Boiler Modelling and Optimal Control of Steam Temperature in Thermal Power Plants

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Abstract: Achieving accurate control of main steam temperature is a very difficult task in thermal power plants due to the large process lag (8 to 10 minutes) associated with the superheater system and there exists a deviation of ±10 °C in closed loop control. A control oriented boiler model and an appropriate optimal control strategy are the essential tools for improving the accuracy of this control system. This paper offers a comprehensive integrated 8th order mathematical model for the boiler and a Kalman Filter based state predictive controller for effectively controlling the main steam temperature within ±2 °C and to enhance the efficiency of the boiler. It is proved through simulation that the predictive controller method with Kalman filter state estimator and predictor is the most appropriate one for the optimization of main steam temperature control as compared to other methods. This control system is under field implementation in a 210 MW boiler of a thermal power plant.

Key words: State observer, Kalman filter, N-step prediction, pole placement controller, optimal controller, adaptive predictive controller.

1. Introduction

A coal-fired thermal power plant in general consists of a number of complex subsystems characterized by nonlinearity, uncertainty, large process lag and random load disturbances. The boiler furnace, drum, superheaters and reheaters are examples wherein these undesirable characteristics have to be accommodated gracefully to achieve optimum power generation from the plant. Traditionally, plant controller designers have developed control strategies based on Proportional-Integral-Derivative (PID) controllers for such types of processes and systems in the same way they did for simple processes. While the PID controllers have produced very good results in the case of simple deterministic plants, their performance was no closer to the expectation in the complex systems [1-3]. Therefore, controlling of such complex systems is not only technically challenging but also economically important vis-à-vis the energy crisis throughout the world.

In this background, automation vendors world over have developed advanced control techniques to realize accurate control of process variables and achieve maximum plant and energy efficiencies [4-6]. Obviously, besides achieving better product quality, the new control schemes seem to be very good energy conservation agents to meet world’s energy crisis likely to arise from the diminishing fossil fuels. The most relevant application of the multivariable optimal control techniques is the linear quadratic regulator for the steam temperature in the boiler of a 500 MW unit at the Kyushu Electric Company in Japan. This kind of steam temperature control schemes, including other state space identification, non-linear programming and model reference adaptive control techniques, have become a standard feature in Japanese fossil power...
plants during the last 25 years, allowing them to operate with highest levels of availability and thermal efficiency [7].

In principle, Adaptive Control seems to be well suited for overall power plant control. Recent approaches utilize artificial intelligence techniques with a judicious mix of conventional and advanced control techniques. Fuzzy set algorithms, neural network classifiers, genetic algorithm based tuning mechanisms, state observers and Kalman filter based process state estimators perform fault diagnosis and fault accommodation functions [8, 9]. In this paper, we make an attempt to illustrate the applications of Kalman filtering, state estimation and prediction in power plant optimization and control.

2. Thermal Power Plant Operation and Problems in Steam Temperature Control

Fig. 1 illustrates the schematic diagram for water, steam and flue gas flow lines of a drum type boiler. The feed water pressurized by the boiler feed pumps goes through many heat exchangers such as the economizer, drum-evaporator, Primary Superheater (PSH), Secondary Superheater (SSH) etc. and undergoes the phase change to steam. The saturated steam from the drum is superheated to the final required temperature in the PSH and SSH and fed in to the High Pressure (HP) turbine. After isentropic expansion there, the steam is reheated in the reheaters and fed into the Intermediate Pressure (IP) and Low Pressure (LP) turbines.

Fig. 2 illustrates the conventional superheater steam temperature control system that aims at the control of the SSH outlet temperature as the final target. This is a cascade control system employing PID Controllers that regulates the spray water flow in the attemperator so that the deviation of the main steam temperature from the set value is zero. Steam temperature at the inlet as well as the outlet are measured with thermocouples and fed to the PID Controllers. Spray water flow is measured using a differential pressure transmitter and a square root extractor. The main steam temperature controller also regulates the fuel flow rate for better control, if required.

However, the following problems exist while controlling the steam temperature using the scheme shown in Fig. 2:

(a) Owing to the inherent process dynamics, the SSH exhibits a large process lag ($\tau_p$) of the order of 8 to 10 minutes as shown in Fig. 3. This is an undesirable feature for the PID controllers.

