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MODELLING APPROACH TO SUPERHEATER OF A BOILER

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ABSTRACT

In a coal fired thermal power plant the time constants of the boiler and firing control are much larger than the mechanical time constants of the turbine. The mechanical time constants of the turbine are again much larger than the electrical time constants of the generator-transformer. For this reason, modeling of boiler and its firing control are generally omitted and the turbine modeled approximately while modeling a turbo-generator for transient stability analysis. However, under small perturbation, there may be growing oscillation due to negative damping of the system which may eventually lead to dynamic instability. For analysis of dynamic stability, the turbine and the boiler along with super heater must be modeled in details. The present work gives an account of state space model of the super-heater of a boiler along with case studies. The model of the super-heater will be presented in this paper.

Key Words: *Thermal Power Plant, State Space Model, Mech. Time Constant, Elec. Time Constants and Dynamic Stability*

INTRODUCTION

The model is a miniature of the real object. It is used for understanding the behavior of an object for the prediction (Profos, 1955) of its performance. In essence, it is an analytical tool. A simulation (Anderson and Qualthrough, 1966) on the other hand, is a specially constructed model used for experimentation. It is used to improve or refine a system. A model (Anderson and Nanakram, 1975) or a simulation may be concrete or physical. An example is the micro-alternator (Bhattacharya, 1990) to represent a large alternator. It may be abstract or mathematical. A digital simulation of a power system is an example. The digital simulations are cheaper and can handle complicated models. Hence such models wide-spread use now a day.

A Power System has the Following Components

- a. The boiler and its firing control (for thermal power sets).
- b. The turbine and its governor control.
- c. The generator-transformer.
- d. The excitation control.
- e. The transmission line and interties.
- f. The VAR-Compensators and the load.

For electromechanical analysis, there is little need for modeling the boiler and its firing control as the associated time constants are large. This slow and sluggish control cannot (Idris *et al.*, 2000) appreciably affect the transient performance of the turbine-generator. Also the mechanical time constants are much larger than the electrical time constants. Therefore the turbine governor should be represented by a reduced order model to limit the dimension of the composite model.

The dynamic stability means long term stability of the system under small impact in the presence of various control actions. The various control actions in a thermal generating set are as given below.

- a. Boiler-Firing control.
- b. Trubine-Governor control.
- c. AVR-Excitation control.

For dynamic stability analysis, (Joo *et al.*, 2005) these control actions should be accounted for and detailed modeling of the components is necessary. The usual practice for dynamic stability analysis is to

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develop a state space description of the system for the fundamental relations. The state space model is inevitably non-linear. It contains limiter actions, dead-bands, saturation and other non-linearity (Yukong *et al.*, 2004). It is linearised about the quiescent point to develop the state matrix. The stability of the system is inferred (Li and Lin, 2002) from the Eigen values of the state matrix. If all the Eigen values are negative real or complex with negative real parts, then the system is stable.

The transfer function approach based on block diagram and signal flow graph can also be used on the linearised model. However, it gives only the input and output relation of a system. It can give the response characteristics of a system to a forcing function but cannot take care of the initial conditions and inter-relation of states. But the state space model (Xi-yun *et al.*, 2005) can take care of these effects. Therefore state-space approach (Anderson, 1997; Dangvan and Normanncyort, 1984) is much superior and has been used in this work.

