DCS Model Calculation for Steam Temperature System

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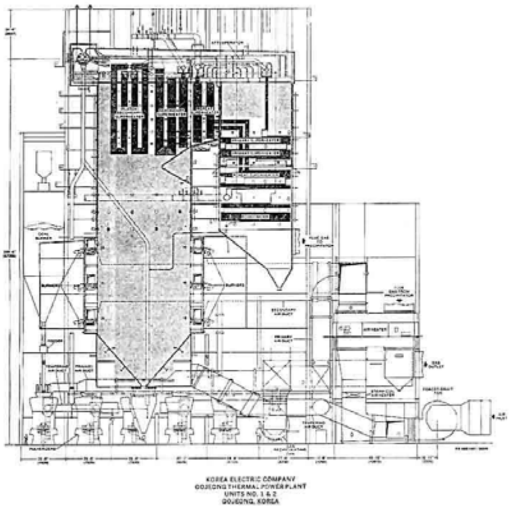
Abstract: This paper suggests a DCS (Distributed Control System) model for steam temperature system of the thermal power plant. The model calculated within sectional range is linear. In order to calculate mathematical models, the system is partitioned into two or three sectors according to its thermal conditions, that is, saturated water/steam and superheating state. It is divided into three sections; water supply, steam generation and steam heating loop. The steam heating loop is called 'superheater' or steam temperature system. Water spray supply is the control input. A first order linear model is extracted. For linear approach, sectional linearization is achieved. Modeling methodology is a decomposition-synthetic technique. Superheater is composed of several tube-blocks. For this block, linear input-output model is to be calculated. Each tiny model has its transfer function. By expanding these block models to total system, synthetic DCS linear models are derived. Control instrument include/exclude models are also considered. The resultant models include thermal combustion conditions, and applicable to practical plant engineering field.

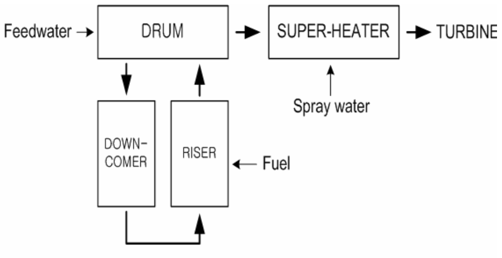
Keywords: DCS, Steam Temperature, Power Plant, Superheater

1. INTRODUCTION

Thermal power plant is one of the systems which generate electric power. The physical dynamics is due to high quality steam. Steam generator which is called a boiler transforms fuel energy into thermal energy and generates the tremendous high pressure/temperature steam for turbine-generator. It is made up of large-scale tubes and pipes which are all welded and has a reservoir at the top. A fuel, such as oil, coal or gas, is injected into the furnace and burns, typically the bottom many stories of the furnace are just for combustion. A typical feature of a thermal boiler is that there is a very efficient heat and mass transfer between all sections that are in contact with steam. The mechanism responsible for steam generation is heat recirculation. Boiling and condensation are typical conditions for water-steam circulation. With this procedure, boiler is constructed according to its proper state, for example the components are heat exchangers, economizer, water-wall tubes, drum, superheater, reheater, main steam pipe and so on. Among these superheater is the last section connected to turbine. Its steam is the resultant one generated in boiler and very important to decide electric power quality. Fig. 1 shows the example of steam generator of thermal power plant and block diagram.



(a)



(b)

Fig. 1 Steam Generator of Thermal Power Plant

To maintain thermal equilibrium, steam state is to be controlled by distributed control loops. Control loops are interconnected with each other. Each loop has not only its own system dynamics and control strategy but also the other state-variables as disturbance or feedforward [13]. In order to achieve effective control, a linear approach of object system is required. Rankine-cycle's model division approach is not always precise because of its largeness and nonlinearity. They are too large to extract accurate equations. Nonlinear modelling is also bounded [1-3,5]. And every state variable, for example temperature, pressure and flow, is diverse at every checking point. Therefore pre-present nonlinear models can be used only theoretically, not practically. Control engineers want linear models and like actual types. In this paper, linear model for thermal power plant temperature system is calculated. Physical parameters are obtained from construction data.