(b) In a thermal power station, the highest work efficiency can be achieved by maintaining the highest possible steam temperatures as limited by plant metallurgy. If these temperatures can be controlled with extreme precision, they can be pushed closer to the set point value of 541 °C. With the conventional
control method described above, due to the boiler and superheater dynamics and associated large process lag, it takes a long time to estimate whether the amount of spray/fuel provided is proper or not. As a result, correction is delayed and a temperature deviation of minimum ± 10 °C occurs during load change as illustrated in Fig. 4. With an advanced control system, it is possible to reduce the temperature deviation and elevate the set point as close as to 539 °C.

(c) The value of \( \tau_p \) changes heavily according to factors such as main steam flow, heat value of fuel etc.

(d) The plant start-up time is nearly 330 minutes and during this time, fuel is used in an unproductive way. Further, during plant start-up, the process gain and time constant of the superheater system changes more than 10 times.

Fig. 3  SSH exhibits a large process lag (\( \tau_p \)) of the order of 8 to 10 minutes.

Fig. 4  Advanced control pushes the practical setpoint very close to the ideal setpoint.

3. Development of Steam Temperature Prediction Control System

3.1 Concept

The characteristics of the main steam temperature control can be improved to the optimum level by calculating the optimum amount of spray/fuel currently to be provided from the current value of the main steam temperature \( T_s \) and from the past data. In order to take care of the large process lag \( \tau_p \) associated with the SSH, a novel approach would be to predict the value of \( T_s(t) \) into the future for \( \tau_p \) secs using the Least Squares or Recursive estimation techniques and use the predicted value of \( T_s(t) \) as the measured variable for the conventional steam temperature control system as depicted in Fig. 5. If \( \tau_p \) accommodates N sampling periods in it, then an N-step prediction is essential for discrete time implementation of the system [10].

3.2 System Architecture

The new control system consists of six important building blocks namely: (1) conventional steam temperature control system, (2) boiler plant model in state space form, (3) Kalman filter state estimator, (4) adaptive process identifier, (5) N-step Kalman filter state predictor and (6) adaptive controller as shown in Fig. 6. The conventional steam temperature control system (employing PID controller) depicted in Fig. 2 is a proven control system and has been accepted by the thermal power plants since many years. Due to this reason, this control system is chosen as the basic building block for the predictive control system. Building blocks (2) to (6) are used to enhance and optimize the performance of building block (1) in order to obtain minimum possible steam temperature deviation from the setpoint in close loop control.

3.3 Statespace Model for Boiler Plant

From modelling point of view, the boiler is divided into five subsystems and for each subsystem, mathematical
models are developed from first principles following
the approaches of the previous works [11-13] and
applying the knowledge gained by the authors from
designing and commissioning of boiler automation
systems. Reheater model is not discussed here due to
space constraint and it is very similar to the SSH model.
The subsystem models are then integrated to obtain a
full-fledged 8th order integrated state space model for
the boiler. The nomenclature of system variables and
parameters used in the boiler plant model are given in
Appendices A and B. In general, the following
mathematical equations form the backbone of the
boiler model:

I. Boiler Furnace Model

\[
\frac{d}{dt} \rho_e = F_e + F_s + F_{1s} - F_{2s} \tag{1}
\]

\[
V_{st} \frac{d}{dt} (\rho_s h_{es}) = C_s F_s + h_s F_b + h_s q_s - q_s - F_{1s} e (1 + e_s / 100) h_{es} \tag{2}
\]

II. Boiler Drum Model

\[
\frac{d}{dt} \left[ (V_d - V_{sd}) \rho_d + V_{sd} \rho_{sd} \right] = F_d - F_{sd} \tag{3}
\]

\[
\frac{d}{dt} \left[ (V_d - V_{sd}) \rho_d + V_{sd} \rho_{sd} \right] = F_d - F_{sd} \tag{4}
\]

\[
P_s = 1701297.89 \rho_s + 36.93 \tag{5}
\]

\[
T_d = 968192.55 \rho_s + 274.405 \tag{6}
\]

\[
V_{sd} = \frac{1}{2} \int_{y=-l_s}^{y=+l_s} \int_{x=0}^{x=+l_s} \rho dV_d + 2 \int_{y=-l_s}^{y=+l_s} \int_{x=0}^{x=+l_s} \rho dV_d \tag{7}
\]

\[
f (l_d) + V_{sd} = \frac{1}{3} \pi l_d (3l - l_d) + \frac{\pi l_d^2}{2} + l_d \sin ^{1} \left( \frac{l_d}{r} \right)
\]

\[
+ \left( \frac{l_d}{r} \right) 2 \pi l_d - l_d^2 \tag{8}
\]

\[
l_{d, k+1} = l_{d, k} - f \left( \frac{l_{d, k}}{f} \right) \tag{9}
\]