The super heater

Nomenclature—

m_i	=	Mass flow rate at super heater inlet;(Kg/s)
m_o	=	Mass flow rate at super heater outlet;(Kg/s)
m_a	=	Mass flow rate of water for attemperation;(Kg/s)
h_i	=	Specific enthalpy at super heater inlet;(Kj/Kg)
h_o	=	Specific enthalpy at super heater outlet;(Kj/Kg)
h_a	=	Specific enthalpy of water for attemperation;(Kj/Kg)
h_{gi}	=	Specific enthalpy of flue gas at super heater inlet;(Kj/Kg)
h_{go}	=	Specific enthalpy of flue gas at super heater outlet;(Kj/kg)
ρ_o	=	Mean density of fluid in super heater; (Kg/m ³)
ρ_g	=	Mean density of flue gas; (Kg/m ³)
Q_{mf}	=	Heat flow rate from metal to fluid ;(Kj/s)
Q_{gm}	=	Heat flow rate from gas to metal; (Kj/s)
m_g	=	Mass flow rate of flue gas ;(Kg/s)
T_m	=	Mean temperature of super heater ;(0 Kelvin)
p_i	=	Fluid pressure at super heater inlet;(Pa)
p_o	=	Fluid pressure at super heater outlet;(Pa)
f	=	frictional coefficient ;(M ⁻⁴)
V	=	Total volume of steam flow passage of super heater ;(m ³)
V_g	=	Volume of flue gas space in super heater ;(m ³)
M	=	Total metal mass of super heater ;(Kg)
a	=	Mean total heat transfer area of super heater ;(m ²)
C_p	=	Thermal capacity of metal mass of super heater ;(Kj/Kg.0 k)
C_{pg}	=	Thermal capacity of flue gas ;(Kj/Kg.0 k)
α_{ms}	=	Heat transfer coefficient from metal to steam;(W/m ² .o k)
α_{gmc}	=	Heat transfer coefficient from gas to metal by convection;(W/m ² .0 K)

The Modeling Approach

A super-heater is modeled using mass, energy and momentum balance equations and is divided into two blocks viz. the gas to metal heat transfer block and the metal to fluid heat transfer block.

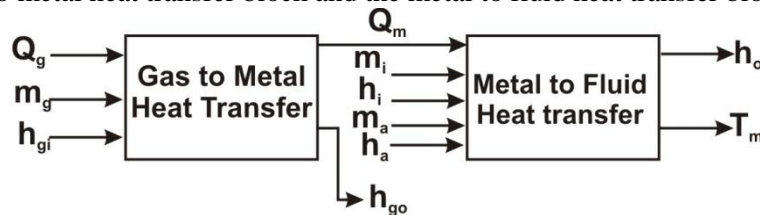


Figure 1

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The Gas to Metal transfer block of a super heater can be described by equations set—

$$Q_{gm} - Q_{mf} = MC_p \frac{d}{dt}(T_m) \quad 1.1 (a)$$

$$m_g(h_{gi} - h_{go}) - Q_{gm} = V_g \rho_g \frac{d}{dt}(h_{go}) \quad 1.1 (b)$$

$$Q_{gm} = \alpha_{gmc} a \left(0.5 \frac{h_{gi}}{c_{pg}} + 0.5 \frac{h_{go}}{c_{pg}} - T_m \right) \quad 1.1 (c)$$

$$m_i - m_o + m_a = V \frac{d}{dt}(\rho_o) \quad 1.1 (d)$$

$$m_i h_i - m_o h_o + m_a h_a + Q_{mf} = V \frac{d}{dt}(\rho_o h_o) \quad 1.1 (e)$$

$$Q_{mf} = \alpha_{ms} a (T_m - 0.5 f(h_o, p_o) - 0.5 f(h_i, p_i)) \quad 1.1 (f)$$

$$p_o = p_i - \frac{f}{m_o^2} \quad 1.1 (g)$$

It is observed that equations 1.1(a), 1.1(b) and 1.1(e) are non-linear. This non-linearity is eliminated by using Taylor's series expansion about the operating point, and neglecting its higher order terms. On linearization, we get the following expression for state equations:

$$\dot{X} = AX + BU \quad 1.2 (a)$$

$$Y = CX + DU \quad 1.2 (b)$$

Where,

X = column matrix for the state variables

$$= (X_1, X_2, X_3)^T = (h_o, h_{go}, T_m)^T \quad 1.2 (c)$$

U = column matrix for the input variables

$$= (U_1, U_2, U_3, U_4, U_5, U_6)^T = (m_i, h_i, m_g, h_{gi}, m_a, h_a)^T \quad 1.2 (d)$$

Y = column matrix for the output variables

$$= (Y_1, Y_2, Y_3)^T = (h_o, h_{go}, T_m)^T \quad 1.2 (e)$$

The state matrix =

$$A = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \quad 1.3 (a)$$

The input matrix =

$$B = \begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} & B_{15} & B_{16} \\ B_{21} & B_{22} & B_{23} & B_{24} & B_{25} & B_{26} \\ B_{31} & B_{32} & B_{33} & B_{34} & B_{35} & B_{36} \end{bmatrix} \quad 1.3 (b)$$

