A Study on Power Plant Modeling for Control System Design

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Abstract: For many industrial processes there are good static models used for process design and steady state operation. By using system identification techniques, it is possible to obtain black-box models with reasonable complexity that describe the system well in specific operating conditions [1]. But black-box models using inductive modeling(IM) is not suitable for model based control because they are only valid for specific operating conditions. Thus we need to use deductive modeling(DM) for a wide operating range. Furthermore, deductive modeling is several merits: First, the model is possible to be modularized. Second, we can increase and decrease the model complexity. Finally, we are able to use model for plant design.

Power plant must be able to operate well at dramatic load change and consider safety and efficiency. This paper proposes a simplified nonlinear model of an industrial boiler, one of component parts of a power plant, by DM method and applies optimal control to the model.

Keywords: Boiler, power plant modeling, optimal control, deductive model

1. INTRODUCTION

In general, the heat power plant consists of a boiler and turbines. Furthermore the boiler is used at large plants, buildings and housing-development apartments. In this paper the discussion scope is limited to the boiler which has a natural circulation water tube as showed in Fig. 1.1. It is able to be applied to high pressure and large capacity boiler because heat transfer area is made up thin water tubes(risers) [2]. It is difficult to control because of the rapid response to a load change. Therefore it requires some good model to get a good control performance. It can be modeled using energy balance, mass balance, momentum balance, plant construction data and empirical data [3].

A boiler consists of burner, riser, drum, downcomer, superheater, reheater, economizer, etc [4]. In this paper we will model risers, drum, downcomers which are important parts of the boiler system by DM method. The deductive modeling of the boiler will give a descriptor nonlinear system. It should be linearized for applications of model based controls. A descriptor nonlinear model is difficult to be linearized [5], and so this research also presents some linearized models.

A performance objective of the boiler is to get quantity of steam under demanded temperature and pressure conditions, and the boiler needs to control the drum level for safety. To achieve it, we will select the LQ(linear quadratic) controller using integration of the error.

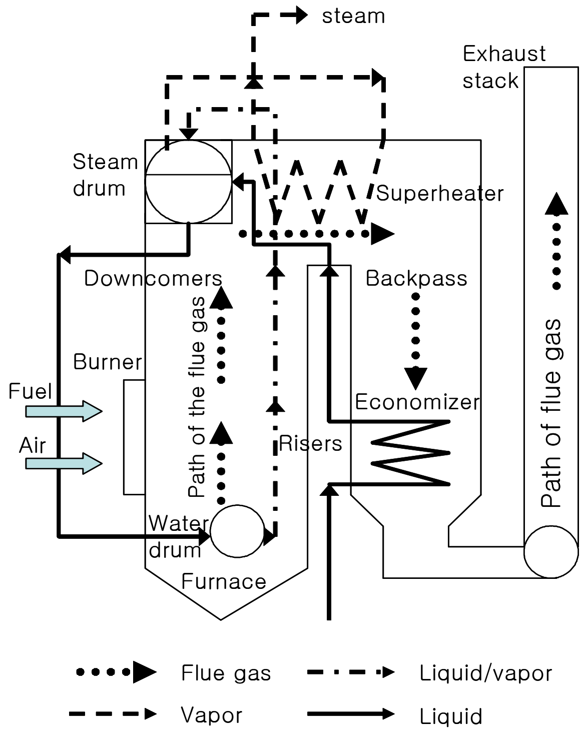

Fig. 1.1 A natural circulation water tube boiler

2. BOILER MODELING

State variables can be chosen in many different ways but it is convenient to choose states variables with good physical interpretation that describe storage of mass and energy. In this research the drum means a steam-drum. Abbreviations used in this paper are summarized in Appendix.

