Mathematical Modelling of Boiler

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Abstract- *Power plants are undoubtedly the place where electricity is produced. now most of the power plant, chemical energy that is fuel or any combustible substances can be converted into heat, and then power production can be done. The boiler is the main part of the power plant. A steam boiler is a system consist of number of components. The steam boiler's efficiency and safety is affected due to pressure variation phenomenon of boiler[4]. In this project a simple mathematical model describing the thermodynamic processes, which take place inside the furnace, is presented. The simulation model is applied to a boiler. Each component of boiler has been modeled individually and after that they are fitted together, the complete boiler can be simulated. To build the model a real industrial boiler is taken as a reference.*

I. INTRODUCTION

The boiler's operating conditions is very necessary to control because the high pressures and temperatures are the main hazard problems and it has the risk of explosion. The manufacturing cost, operating cost and maintenance cost of steam boiler is very high.The operating conditions of steam boiler are very complex to control because all the variables (pressure, temperature, flow, level) are interrelated. Taking measurement directly on boiler is very difficult due to dangers from the operating conditions and not economical That is why we use mathematical modeling method. Basically we concentrate on three accessories of boiler as follows Boiler furnace model.

1)Primary Superheater model
2)Secondary superheater model

What is mathematical modeling:- Mathematical modeling is the description of process using mathematical concept and mathematical equation.[1] Mathematical model can take many forms including dynamical system, statistical model, differential equation.

The advantages of using mathematical models can be summarized as follows:

- A process can be analyzed in depth, determining which variables or parameters are critical and have a significant effect on overall system behavior[2].
- They can be used for operator training purposes. [2]
- They are of great help to determine best possible Operating conditions.[2]

1] BOILER FURNACE:

The behavior of the boiler furnace is derived by mass and energy balances. The mass balance for furnace is given by, Rate of change of furnace gas flow = Fuel flow + Air flow + Recirculation gas flow – gas flow through boiler.

This equation is mathematically represented as:-

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

Where,

ρ_{eg}	–	Density of furnace gas
F_f	–	Fuel flow
F_a	–	Air flow
F_r	–	Recirculation gas flow
F_{eg}	–	Mass flow of the boiler
V_{bf}	–	chamber volume of boiler

The energy balance for furnace is given by:

Rate of change of energy of hot gas=Energy from fuel input + Energy from air input + Energy from recirculation – Heat energy transferred to risers – Heat energy transferred to SSH – Heat energy carried by furnace gas.

This equation is described by the differential equation,

$$V_{bf}\frac{d}{dt}(\rho_{eg}h_{eg}) = C_fF_f + h_aF_a + h_rF_r - q_r - q_s - F_{eg}\varepsilon_{(1+}e_x/100)\, h_{eg} \ldots(2)$$

Where,

h_{eg} – Specific enthalpy of furnace gas
C_f – Calorific value of coal
h_a – Specific enthalpy of air
h_r – Specific enthalpy of Recirculation gas
q_r – Heat transferred by radiation to risers
q_s – Heat transferred to SSH
ε – Stoichiometric air/fuel volume ratio
e_x – Percentage excess air level

$\frac{dh_{eg}}{dt} = \frac{1}{V_{bf}\rho_{eg}}$ = $(C_f - h_{eg})F_f + (h_a - h_{eg})F_a + (h_r - h_{eg})+F_r + h_{eg}F_{eg} - q_r - q_s - F_{eg}\,\varepsilon$

$e_x/100)h_{eg}$ ………(3)

$\frac{dh_{eg}}{dt} = \frac{1}{V_{bf}}(F_f + F_a + F_r - F_{eg})$ ……(4)

By using Stefan –Boltzman law of radiation we can determine q_r and q_s

$q_r = \eta\dot{\theta}a_r\,\sigma(T_g^4 - T_w^4),\quad T_w^4 \ll T_g^4$ …….(7)

$q_s = \eta^1(1-\theta)a_r\,\sigma(T_g^4 - T_m^4)$ ……(5)

Here, θ is burner tlit angle, a_r heat transfer area of furnace, σ is the Stefan Boltzman constant, T_g is furnace gas, T_w is riser wall temperature and T_m is SSH metal temperature.η and η^1 are attenuation coefficients for the riser and SSH respectively

$T_g = \frac{h_{eg}}{C_{pg}}$…….(6)

C_{pg} is specific heat exhaust gas at constant pressure. .