The output matrix =

$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} \quad 1.3 (c)$$

The following values are obtained for the (3, 3) state matrix A :

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$$\begin{aligned}
 A_{11} &= -\frac{(m_i + m_a)}{V\rho_o} - 0.5 \frac{\alpha_{ms} a}{V\rho_o} \frac{dT}{dh} \bigg|_{\substack{p=p_o \\ h=h_o}} \\
 A_{12} &= 0; \\
 A_{13} &= \frac{\alpha_{ms} a}{V\rho_o}; \\
 A_{21} &= 0; \\
 A_{22} &= -0.5 \frac{m_g}{V_g \rho_g} - \frac{\alpha_{gmc} a}{V_g \rho_g C_{pg}} \\
 A_{23} &= \frac{\alpha_{gmc} a}{V_g \rho_g}; \\
 A_{31} &= 0.5 \frac{\alpha_{ms} a}{MC_p} \frac{dT}{dh} \bigg|_{\substack{p=p_o \\ h=h_o}}; \\
 A_{32} &= 0.5 \frac{\alpha_{gmc} a}{MC_p C_{pg}}; \\
 A_{33} &= -\frac{\alpha_{gmc} a}{MC_p} - \frac{\alpha_{ms} a}{MC_p}
 \end{aligned} \tag{1.3 (d)}$$

The coefficients of the input matrix **B** are as given below:

$$\begin{aligned}
 B_{11} &= \frac{h_i - h_o}{V\rho_o}; & B_{12} &= \frac{m_i}{V\rho_o} - 0.5 \frac{\alpha_{ms} a}{V\rho_o} \frac{dT}{dh} \bigg|_{\substack{h=h_i \\ p=p_i}} & B_{13} &= 0; \\
 B_{14} &= 0; & B_{15} &= \frac{h_a - h_o}{V\rho_o}; & B_{16} &= \frac{m_a}{V\rho_o}; \\
 B_{21} &= 0; & B_{22} &= 0; & B_{23} &= \frac{h_{gi} - h_{go}}{V_g \rho_g}; \\
 B_{24} &= \frac{mg}{V_g \rho_g} - 0.5 \frac{\alpha_{gmc} a}{V_g \rho_g C_{pg}}; & B_{25} &= 0; & B_{26} &= 0; \\
 B_{31} &= 0; & B_{32} &= 0.5 \frac{\alpha_{ms} a}{MC_p} \frac{dT}{dh} \bigg|_{\substack{h=h_i \\ p=p_i}}; & B_{33} &= 0; \\
 B_{34} &= 0.5 \frac{\alpha_{gmc} a}{MC_p C_{pg}}; & B_{35} &= 0; & B_{36} &= 0;
 \end{aligned} \tag{1.3 (d)}$$

The parameters m_o and p_o can be computed from eqns. 1.1 (b) and 1.1 (f)

The Computer Simulation and Case Studies

The simulation has been made on the basis of representative data collected from power plants. The parameters have been given in Figure 2 and operating variable in Figure 3. The dynamic model based

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these parameters have been made using MATLAB. The values for the Jacobian matrices A, B, C, D have been given below. The step responses using scopes have been shown in Figure 1.4, 1.5, and 1.6.

Table 2: Typical Super heater parameters

S. No.	Parameters	Value
1	V	0.102 m ³
2	V _g	35.04 m ³
3	M	380.3 Kg
4	a	11.8 m ²
5	ρ_o	1000 Kg/m ³
6	ρ_g	0.67 Kg/m ³
7	f	65.26m ⁻⁴
8	C _p	0.47 KJ/Kg ^o K
9	C _{pg}	1.41 KJ/Kg ^o K
10	α_{ms}	140 W/m ^{2o} K
11	α_{gmc}	30.0 W/m ^{2o} K

Table 3: Typical operating variables

S. No.	Parameters	Value
1	m _i	50 Kg/s
2	a	11.8 m ²
3	m _g	1,000 Kg/s
4	h _i	2,550 KJ/Kg
5	h _o	3,450 KJ/Kg
6	h _{gi}	30,000 KJ/Kg
8	m _a	2 Kg/sec