III. Primary Superheater Model

\[
V_{sp} \frac{\partial u_{sp}}{\partial T_{sp}} \frac{dT_{sp}}{dt} = a_p \alpha_{sp} (T_{sp} - T_{sp}) + F_{sp} h_d - F_{sp} h_{sp} \tag{10}
\]

\[
du_{sp} = \left( \frac{\partial u_{sp}}{\partial T_{sp}} \right)_{\tau} dT_{sp} + \left( \frac{\partial u_{sp}}{\partial V_{sp}} \right) \frac{dV_{sp}}{dt} \tag{11}
\]

\[
M_{sp} C_{sp} \frac{dT_{sp}}{dt} = a_p \alpha_{sp} (T_{sp} - T_{sp}) - a_p \alpha_{sp} (T_{sp} - T_{sp}) \tag{12}
\]

IV. Attemporator Model

\[
F_{at} = F_{sp} + F_{at} \tag{13}
\]

\[
F_{at} \Delta h_{at} + h_{at} \Delta F_{at} = F_{sp} \Delta h_{sp} + h_{sp} \Delta F_{sp} + F_{qat} \Delta h_{qat} + h_{qat} \Delta F_{qat} \tag{14}
\]

\[
\Delta T_{at} = \frac{1}{F_{C_{at}}} \left( (h_{at} - h_{at}) \Delta F_{at} + F_{sp} C_{at} \Delta T_{sp} - (h_{at} - h_{at}) \Delta F_{at} \right) \tag{15}
\]

V. Secondary Superheater Model

\[
V_{s} \frac{\partial u_{s}}{\partial T_{s}} \frac{dT_{s}}{dt} = a \alpha_{s} (T_{s} - T_{s}) + F_{s} (h_{s} - h_{s}) \tag{16}
\]

\[
du_{s} = \left( \frac{\partial u_{s}}{\partial T_{s}} \right)_{\tau} dT_{s} + \left( \frac{\partial u_{s}}{\partial V_{s}} \right) \frac{dV_{s}}{dt} \tag{17}
\]

\[
M_{s} C_{s} \frac{dT_{s}}{dt} = a \alpha_{s} (T_{s} - T_{s}) - a \alpha_{s} (T_{s} - T_{s}) \tag{18}
\]

3.4 State Estimation and Prediction Using Kalman Filter

In order to deal with the stochastic variations and to
take into account of the inaccuracies in the boiler
models, a stochastic state space model for the SSH is
constructed as

\[
X_{i}(k) = \Phi_{i} X_{i}(k-1) + \Gamma_{i} U_{i}(k-1) + \Omega_{i} W(k-1)
\]

and

\[
X_{i}(0) = X_{i,a} \tag{19a}
\]

\[
Y_{i}(k) = C X_{i}(k) + V(k) \tag{19b}
\]

where \( \Phi_{i} \) and \( \Gamma_{i} \) are State and Input transition
matrices and \( \Omega \) is a coefficient matrix. The state, input
and observation vectors are represented by $X_s$, $U_s$ and $Y_s$ respectively. $w(k)$ and $v(k)$ are stationary, zero-mean, and gaussian white noise sequences. The Kalman filter [14, 15] is used to estimate the state vector of SSH by utilizing the plant dynamic model and process on-line measurements described by Eq. (19).

The filter algorithm is organized in five steps as given below with the notations $\hat{X}_s(k/k-1), \hat{X}_s(k/k)$, $\hat{X}_s(k+N/k)$ for the apriori, apposteriori and predicted state estimates respectively and $P(k/k-1), P(k/k), P(k+N/k)$ for the respective error covariance matrices:

\[
P(k/k) = \left[P^{-1}(k/k-1) + C^T R^{-1} C\right]^{-1} \tag{20}
\]

\[
K(k) = P(k/k)C^T R^{-1} \tag{21}
\]

\[
\hat{X}_s(k/k) = \hat{X}_s(k/k-1) + K(k)\left[Y_s(k) - C \hat{X}_s(k/k-1)\right] \tag{22}
\]

\[
\hat{X}_s(k/k-1) = \phi, \hat{X}_s(k-1/k-1) + \Gamma, U_s(k-1) \tag{23}
\]

\[
P(k/k-1) = \phi, P(k-1/k-1)\phi^T + \Omega Q \Omega \tag{24}
\]

The sequence of computations to be performed during each sampling period $\tau$ to obtain the predicted estimate $\hat{X}_s(k+N/k)$ is depicted in Fig. 7.