$p_g = \eta_g\,\mu\rho_{eg}\,T_g$

If O_a denotes the content of fresh air in the recirculation, the percentage excess air in the furnace gas e_x be computed as given below:

$e_x = 100(F_a + O_a F_r - F_f\,\varepsilon)\frac{1}{F_f\,\varepsilon}$ ……….(7)

The heat energy carried by the hot gas after the SSH is given

$q_g = C_fF_f + h_aF_a + h_rF_r - q_r - q_s$ ……….(8)

Nonlinear state space model

The boiler furnace model thus, comprises the nonlinear differential equations and a set of algebraic equations. In order to obtain a state-space model for the system, we define a 2x1 state vector X(t), a 5x1 input vector U(t) and a 5x1 output vector Y(t) for the boiler furnace as follows:

$$X(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = \begin{bmatrix} h_{eg}(t) \\ \rho_{eg}(t) \end{bmatrix}$$

$$U(t) = \begin{bmatrix} u_1(t) \\ u_2(t) \\ u_3(t) \\ u_4(t) \\ u_5(t) \end{bmatrix} = \begin{bmatrix} F_f(t) \\ F_a(t) \\ F_r(t) \\ h_r(t) \\ \theta(t) \end{bmatrix}$$

$$Y(t) = \begin{bmatrix} y_1(t) \\ y_2(t) \\ y_3(t) \\ y_4(t) \\ y_5(t) \end{bmatrix} = \begin{bmatrix} q_r(t) \\ q_s(t) \\ q_g(t) \\ T_g(t) \\ P_g(t) \end{bmatrix}$$

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

X = f(X, U) ……..(9) (1 +

The output Y(t) is expressed in terms of the state vector X and input vector U as

Y (t) = g(X, U)

The state equation (12) is linearized about the operating point (Xo, U0) and the linearized component equation is represented as

$\tilde{X} = A + \tilde{X} + B\tilde{U}$

Where $\tilde{X} = X - X_0$ and $\tilde{U} = U - U_0$

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

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

The individual elements of A and B are derived and the results are listed

$$\frac{\partial f_1}{\partial x_1} = \frac{1}{\rho_{eg}V_{bf}}\left\{F_f - F_a - F_r + \left[1 - \varepsilon\left(1 + \frac{e_x}{100}\right)\right]\left(\frac{\eta_f h_{eg}\mu\rho_{eg}}{C_{pg}} + F_{eg}\right)\frac{4a_r\sigma T_g^3}{C_{pg}}\left(\eta^\theta + \overline{1-\theta}\eta^1\right)\right\} \quad \text{……(10)}$$

$$\frac{\partial f_1}{\partial x_2} = \frac{1}{V_{bf}\,\rho_{eg}^2}\left[(C_f - h_{eg})F_f + (h_a - h_{eg})F_a + (h_r - h_{eg})F_r + h_{eg}F_{eg} - q_r\right] \quad \text{…(11)\_}$$

$$\frac{\partial f_2}{\partial x_1} = -\frac{\eta_f\mu\rho_{eg}}{V_{bf}C_{pg}} \quad \text{…(12)}$$

$$\frac{\partial f_2}{\partial x_2} = -\frac{\eta_{f\mu}T_g}{V_{bf}} \quad \text{….(13)}$$

$$\frac{\partial f_1}{\partial u_1} = \frac{1}{V_{bf}\,\rho_{eg}}\left(C_f + h_{eg}F_{eg}\left[\frac{F_a + OaF_r}{F_r\,2}\right] - \varepsilon h_{eg}\left(1 + \frac{e_x}{100}\right)\right) \quad \text{…(14)}$$

$$\frac{\partial f_1}{\partial u_2} = \frac{1}{V_{bf}\,\rho_{eg}}\left(h_a - \frac{h_{eg}F_{eg}}{F_f}\varepsilon h_{eg}\left(1 + \frac{e_x}{100}\right)\right) \quad \text{…(15)}$$

$$\frac{\partial f_1}{\partial u_3} = \frac{1}{V_{bf}\,\rho_{eg}}\left(h_r - \frac{h_{eg}F_{eg}\,Oa}{F_f}\varepsilon h_{eg}\left(1 + \frac{e_x}{100}\right)\right) \quad \text{…(16)}$$

$$\frac{\partial f_1}{\partial u_4} = \frac{F_r}{V_{bf}\,\rho_{eg}} \quad \text{…(17)}$$

$$\frac{\partial f_1}{\partial u_5} = \frac{ar\sigma}{V_{bf}\,\rho_{eg}}\left(\eta^1(T_g^4 - T_m^4) - \eta(T_g^4 - T_w^4)\right) \quad \text{…(18)}$$

$$\frac{\partial f_2}{\partial u_1} = \frac{1}{V_{bf}} \quad \text{…(19)}$$

$$\frac{\partial f_2}{\partial u_2} = \frac{1}{V_{bf}} \quad \text{…(20)}$$

$$\frac{\partial f_2}{\partial u_3} = \frac{1}{V_{bf}} \quad \text{…(21)}$$

$$\frac{\partial f_2}{\partial u_4} = 0 \quad \text{…(22)}$$

$\frac{\partial f_2}{\partial u_5} =$ -η_f…(23)