The first step for modeling is to partition large scale system into sections [4,5]. It is constructed of many blocks, for example hopper, connecting pipes, spiral evaporator, intermediate header, roof tubes, hanger tubes, platen superheater, final superheater and so on. Each lump has its parameters, construction data and thermal qualities [7]. And also an attemperator which supply spray-water into the inlet of superheater tubes is included. Steam temperature is controlled by water supply system. The other is a genuine superheater (heat-exchanger). And the next step is to extract a mathematical model from these lumps. Model of each block is modified as input/output or state-variables. From thermal dynamic principle they can be calculated linear and available for extension. These small size models are synthesized into total model by the method of transfer-function simplification.

2. A FIRST ORDER MOEL

Steam temperature system is a large heat-exchanger which is composed of long and tremendous metal tubes. A first order approach is to handle it as a lumped block. The reason is that this model represents the condition of heat balance. Energy supplied by fuel combustion in furnace will change the temperature of steam through the change of tube metal temperature. The total input-output energy /mass balance can be maintained. There are two state variables; steam and metal temperature. A few system parameters and coefficients can be obtained from lump construction data and thermal qualities/constants, such as tube length, thickness, diameter, volume, mass, mass flow, specific heat/volume, enthalpy, temperature, steam/water velocity and so on. A first order model equation is written as [6,11,12]

$$\dot{X} = AX + BU_1 + CU_2 \tag{1}$$

where

$$X = (T_s \quad T_m)^T, \qquad U_1 = W_{wsp}, \qquad U_2 = (T_g \quad W_s)^T$$

$$A_0 = \begin{pmatrix} V_s\rho_s \frac{\partial h_s}{\partial T_s} & 0 \\ 0 & M_m C_m \end{pmatrix} \qquad A = A_0^{-1}\begin{pmatrix} -A_i\alpha_{ms} & A_i\alpha_{ms} \\ A_i\alpha_{ms} & -(A_0\alpha_{gm} + A_i\alpha_{ms}) \end{pmatrix}$$

$$B = A_0^{-1}\begin{pmatrix} h_{wsp} - h_s \\ 0 \end{pmatrix} \qquad C = \begin{pmatrix} 0 & h_{sd} - h_{ssho} \\ A_o\alpha_{gm} & 0 \end{pmatrix}$$

α denotes heat transfer coef., W mass flow, h enthalpy, V volume, ρ density, M mass, C specific heat, A area, and T temperature. The indices s refers to steam, g gas, sd drum steam, so outlet steam, ssho superheater outlet steam, sh superheater, ssh superheater steam, m metal, p pressure, wsp water spray, gm gas-metal, ms metal-gas, i input and o output.

In state equation (1), the output equation can be obtained, written as (2). Tube outlet temperature is system output.

$$Y = DX + EU_1 + FU_2 \tag{2}$$

where

$$D = (1 \quad 0), \quad E = \frac{h_{ssho} - h_s}{C_p}, \quad F = \begin{pmatrix} 0 & \frac{h_{ssho} - h_s}{C_p} \end{pmatrix}$$

Superheater system has three inputs; water spray flow, steam flow and combustion gas temperature. Among these, water spray flow (attemperator) is only related to control action and the others are determined by the operation of boiler combustion. Outlet steam temperature is output. State equation of each block can be represented as equation (1) and (2), two state variables, one control input, two outer inputs and one output [12]. In case of not including attemperator, control input U_1 is zero and the model equation is modified as bellow.

$$\dot{X} = AX + CU_2 \tag{3}$$
$$Y = DX + FU_2 \tag{4}$$

In equations (3) and (4), water spray control action is not found. Combustion gas temperature and steam flow rate are not controllable inputs but just can be considered as disturbances. These are determined by the combusting operation, assuming that gas temperature T_g is linear continuously decreasing and steam flow rate W_s is approximately constant. Although steam flow affects heat transfer coefficient α_{ms}, the perturbation is negligibly small in equilibrium state.