3.5 Adaptive Process Identification and Control

The control system makes use of a velocity type PID controller algorithm. The controller parameters (proportional gain $k_p$, integral time $\tau_i$ and derivative time $\tau_d$) are derived in terms of the identified model parameters $\hat{\phi}$, and $\hat{\Gamma}$. In order to achieve a stable control system, the closed loop poles in the Z-domain are fixed inside the unity circle. The derivation of the controller parameters in terms of the process model parameters need rigorous mathematical treatment and control system design and therefore, the same is not presented in this paper. This design ensures that whenever there is a change in the process vis-a-vis process gain, time constant and its environment, the controller parameters are updated automatically. To carryout adaptive process identification and obtain $\hat{\phi}$, and $\hat{\Gamma}$, the innovation sequence of the Kalman filter is used. The authors can also perform this task by constructing an augmented state vector with the system parameters and then estimating it by extended Kalman filter.

The predictive control algorithm for controlling $T_s$ to the set point $T_{set}$ with the help of spray flow $F_{spa}$ is organized as follows:

\[
e_c(k) = \hat{T}_s(k+N/k) - T_{set} \tag{25}
\]

\[
F_{spa}(k) = F_{spa}(k-1) + k_p[e_c(k) - e_c(k-1)] + \frac{k_i}{\tau_i}[e_c(k) - 2e_c(k-1) + e_c(k-2)] \tag{26}
\]

3.6 System Simulation and Comparison of Performance

Fig. 8 gives a comparison of the controlled response of main steam temperature $T_s$ for five control methods namely, (i) PID controller, (ii) adaptive pole placement controller with observer, (iii) adaptive optimal controller with observer, (iv) adaptive optimal controller with Kalman filter state estimator and predictor, and (v) adaptive predictive controller with Kalman filter state estimator and predictor.

Control strategies (i) and (v) employ ordinary PID controllers; the former is tuned optimally by applying
the quarter-decay ratio criterion and the later by adaptive process identification scheme. Out of these two, the behaviour of (v) is well suiting to the plant. Though overshoot is minimum, the dynamic response of controller (ii) seems to be quite poor. State controllers (iii) and (iv) whose settings are derived based on optimal control algorithms always exhibit over-damped response, therefore they do not achieve maximum plant efficiency. Thus it is illustrated that the adaptive control method (v) which utilizes the Kalman filter for state estimation and prediction is the most appropriate controller for main steam temperature control as it gives lesser overshoot, better dynamic response and a compromised speed of response compared to the other controllers.

4. Conclusions

In recent years, thermal power plants have been required to attain higher efficiency due to increasing fuel costs, growing electricity demand and load varying operations. This has imposed stringent requirements on the control systems of the boiler, particularly to handle slow responses with high time constants. Due to this reason, the subject of boiler optimal control has been gaining more attention and significance in the power industry these days. As part of this new horizon in power plant control, we have developed and tested through simulation a mathematical model for the boiler and an adaptive predictive steam temperature control system; the major features of this research and development effort has been reported in this paper. We are now in the process of implementing this technology in running thermal power stations with the objective of reducing the steam temperature excursion from the current level of $+10\,\text{°C}$ to at least $+3\,\text{°C}$.

In order to control a real boiler operation with precision, one must build a three-in-one model comprising (i) boiler plant model, (ii) control system model and (iii) expert plant operator model. The development and implementation of (i) and (ii) vis-à-vis steam temperature control has been discussed briefly in this paper. Development of (iii) leads to the modelling of expert plant operators using the Neuro-Fuzzy-Genetic algorithms and this research would be a wonderful experience. The implementation of three-in-one model and its parameter and state estimation schemes envisage the applications of extended Kalman filters and appropriate schemes for tackling divergence problems. Our future research work is being focused in this direction.