State space model:

$$A = \begin{bmatrix} -2.00135 & 244.111282 \\ -0.00236 & -0.192285 \end{bmatrix}$$

$$B = \begin{bmatrix} 7.0959 & -1.7815 & -0.7815 & 0.0130 & 37.0643 \\ 0.000192 & 0.000192 & 0.000192 & 0.0000 & 0.0228 \end{bmatrix}$$

The operating point chosen is

$$X_0 = \begin{bmatrix} 289.896 \\ 0.45052 \end{bmatrix}$$

$$U_0 = [119.3\ x\ 10^3 \quad 715.8\ x\ 10^3 \quad 109.9\ x\ 10^3 \quad 169.92 \quad 0.88041]^T$$

2] PRIMARY SUPER HEATER

The poor attention of the power plant experts to the PSH may be due to the fact that the PSH is not directly associated with the boiler control systems. Besides there is no manipulated variable in the PSH for controlling the process variables of the boiler. One must remember that the PSH is a bridge between the boiler drum and the SSH and it is a significant heat exchanger for the boiler.

Energy Balance

In the mathematical treatment of the PSH, a single section lumped parameter representation is used as shown in figure and the mass and energy balance equations are written. Applying the law of conservation of energy for the PSH steam line and the PSH tube separately, the energy balance equations are written as follows:

(a) Energy balance for steam

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

i.e,

$$V_{sp}\, Y_{sp} \left[\frac{\partial U_{sp}}{\partial T_{sp}}\right] = \frac{dT_{sp}}{dt} = a_{ip} a_{msp} \ (T_{mp} - T_{sp}) + F_d\, hd - F_{sp}\, h_{sp} \text{ ……(24)}$$

where T_{sp} - PSH outlet steam temperature

T_{mp} - PSH metal temperature

V_{sp} - Volume of PSH

Y_{sp} - Specific weight of steam in PSH

U_{sp} - Internal energy of steam

a_{ip} - Inside heat transfer area of PSH

a_{msp} - Metal to steam heat transfer coefficient

F_{sp} - Mass flow rate of steam in PSH

h_{sp} - Enthalpy of steam in PSH

From thermodynamical principles, we know that the internal energy of steam u_{sp} is a function of steam temperature T_{sp} and volume V_{sp} According to Joule's law for gases (steam in this case), the internal energy us is independent of volume V_{sp} and depends only on temperature T_{sp}.

$$0\left[\frac{\partial U_{sp}}{\partial V_{sp}}\right]_{T_{sp}} = 0$$

$$\frac{du_{sp}}{dT_{sp}} = \left[\frac{\partial U_{sp}}{\partial T_{sp}}\right]_{V_{sp}} = Cv_p$$

Besides, it is assumed that $F_d = F_{sp}$

$$\frac{dT_{sp}}{dt} = \frac{1}{T_{sp}\, Y_{sp}\, C_{vp}}\, a_{ip} \propto_{msp} \left(T_{mp} - T_{sp}\right) + F_d\, hd - F_{sp}\, h_{sp}$$

$$\frac{dT_{sp}}{dt} = \frac{1}{T_{sp}\, Y_{sp}\, C_{vp}} \left[\propto_{ip} \propto_{msp} \left(T_{mp} - T_{sp}\right) + F_{sp}\, hd - F_{sp}\, h_{sp}\right]$$

……(24)

(b) Heat balance of PSH tube

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

$$M_{mp}\, C_{mp} \frac{dT_{mp}}{dt} = a_{op} \propto_{gmp} (T_{gp}\, T_{mp}) - a_{ip}\, x_{msp} (T_{mp}\, T_{sp}) \quad \text{…(25)}$$

M_{mp} - Mass of PSH section

C_{mp} - Specific heat of PSH metal

a_{op} - Outside heat transfer surface area of PSH

$\propto_{gmp}$ - Gas to metal heat transfer coefficient

T_{gp} - Gas temperature at PSH

State-space model

a linear second order state space model is derived for the PSH as given below :

$X_P = A_P\, X_P + B_P\, U_P$

Where state vector

$X_P = \begin{bmatrix} T_{sp} \\ T_{msp} \end{bmatrix}$ And input vector $U_P = \begin{bmatrix} T_d \\ T_{gp} \end{bmatrix}$