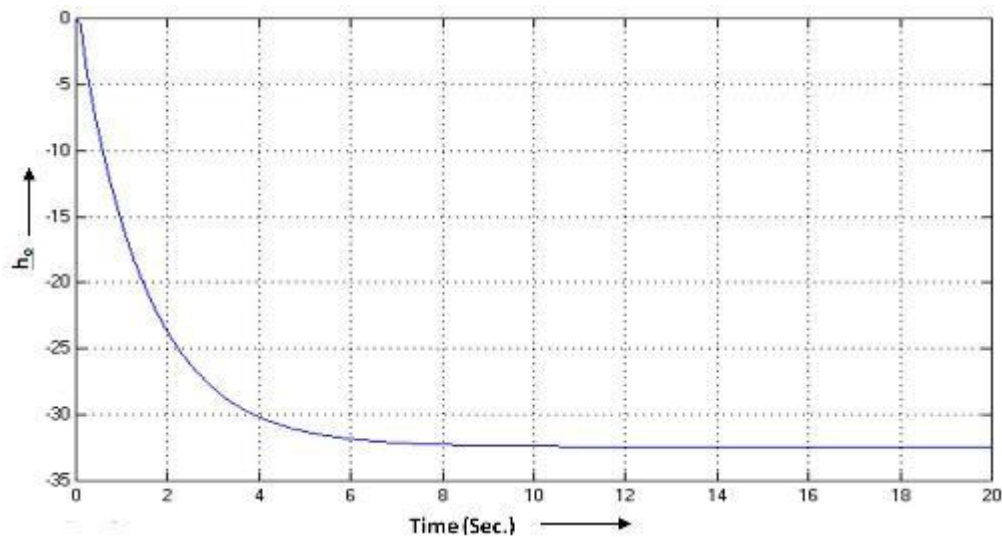


Figure 1.1: Time response of Specific enthalpy of flue gas at super heater outlet

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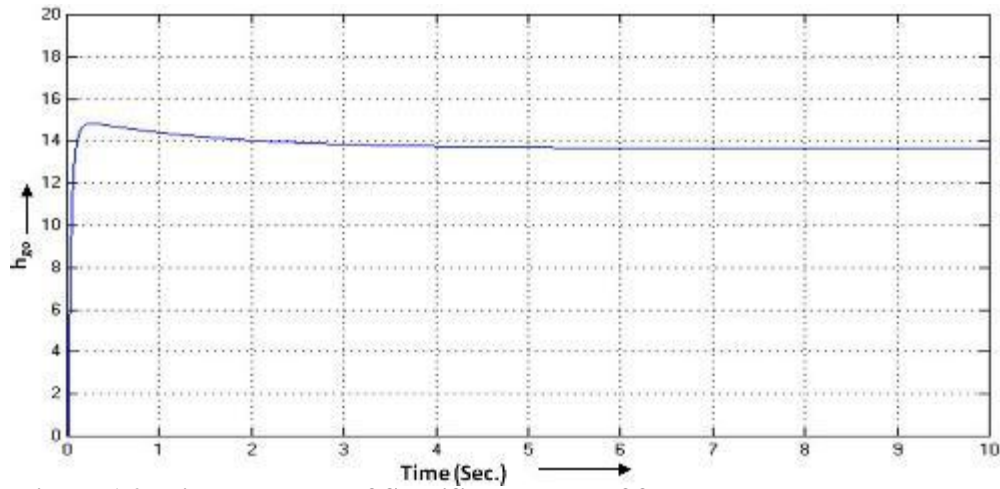


Figure 1.2: Time response of Specific enthalpy of flue gas at super heater outlet