References

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Appendix A: Nomenclature of System Variables and Nominal Values

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
<th>Nominal value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ&lt;sub&gt;eg&lt;/sub&gt;</td>
<td>Density of boiler furnace gas</td>
<td>0.45052</td>
<td>kg/m³</td>
</tr>
<tr>
<td>h&lt;sub&gt;eg&lt;/sub&gt;</td>
<td>Specific enthalpy of furnace gas</td>
<td>289.896</td>
<td>kcal/kg</td>
</tr>
<tr>
<td>F&lt;sub&gt;f&lt;/sub&gt;</td>
<td>Fuel flow (coal)</td>
<td>119.3 × 10³</td>
<td>kg/hr</td>
</tr>
<tr>
<td>F&lt;sub&gt;a&lt;/sub&gt;</td>
<td>Air flow</td>
<td>715.8 × 10⁶</td>
<td>kg/hr</td>
</tr>
<tr>
<td>F&lt;sub&gt;r&lt;/sub&gt;</td>
<td>Recirculation gas flow</td>
<td>109.9 × 10³</td>
<td>kg/hr</td>
</tr>
<tr>
<td>F&lt;sub&gt;eg&lt;/sub&gt;</td>
<td>Mass flow of furnace gas through the boiler</td>
<td>945 × 10³</td>
<td>kg/hr</td>
</tr>
<tr>
<td>T&lt;sub&gt;g&lt;/sub&gt;</td>
<td>Temperature of furnace gas</td>
<td>1301</td>
<td>°K</td>
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<tr>
<td>T&lt;sub&gt;m&lt;/sub&gt;</td>
<td>SSH metal temperature</td>
<td>823</td>
<td>°K</td>
</tr>
<tr>
<td>T&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Main steam temperature</td>
<td>814</td>
<td>°K</td>
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<tr>
<td>q&lt;sub&gt;r&lt;/sub&gt;</td>
<td>Heat transferred by radiation to risers</td>
<td>30.445 × 10⁷</td>
<td>kcal/hr</td>
</tr>
<tr>
<td>q&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Heat transferred to SSH</td>
<td>592.37 × 10⁴</td>
<td>kcal/hr</td>
</tr>
<tr>
<td>ρ&lt;sub&gt;d&lt;/sub&gt;</td>
<td>Density of drum steam</td>
<td>8.221 × 10⁻⁵</td>
<td>kg/cm³</td>
</tr>
<tr>
<td>ρ&lt;sub&gt;dw&lt;/sub&gt;</td>
<td>Density of water in drum</td>
<td>63.097 × 10⁻⁵</td>
<td>kg/cm³</td>
</tr>
<tr>
<td>F&lt;sub&gt;fw&lt;/sub&gt;</td>
<td>Feedwater flow</td>
<td>163.5023</td>
<td>kg/sec</td>
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<tr>
<td>h&lt;sub&gt;fw&lt;/sub&gt;</td>
<td>Enthalpy of feedwater</td>
<td>131.97</td>
<td>kcal/kg</td>
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<tr>
<td>F&lt;sub&gt;d&lt;/sub&gt;</td>
<td>Steam flow from drum</td>
<td>175.014</td>
<td>kg/sec</td>
</tr>
<tr>
<td>l&lt;sub&gt;d&lt;/sub&gt;</td>
<td>Drum level</td>
<td>88.90</td>
<td>cm</td>
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<tr>
<td>ρ&lt;sub&gt;d&lt;/sub&gt;</td>
<td>Steam pressure in the drum</td>
<td>176.8</td>
<td>kg/cm²</td>
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<tr>
<td>T&lt;sub&gt;d&lt;/sub&gt;</td>
<td>Saturated steam temperature</td>
<td>354</td>
<td>°C</td>
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<tr>
<td>V&lt;sub&gt;dw&lt;/sub&gt;</td>
<td>Drum water volume</td>
<td>20092734.7</td>
<td>cm³</td>
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<tr>
<td>u&lt;sub&gt;p&lt;/sub&gt;</td>
<td>Internal energy of steam in PSH</td>
<td>500.00</td>
<td>kcal/kg</td>
</tr>
<tr>
<td>T&lt;sub&gt;p&lt;/sub&gt;</td>
<td>Temperature of PSH steam</td>
<td>420.00</td>
<td>°C</td>
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<tr>
<td>T&lt;sub&gt;mp&lt;/sub&gt;</td>
<td>PSH metal temperature</td>
<td>430.00</td>
<td>°C</td>
</tr>
<tr>
<td>F&lt;sub&gt;r&lt;/sub&gt;</td>
<td>Mass flowrate of PSH steam</td>
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<td>kg/hr</td>
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<tr>
<td>T&lt;sub&gt;rp&lt;/sub&gt;</td>
<td>Gas temperature at PSH</td>
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<td>F&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Mass flowrate of SSH steam</td>
<td>690 × 10³</td>
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<td>F&lt;sub&gt;spa&lt;/sub&gt;</td>
<td>Attemperator spray flow</td>
<td>29984</td>
<td>kg/hr</td>
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<td>h&lt;sub&gt;ij&lt;/sub&gt;</td>
<td>Enthalpy of SSH inlet steam</td>
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<tr>
<td>h&lt;sub&gt;ip&lt;/sub&gt;</td>
<td>Enthalpy of PSH steam</td>
<td>720.00</td>
<td>kcal/kg</td>
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<tr>
<td>h&lt;sub&gt;pa&lt;/sub&gt;</td>
<td>Enthalpy of spray water</td>
<td>131.97</td>
<td>kcal/kg</td>
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<tr>
<td>T&lt;sub&gt;si&lt;/sub&gt;</td>
<td>SSH inlet steam temperature</td>
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<td>°C</td>
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<td>u&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Internal energy of steam in SSH</td>
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<td>kcal/kg</td>
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<tr>
<td>h&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Enthalpy of SSH steam</td>
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<td>kcal/kg</td>
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## Appendix B : Nomenclature of System Parameters and Nominal Values