3. A TRANSFER FUNCTION CALCULATION FOR DCS

As described that steam temperature system is constructed with many diverse blocks and each block has a simple first order model, the total system model which is linear and transfer function type may be calculated by multiplying between transfer-functions of blocks under some assumptions and thermal dynamic condition. Each heat exchanger, that is block, is considered as little superheater. Fig. 2 shows the steam temperature system with blocks.

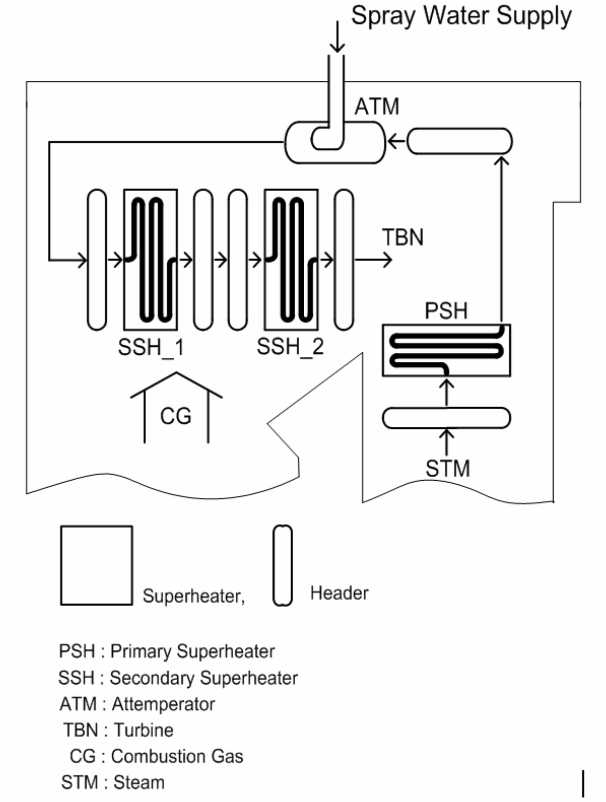


Fig. 2 Steam Temperature System

3.1 Combusting Heat and State Variables

In a first model three thermal variables are found, such as input, output and representative one. Superheater total heat is

$$V_{sh}\rho_s h_s + M_m C_m T_m \tag{5}$$

Since system is in thermal equilibrium, the state of heat exchanger can be represented by one variable chosen as the steam pressure. Similarly under the condition of constant steam pressure, steam enthalpy is the function of temperature [8-10]. So that enthalpy in equation (5) is

$$h_s = k_1 + k_2 T_s \tag{6}$$

The total energy, equation (5), is

$$V_{sh}\rho_s h_s + M_m C_m T_m = V_{sh}\rho_s (k_1 + k_2 T_s) + M_m C_m T_m \qquad (7)$$

As shown figure 2, steam temperature system is consisted of several blocks. The heat energy absorbed in k'th block is

$$Q_k = W_g \alpha_{gm}(T_{gk} - T_{g(k-1)}) \qquad (8)$$

$$T_{gk} = T_{gp}\alpha_k (T_p - T_k) \qquad (9)$$

where k=1,2,…,p. T_{gp} is the furnace inlet combustion gas temperature and the value is the highest.

If superheater can be divided into i'th(i=1,2,..,n)short elements, and mass, volume and temperature of the element are V_{shi}, T_{si}, M_{mi} and T_{mi} respectively, then equation (5) is equal to

$$nV_{shi}\rho_s (k_1 + k_2 \frac{1}{n}\sum_{i=1}^{n} T_{si}) + nM_{mi}C_m \frac{1}{n}\sum_{i=1}^{n} T_{mi} \qquad (10)$$

In equation (10) let state variables T_s and T_m as bellow.

$$T_s = \frac{1}{n}\sum_{i=1}^{n} T_{si} \qquad (11)$$

$$T_m = \frac{1}{n}\sum_{i=1}^{n} T_{mi} \qquad (12)$$

If temperature varying is linear continuous, T_s and T_m are mean value between input and output.

$$T_s = \frac{1}{2}(T_{so} - T_{si}) \qquad (13)$$

$$T_m = \frac{1}{2}(T_{mo} - T_{mi}) \qquad (14)$$

3.2 Implementation of DCS Model Equations

As described in chapter 2, the lumps constructed in steam temperature system are divided into two sorts. One is attemperator included block, the other is attemperator excluded one. Analogously there can be two kinds of model equations. Each block is represented as different equation.