Ap is the 2 x 2 System matrix and Bp is the 2 x 2 Input matrix. The nominal values of PSH variables and parameters collected during the study of 210MW boiler. Using that parameters, the system matrix A_p and Input matrix B_p are computed as:

$$A_P = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} \end{bmatrix} \quad B_P = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \frac{\partial f_1}{\partial u_2} \\ \frac{\partial f_2}{\partial u_1} & \frac{\partial f_2}{\partial u_2} \end{bmatrix}$$

$$A_P = \begin{bmatrix} \frac{a_{ip} \propto_{msp}}{T_{sp}\, Y_{sp}\, C_{vp}} & \frac{a_{ip} \propto_{msp}}{T_{sp}\, Y_{sp}\, C_{vp}} \\ \frac{a_{ip} \propto_{msp}}{M_{mp}\, C_{mp}} & \frac{-a_{op} \propto_{gsp} - a_{op} \propto_{msp}}{M_{mp}\, C_{mp}} \end{bmatrix} \quad B_P = \begin{bmatrix} \frac{a_i \propto_{msp}}{T_{sp}\, Y_{sp}\, C_{vp}} & 0 \\ 0 & \frac{a_{op} \propto_{gmp}}{M_{mp}\, C_{mp}} \end{bmatrix}$$

3] SECONDARY SUPERHEATER MODEL

The function of primary and secondary supearheater is same but in secondary superheater the temperature of steam is increase upto extreme level. It is basically use to increase the temperature of steam above its saturation level.

The maximum work efficiency is achieved in a thermal power plant when the steam temperatures are maintained at the highest possible values permitted by the plant metallurgy. Therefore, in recent years there has been a growing interest in the optimization of control systems for thermal power plants with more emphasis on steam temperature control. The design procedure for the steam temperature optimal control system normally makes use of a model for the SSH in the state-space form. In this section, the analytical modelling approach is used for developing a state-space model for the SSH.

Continuous-time state space model: The main steam temperature T_s is influenced by three different variables; the heat transfer rate from the hot gas through the superheater tubes, the SSH inlet steam temperature T_{si} and the main steam flow F_s . Pressure fluctuations within the SSH have a limited influence on Ts and may be neglected. Adequate modelling of the SSH requires a distributed parameter approach. However, a reasonable lumped parameter approximation is used to keep the SSH model a control oriented one. Applying the law of conservation of energy for the main steam line and the SSH lube separately, the energy balance equations are written.For the main steam line,

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

$$V_{\mathbf{s}} \frac{d}{dt} \ (P_s h_s) \ = \ a_i \propto_{mp} (T_m - T_s) \ + \ F_{sp} h_{sp} + \ (h_{spa} - h_f) \ F_{spa} - F_s h_s \qquad \ldots\ldots(34)$$

Where,

V_s - Control volume of SSH

P_s - Density of SSH steam

h_s - Enthalpy of SSH steam

a_i - Inside heat transfer area of SSH

$\propto_{mp}$ - Metal to steam heat transfer coefficient

h_f - Specific enthalpy of evaporation

and also

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

i.e. $F_s h_{si} = F_{sp}.h_{sp} + F_{spa} h_{spa}$ …(34)

where h_{si} - Enthalpy of SSH inlet steam

h_{spa} - Enthalpy of attemperator spray water

from above equation we can write that,

$$V_s Y_s \left[\frac{\partial U_s}{\partial T_p}\right] \frac{dT_s}{dt} \ = \ a_i \propto_{ms} (T_m - T_s) \ + \ F_s + \ (h_{si} - h_s) \qquad \ldots\ldots.(35)$$

where Y_s is the specific weight of steam in the SSH and U_s is the internal energy of steam in the SSH

From thermodynamical principles, we know that the internal energy of steam us is a function of main steam temperature T_s and volume V_s

$$u_s = u_s (T_s - V_s)$$

Therefore, the change in internal energy can be expressed as

$$du_s = \left[\frac{\partial u_s}{\partial T_s}\right]_{V_s} dT_s + \left[\frac{\partial U_s}{\partial V_s}\right] T_s \, dV_s \qquad \ldots(36)$$

According to Joule’s law for gases (steam in this case), the internal energy us is independent of volume Vs and depends only on temperature Ts. Hence

$$\left[\frac{\partial U_s}{\partial V_s}\right]_{T_s} = 0$$

C_v denotes the specific heat of SSH steam at constant volume. Thus the partial derivative quantity is converted into the known quantity $C_{v.}$ We also know that $h_{si} = C_{si.}T_{si}$ and $h_s = C_s T_s$ where C_s is the specific heat of SSH steam.