<table>
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<th>Parameters</th>
<th>Description</th>
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<th>Unit</th>
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<tr>
<td>$V_{bf}$</td>
<td>Furnace combustion chamber volume</td>
<td>5200</td>
<td>m$^3$</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Stoichiometric air/fuel ratio</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>$e_x$</td>
<td>Percentage excess air level</td>
<td>5</td>
<td>%</td>
</tr>
<tr>
<td>$C_r$</td>
<td>Calorific value of coal</td>
<td>4400</td>
<td>kcal/kg</td>
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<tr>
<td>$h_a$</td>
<td>Specific enthalpy of air</td>
<td>59.7515</td>
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<td>$h_r$</td>
<td>Specific enthalpy of recirculation gas</td>
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<td>kcal/kg</td>
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<td>$V_d$</td>
<td>Volume of drum</td>
<td>40185469.4</td>
<td>cm$^3$</td>
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<td>$L$</td>
<td>Length of drum</td>
<td>1500</td>
<td>cm</td>
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<td>$R$</td>
<td>Radius of drum</td>
<td>88.9</td>
<td>cm</td>
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<td>$a_{ip}$</td>
<td>Inside heat transfer area of PSH</td>
<td>2100.25</td>
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<td>$\alpha_{msp}$</td>
<td>Metal to steam heat transfer coefficient of PSH</td>
<td>3316</td>
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<td>Outside heat transfer surface area of PSH</td>
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<td>$\alpha_{gmp}$</td>
<td>Gas to metal heat transfer coefficient of PSH</td>
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<td>$M_{mp}$</td>
<td>Mass of PSH section</td>
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<td>kg</td>
</tr>
<tr>
<td>$C_{mp}$</td>
<td>Specific heat of PSH metal</td>
<td>0.15</td>
<td>kcal/kg·℃</td>
</tr>
<tr>
<td>$C_{si}$</td>
<td>Specific heat of steam at SSH inlet</td>
<td>0.4634</td>
<td>kcal/kg·℃</td>
</tr>
<tr>
<td>$V_s$</td>
<td>Control volume of SSH</td>
<td>23.00</td>
<td>m$^3$</td>
</tr>
<tr>
<td>$\gamma_s$</td>
<td>Specific weight of steam in SSH</td>
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<td>kg/m$^3$</td>
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<tr>
<td>$a_{I}$</td>
<td>Inside heat transfer area of SSH</td>
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<td>m$^2$</td>
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<tr>
<td>$\alpha_{ms}$</td>
<td>Metal to steam heat transfer coefficient of SSH</td>
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<td>kcal/(hr·m$^2$·℃)</td>
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<tr>
<td>$M_m$</td>
<td>Mass of SSH metal</td>
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<td>$a_o$</td>
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<td>kcal/Kg·℃</td>
</tr>
<tr>
<td>$V_{sp}$</td>
<td>Volume of PSH</td>
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<td>m$^3$</td>
</tr>
<tr>
<td>$\gamma_{sp}$</td>
<td>Specific weight of steam in PSH</td>
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<td>kg/m$^3$</td>
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