Attemperator included model

- State equation

$$\dot{X}_{ai} = A_{ai}X_{ai} + B_{ai}U_{1ai} + C_{ai}U_{2ai} \qquad (15)$$

$$Y_{ai} = D_{ai}X_{ai} + E_{ai}U_{1ai} + F_{ai}U_{2ai} \qquad (16)$$

- Transfer function

$$Y_{ai} = G_{1ai}U_{1ai} + G_{2ai}U_{2ai} \qquad (17)$$

where a is attemperator included one, i=1,2,…,n.

$$G_{1ai} = E_{ai} + D_{ai}(sI - A_{ai})^{-1}B_{ai} \qquad (18)$$

$$G_{2ai} = F_{ai} + D_{ai}(sI - A_{ai})^{-1}C_{ai} \qquad (19)$$

Attemperator excluded model

- State equation

$$\dot{X}_{bj} = A_{bj}X_{bj} + C_{bj}U_{2bj} \qquad (20)$$

$$Y_{bj} = D_{bj}X_{bj} + F_{bj}U_{2bj} \qquad (21)$$

- Transfer function

$$Y_{bj} = G_{2bj}U_{2bj} \qquad (22)$$

where b is attemperator excluded one, j=1,2,…,m.

$$G_{2bj} = F_{bj} + D_{bj}(sI - A_{bj})^{-1}C_{bj} \qquad (23)$$

Two types of transfer function are presented in equation (17) and (22). Each equation can be modified with inputs respectively.

$$Y_{ai} = G_{1ai}U_{1ai} + G_{2a1i}U_{2a1i} + G_{2a2i}U_{2a2i} \qquad (24)$$

$$Y_{bj} = G_{2b1j}U_{2b1j} + G_{2b2j}U_{2b2j} \qquad (25)$$

U_{2a1i} and U_{2a2i} are combustion gas temperature inputted into superheater side. U_{2b1j} and U_{2b2j} are steam flows rate in tubes. Fig. 3 shows the block diagram of Poyrung T/P (Korea) steam temperature system which has inputs, outputs and block's transfer function.

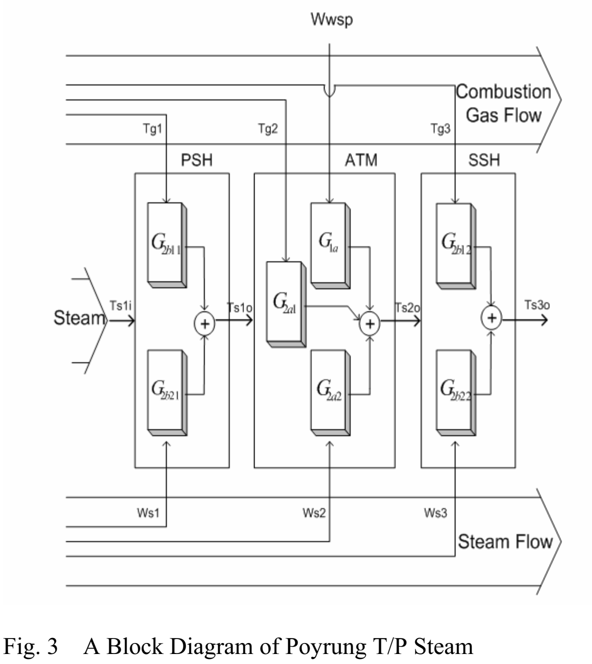


Fig. 3 A Block Diagram of Poyrung T/P Steam Temperature System

In equation (2), (4), (24), and (25), system input is superheater inlet steam temperature and output is outlet steam temperature, not only in case of every lump but also total superheater. So that input-output relations of blocks, which includes attemperator, can be written, for i=1,2,…,n , as bellow.

