bell and Astrom.[9] A non-linear dynamic model for drum boilers is derived from first principles approach[10]. A linearized model of the drum-downcomer-riser loop based on detailed mathematical calculations has been derived[11]. A time invariant model based on lumped parameter approximation has also been attempted[12]. Lower order models of dynamically significant boiler subsystems based on input-output records generated from the detailed physical model of a 210MW thermal power plant[13]. Researchers have developed the mathematical model of a 200 MW boiler based on first principles approach[14]. A non-linear mathematical model of a 100MW power boiler for dynamic analysis has been developed.[15]

A heuristic approach to model the furnace of a 500MW utility boiler is presented.[16] The efficacy of classical tuning method to control main steam pressure of a 500MW boiler has been discussed.[17] The calculation of PID controller to control the critical parameters for a 500 MW steam generator is analysed.[18] The development of reduced order model of circulation system of a 500MW utility boiler is presented.[19] The analysis of the critical parameter variations in open loop method of a multivariable control system is explained.[20]

This paper presents the procedure for development of the detailed mathematical model and the chemical equations involved in a 500 MW utility boiler.

2. System Description

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. Coal and air is burnt in the furnace in which the chemical energy is converted to thermal energy. This thermal energy is used to heat water from the boiler drum to turn it to steam and superheat it. The superheated steam is used to drive a steam turbine. In this process, thermal energy is turned into mechanical energy. The steam turbine is coupled to the rotor of an electrical generator, where the mechanical energy is converted to electrical power. After it passes through the turbine, the steam is condensed in a condenser and recycled to where it was heated. The path taken up by the water-steam in this process is called Rankine cycle.

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 water walls receive the water from the downcomers 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 downcomers, 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.

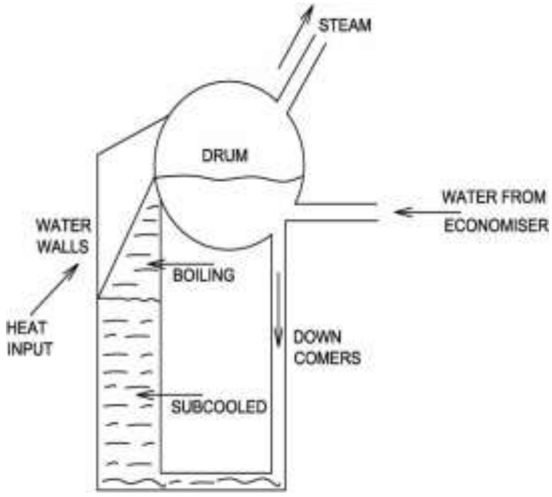

Fig. 1 Schematic Diagram of Circulation system

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. 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.

3. 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), sulphur (S) etc., carbon, hydrogen and sulphur are the combustible components. Owing to the extremely high temperatures produced during combustion, the carbon and hydrogen present in the coal are oxidized to carbondioxide(CO_2) and water(H_2O) respectively. Similarly the sulphur 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 chemical reactions involved in the combustion process are described in the following equations. The calculations pertaining to determination of the stochiometric air required for combustion is also presented.

$C + O_2 \quad CO_2 \rightarrow$

1 Kg of C requires 2.6644 Kg of O_2 and gives 3.66 Kg of CO_2

$2\ H_2 + O_2 \quad 2H_2O \rightarrow$

1 Kg of H_2 requires 7.937 Kg of O_2 and gives 18Kg of H_2O

$S + O_2 \quad SO_2 \rightarrow$

1 Kg of ‘S’ requires 0.9978 Kg of O_2 and gives 18 Kg of H_2O
Total O_2 required = CO_2 + HO_2 + O_2S - O_2 in Fuel
Stoichometric dry air=(O_2 Total/K-O_{2Frac}) x (1-(Carbon Loss %/100)O $_2C/O_2$ total))
Where K - O_{2Frac} = 0.2315
Calculated Wet Air = Stoichometric dry air x (1 + M_{amb})
M_{amb}=Moisture in ambient air=0.013
Excess air = Excess air%/100

4. First Principles Approach for Boiler Modeling

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

- Linear or Non-Linear Algebraic Equations.
- Linear or Non-Linear Differential Equations
- Transfer Functions
- Neural Networks

The mathematical model of a boiler based on first principles approach involves the mass balance, energy balance and material balance relations. The heat transfer actions that occur in a boiler is shown in Fig.2.

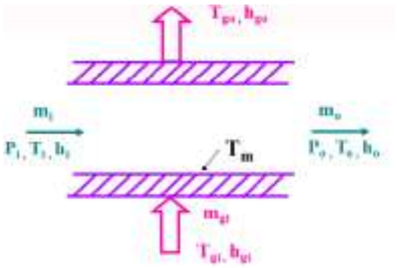

Fig. 2. Heat Transfer in a boiler

$$m_i - m_o = V \frac{d\rho}{dt} \qquad \text{….(1)}$$

$$m_i h_i - m_o h_o + Q_{mf} = V \frac{d(\rho h)}{dt} \qquad \text{…..(2)}$$

$$P_i - l_f \frac{m^2_i}{\rho_i} = P_o \qquad \text{…..(3)}$$

Eq. (1) represents the Mass Balance Equation where
m_i – Mass flow rate of steam Inlet
m_0 - Mass flow rate of steam Outlet
V – Volume of the boiler tubes
ρ - density of steam
Eq. (2) represents the Energy Balance Equation where
h_i – Enthalpy of Inlet Steam
h_0 – Enthalpy of Outlet Steam
Eq. (3) represents the Momentum Balance Equation where
P_i – Inlet Pressure
$W_{si} - W_{so} + W_{wa} = V_s\, dR_{so}/dt$
$W_{si}h_{si} - W_{so}h_{so} + W_{wa}h_{wa} + Q_{ms} = V_s\, d(R_{so}h_{so})/dt$
$Q_{gm} - Q_{ms} = MC_m\, dT_m/dt$