The equation (31) can be written as

$$V_s Y_s C_v \frac{dT_s}{dt} \ = \ a_i \propto_{ms} (T_m - T_s) \ + \ F_s (C_{si} T_{si} - C_s T_s) \qquad \ldots\ldots(37)$$

Heat balance:

For the SSH tube, heat balance is written as

Heat energy stored in the SSH tube metal = Heat energy received from the hot gas - Heat energy transferred to steam

i.e

$$M_m C_m \frac{dT_m}{dt} \ = \ a_o \propto_{gm} (T_g - T_m) \ + \ a_i \propto_{ms} (T_m - T_s) \qquad \ldots(38)$$

Where,

M_{m-} Mass of SSH metal

C_m - Specific heat of SSH tube ao Outside heat transfer area

a_i - Inside heat transfer area

$\propto_{gm}$ -Heat transfer coefficient from gas to metal

Equations (43) and (44) indicate that the system response at any time $t > t_0$ can be determined from the initial values of variables T_s and T_m at $t = t_0$ together with the knowledge of the inputs T_{si} and T_g for $t > t_0$. Thus the state of the system is defined by a 2-element vector X_s as

$$X_s = \begin{bmatrix} T_s \\ T_m \end{bmatrix} = \begin{matrix} x_1 \\ x_2 \end{matrix}$$

T_{si} and T_g are selected as the control input variables. The control input vector, Us is a 2-element vector defined as

$$U_s = \begin{bmatrix} T_{si} \\ T_g \end{bmatrix} = \begin{matrix} u_1 \\ u_2 \end{matrix}$$

With the above notations, a state-space model for the SSH is formulated

$$A_s = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} \end{bmatrix} \quad B_s = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \frac{\partial f_1}{\partial u_2} \\ \frac{\partial f_2}{\partial u_1} & \frac{\partial f_2}{\partial u_2} \end{bmatrix}$$

State space model

$$A_s = \begin{bmatrix} \frac{a_i \propto_{ms} + F_s C_s}{V_s Y_s C_v} & \frac{a_i \propto_{ms}}{V_s Y_s C_v} \\ \frac{a_i \propto_{ms}}{M_m C_m} & -\frac{a_o \propto_{ms} + a_i \propto_{ms}}{M_m C_m} \end{bmatrix} Bs$$

$$= \begin{bmatrix} \frac{-F_s C_{si}}{T_s Y_s C_v} & 0 \\ 0 & \frac{-a_o \propto_{gm}}{M_m C_m} \end{bmatrix}$$

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

we can choose C as [1 0]

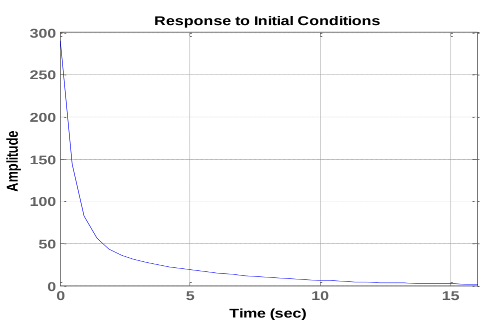
initial condition are

$$X_s = \begin{bmatrix} 491 \\ 501 \end{bmatrix}$$

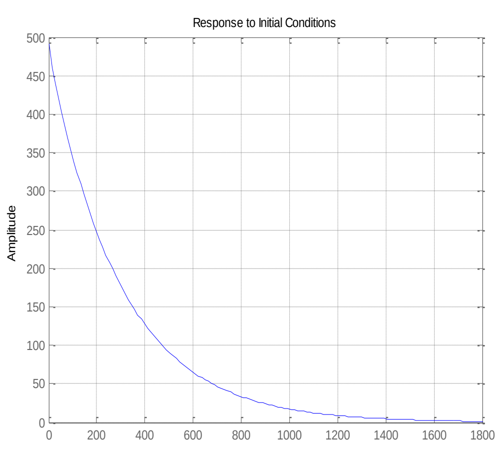
II. RESULTS

Step responses for initial condition of boilers parameters are drawn using MATLAB as shown below

I] Boiler furnace



II]Secondary superheater



III. CONCLUSION

This paper presents our preliminary work on development of mathematical modelling of boiler furnace, primary superheater, secondary superheater and simulation for initial condition of boiler parameters. simulation is carried out by matlab. The model consists of a number of sub models for the different components being present in the boiler. Each of the sub-models is build up as a set of Differential-Algebraic Equations (DAE's). Subsequently the models are merged into a global model for the system.

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