$$T_{s2} = T_{s1} + g_{a1}T_{g1} + g_{b1}W_{s1}$$

$$T_{s3} = T_{s2} + g_{a2}T_{g2} + g_{b2}W_{s2}$$

$$\text{-------------------------}$$

$$\text{-------------------------}$$

$$T_{s,j-1} = T_{s,j-2} + g_{a,j-2}T_{g,j-2} + g_{b,j-2}W_{s,j-2}$$
$$T_{sj} = T_{s,j-1} + g_{a,j-1}T_{g,j-1} + g_{b,j-1}W_{s,j-1} + g_{wsp}W_{wsp}$$
$$T_{s,j+1} = T_{sj} + g_{aj}T_{gj} + g_{bj}W_{sj}$$

$$T_{sn} = T_{s,n-1} + g_{a,n-1}T_{g,n-1} + g_{b,n-1}W_{s,n-1}$$

where $T_{s,j-1}$ and $T_{s,j}$ are input/output steam temperature. $T_{g,j-1}$ and $T_{g,j}$ are combustion gas temperature, and $W_{s,j-1}$ and $W_{s,j}$ steam flow. g_{ai} , g_{bi} and g_{wp} are parameters.

By summing left and right side respectively, inlet/outlet equation can be calculated.

$$T_{sn} = T_{s1} + \sum_{i=1}^{n-1} (g_{ai}T_{gi} + g_{bi}W_{si}) + g_{wsp}W_{wsp} \qquad (26)$$

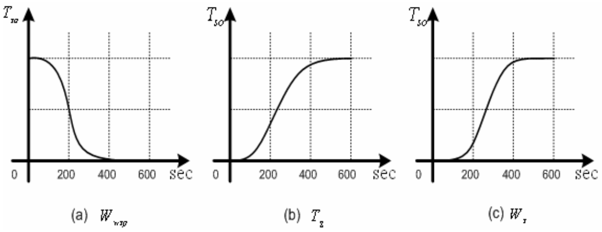
In equation (26), T_{s1} and T_{sn} are superheater inlet/outlet steam temperature.

4. SIMULATION

The target steam temperature system is 'Poryung T/P in Korea. Table 1 shows the construction specification and thermal data. Responses to step input are shown in figure 4. Control input is spray water flow, and according to step input variation of combustion gas temperature and steam flow the responses are also obtained. System output is superheater outlet steam temperature.

Blocks	PSH	ATM	SSH
Mass flow[kg/s]	420.2	420.2	408.3
Mass[kg]	76134	16899	39952
Volume[m^3]	11.67	1.099	7.235
Length[m]	19.7	3.0	19.5
Outside Dia.[mm]	38.0	38.0	42.4
Thickness[mm]	5.0	8.0	5.0
Inlet enthalpy[kj/kg]	3129.4	3310.1	2923.7
Outlet enthalpy[kj/kg]	3189.6	3310.1	3010.8
Cp[kj/kg k]	0.7012	0.7319	0.6641
α [kj/sec m^2 k]	3.93	5.63	6.38

Table 1



(a) W_{wsp} (b) T_g (c) W_s

Fig. 4 Simulation Result; Step Response

5. CONCLUTION

This paper has presented DCS model calculation for steam temperature system of thermal power plant. At first a simple first order dynamic model represented as state equation and transfer function is obtained. This model can be used for modelling a block of heat exchanger and fundamental for linear extensive approach. There are three inputs which affect the thermal variations of superheater tubes, that is, spray water flow, steam flow and combustion gas temperature. Among these, spray water flow is the only controllable input. In this model, state variables, all kind of inputs and output, and attemeprator inclusion/exclusion type are presented. The block diagram shows this situation. Controller designers have always demanded useful linear model for designing controller structure. To achieve this purpose, large-scale superheater is divided into several blocks. Each block is represented with this first order model, considered also spray water flow. Multiplying and summing block' model equations, a linear model for steam temperature system is calculated. This model is powerful and directly applicable to controller/observer design.

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