$$W_g(C_{si}T_{gi} - C_{go}T_{go}) - (Q_{gm} - Q_{df}) = V_gCgo \frac{dTgo}{dt}$$

A combination of the above equations comprise the mathematical model of a boiler. A mathematical model basically 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. 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

5. Boiler Efficiency Calculations

To optimize the cost of the fuel, it is essential to ensure the efficiency of the boiler. The boiler will not work at its rated efficiency at all times. Efficiency of the boiler has to be monitored properly. Else this will affect the performance of the boiler in terms of loss in controlled variables like main steam pressure and main steam temperature.

Boiler efficiency = 100- Total losses.

Where

Total losses = Unburnt carbon loss +Dry gas loss + Fuel moisture loss + Fuel Hydrogen loss + Air moisture loss + Radiation loss + Unaccounted losses

Unburnt Carbon losses = (Fb x Unburnts in bottom ash/(100-Unburnts in bottom ash)) + Fr x Unburnts in Fly ash/(100-Unburnts in Fly ash)) x (Ash percentage/100) x (higher heating value of carbon/HHV of fuel)
Fb - Distribution of Bottom ash
Ff - Distribution of Fly Ash

Dry gas loss = WgxCpm x (Tg exit – Tair)
Cp_1 = Cpgm(VCO2, VSO2, VN2, VO2, Tgexit)
Cp_2= Cpgm(VCO2, VSO2, VN2, VO2, Tair)
Cpm = (Cp1 +Cp2)/2

Fuel Moisture Loss = H_2O% in Fuel/100 x (E_1-E_3)

Air Moisture loss = $M_{amb}W_{da}(E_1-E_2')$
E_2' - enthalpy of entering Air at T_{air} and Pressure

Radiation loss (Heat duty at Max. Continous rating/Heat duty) x radiation loss at maximum continuous rating

Heat duty of a boiler is the summation of all duties.

1. Superheater(SH) Duty
2. Additional SH duty due to SH spray
3. RH duty
4. Additional Duty due to RH Spray

Duty = Flow (Kg/hr)(Outlet Enthalpy in Kcal/kg- Inlet Enthalpy in Kcal/Kg)

Unaccounted loss

Manual entry- if manual entry is zero a loss of 1.2% is taken into consideration

6. Results and Discussions

The model equations are implemented as a computer program, thus representing the detailed mathematical model of a complete boiler. For validation purpose, the dimensions of a 500 MW utility boiler has been utilized. The open loop response of main steam pressure in the boiler for a step change in the calorific value of fuel from 3300Kcal/Kg to 3280 Kcal/kg has been obtained using the detailed mathematical model. The characteristics obtained show that the detailed mathematical model developed is in good conformity with the physical process.

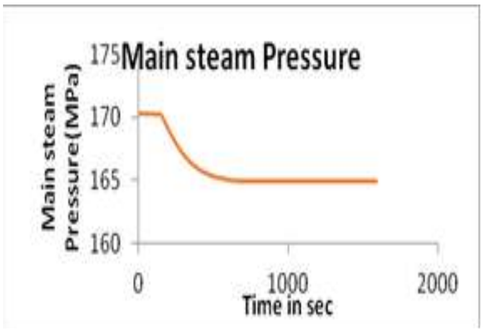

Fig. 3. Step Response of Main Steam Pressure

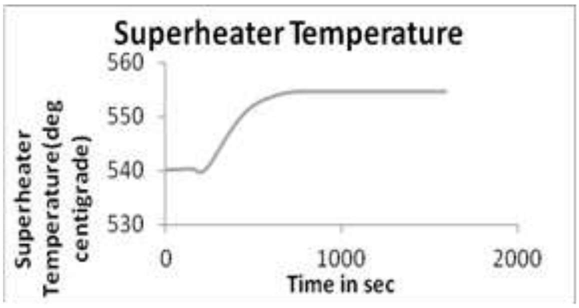

Fig. 4. Step Response of Superheater Steam Temperature

Fig 3. shows the step response of Main Steam Pressure whereas the variation of superheater temperature for a step change in calorific value of the fuel is shown in Fig.4. From the open loop characteristics, it can be concluded that developing the mathematical model.

7. Conclusion

The chemical equations concerned with the reactions that takes place in a 500 MW utility boiler is discussed and the efficiency calculations are presented. The first principle approach for mathematical modeling has been applied to describe the transient behavior of 500 MW boiler. In this paper, the time domain performance of critical variables like main steam pressure, temperature for a change in the heating value of coal has been obtained. The results prove that the response of the system depends on the efficiency, mathematical model and the chemical reactions involved.

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