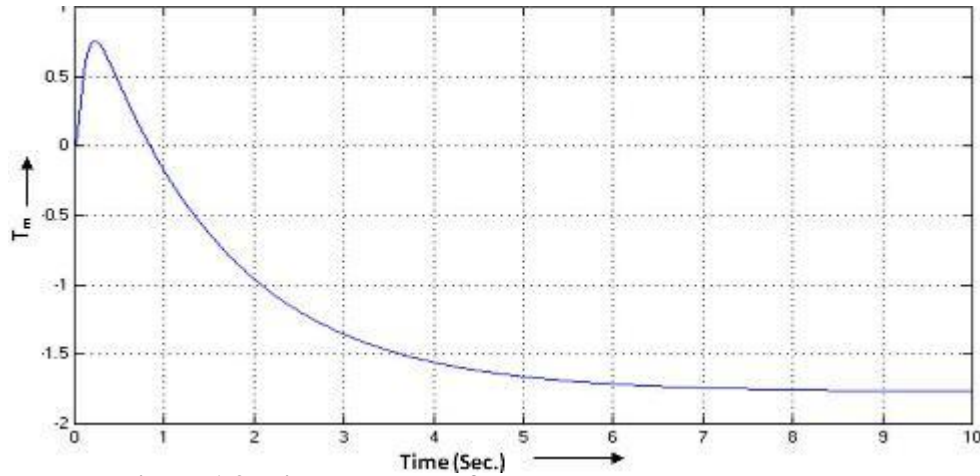


Figure 1.3: Time response of super heater mean temperature

Typical values of **A**, **B**, **C**, **D** (Jacobian matrix)

The state matrix =

$$A = \begin{bmatrix} -2.1909 & 0 & 16.1960 \\ 0 & -31.9911 & 15.0787 \\ 0.95936 & 0.70231 & -11.2229 \end{bmatrix}$$

The input matrix =

$$B = \begin{bmatrix} -8.8235 & -1.1909 & 0 & 0 & -32.8431 & 0.4901 \\ 0 & 0 & 425.952 & 37.2481 & 0 & 0 \\ 0 & 0.9593 & 0 & 0.7023 & 0 & 0 \end{bmatrix}$$

The output matrix =

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The matrix **D** = 0

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Comparative Study with the existing work with reference to (Idris *et al.*, 2000) modeling of a super heater for a combined cycle power plant.

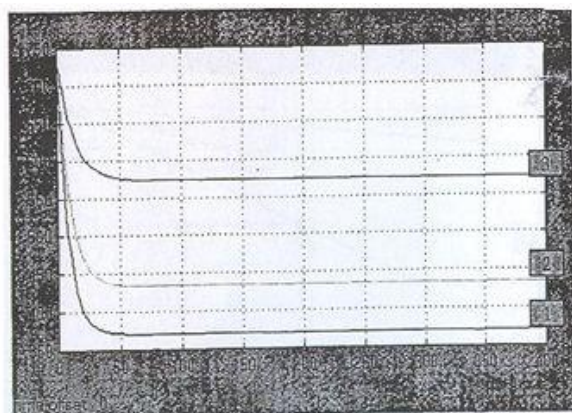


Figure 1.4

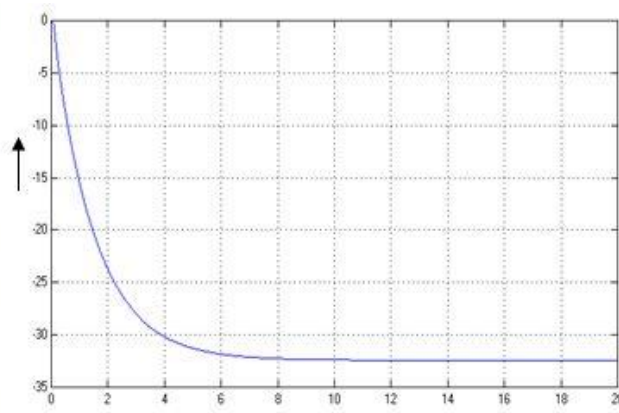


Figure 1.1

Comparative study of specific enthalpy at super heater outlet [ho] Vs [ts]

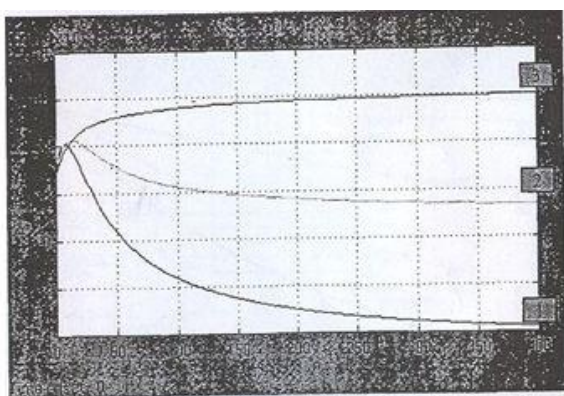


Figure 1.5

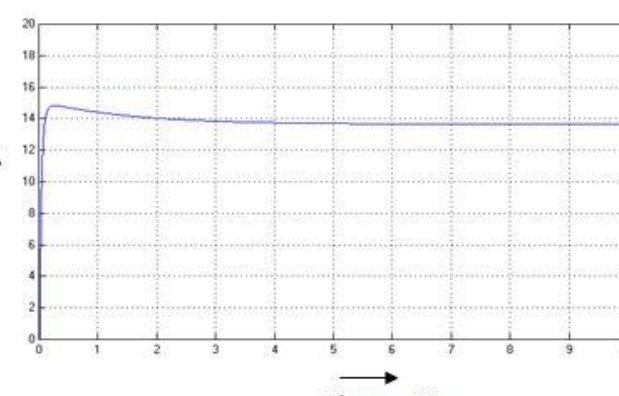


Figure 1.2

Comparative study of specific enthalpy of flue gas at super heater outlet [hgo] Vs [ts]

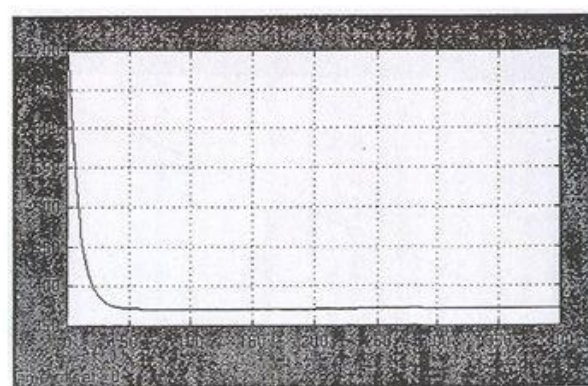


Figure 1.6

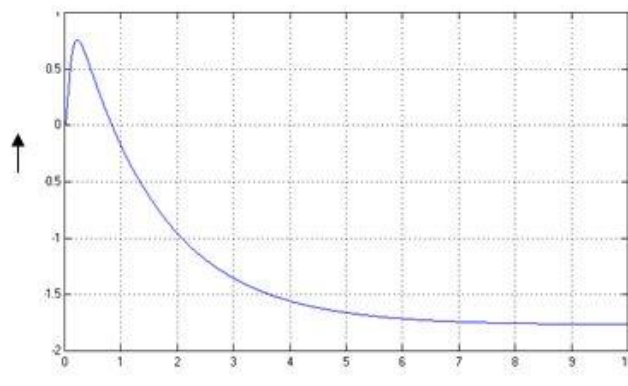


Figure 1.3

Comparative studies of super heater mean temperature [Tm] Vs time [ts]

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SIMULATION OF TIME-DEPENDENT EQUATIONS AND ITS IMPACT

The solution for time –dependant equations for specific enthalpy at super heater outlet (ho), specific enthalpy of flue gas at super heater outlet (hgo) and mean temperature of super heater(Tm) respectively were simulated on Mat lab Simulink and compared with the existing literature.

The steam enthalpy in super heater (ho) reaches steady state after about 20m sec and depend neither on steam density, steam temp and shows better coherence with the contemporary study.

The steam enthalpy of flue gas (hgo) reaches steady state at a positive value faster when steam outlet flow is lower. This characteristic shows better accuracy and faster response with existing one.

The mean temperature (Tm) at first reaches a slight overshoot but steady state faster when steam outlet flow increases. After reaching a certain maximum, the value of temperature decreases. This results logical support with the existing survey of literature and also shows super coherence and better response in regard to the analysis.

CONCLUSION

In the first part of the paper, the super heater model has been developed starting from fundamental concept of mass flow and heat flow. The describing equations have been established and on the basis of these equations the state space model for the super heater has been developed. Computer aided simulation has been made for the MIMO system using MATLAB. The state responses (Figure 1.4, 1.5, and 1.6) show a close degree of coherence and giving a convenient tool for the design of super heater. The computation methodology has been found to be very satisfactory. Other computer simulation using parallel or distributed architecture could be used for real time implementation. However MATLAB has been used for its simplicity. The present work in continuation to boiler has opened up the possibility of development of precise models using Dynamic Network Algorithm (DNA), Fine Element Algorithm (FEA) and Object-Oriented Algorithm (OOA). Also it will enable us to develop expert control strategies taking non-linearities of the system into account.

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