2.1 Modeling of Risers, Drum and Downcomers

It is assumed that energy supplied at model is only able to get through riser. Fig. 2.1 shows a basic concept of model. The mass balance equation for risers, drum and downcomers is as follows:

$$\frac{d}{dt}\left[\rho_s V_{st} + \rho_w V_{wt}\right] = q_{fw} - q_s. \tag{2.1}$$

The energy balance equation for risers, drum and downcomers is

$$\frac{d}{dt}\left[\rho_s H_s V_{st} + \rho_w H_w V_{wt} - pV_t + m_t C_p T\right] = Q_r + q_{fw} H_{fw} - q_s H_s. \tag{2.2}$$

The metal temperature T can be expressed as a function of pressure by assuming that changes in T are strongly correlated to changes in the saturation temperature of steam. The steady state temperature distribution in the metal is close to the saturation temperature. Thus it can be supposed that steam, water and metal are at a thermal equilibrium, that is, it can be said that T is equal to the saturation temperature of steam.

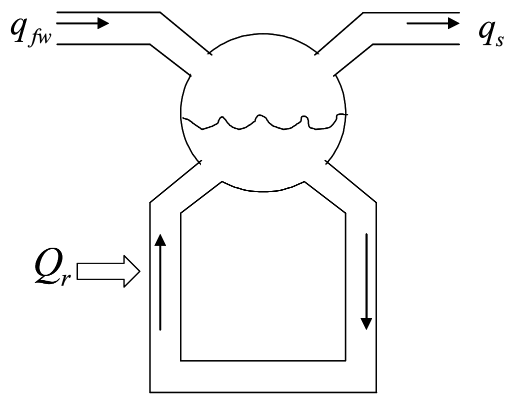

Fig. 2.1 A simple schematic picture of risers, drum and downcomers

The mass equation balance for the riser section is

$$\frac{d}{dt}\left(\rho_s a_v V_r + \rho_w (1-a_v) V_r\right) = q_{dc} - q_r. \tag{2.3}$$

The energy balance equation for the riser section is

$$\frac{d}{dt}\left(\rho_s H_s a_v V_r + \rho_w H_w (1-a_v) V_r - p V_r + m_r C_p T\right)$$
$$= Q_r + q_{dc} H_w - a_m H_s q_r - (1-a_m) H_w q_r. \tag{2.4}$$

The average steam-volume fraction in the flow at the riser is

$$a_v(a_m) = \frac{\rho_w}{\rho_w - \rho_s}\left(1 - \frac{\alpha}{a_m}\ln\left(1+\frac{a_m}{\alpha}\right)\right).$$

where $\alpha = \dfrac{\rho_s}{\rho_w - \rho_s}$. (2.5)

This variable is used on the assumption that the quantity of steam passing through risers varies linearly. The empirical equation for the q_{dc} is

$$q_{dc} = \sqrt{2 a_v V_r (\rho_w - \rho_s)/k}. \tag{2.6}$$

The empirical equation for the drum level is

$$l = \frac{V_{wt} + a_v V_r}{A}. \tag{2.7}$$

This equation is considered the volume water and steam under the liquid level in the drum.

The total volume of water and steam are

$$V_{st} = V_{drum} - V_{wd} + a_v V_r.$$
$$V_{wt} = V_{wd} + V_{dc} + (1-a_v) V_r. \tag{2.8}$$

After substituting Eq. (2.8) into Eq. (2.2), we can get the following equation:

$$\left[\rho_s V_{st}\frac{dH_s}{dp} + H_s V_{st}\frac{\rho_s}{dp} + \rho_w V_{wt}\frac{dH_w}{dp} + H_w V_{wt}\frac{d\rho_w}{dp} - V_t + m_t C_p \frac{dT}{dp}\right]$$
$$\frac{dp}{dt} + (\rho_w H_w - \rho_s H_s)\frac{dV_{wd}}{dt} + (\rho_s H_s - \rho_w H_w) V_r \frac{da_v}{da_m}\frac{da_m}{dt}$$
$$= Q_r + q_{fw} H_{fw} - q_s H_s. \tag{2.9}$$

After substituting Eq. (2.8) into Eq. (2.1), we can get

$$\left(V_{st}\frac{d\rho_s}{dp} + V_{wt}\frac{d\rho_w}{dp}\right)\frac{dp}{dt} + (\rho_w - \rho_s)\frac{dV_{wd}}{dt} + (\rho_s - \rho_w) V_r \frac{da_v}{da_m}\frac{da_m}{dt}$$
$$= q_{fw} - q_s. \tag{2.10}$$

After Eq. (2.3) manipulation about q_r, we substitute q_r into Eq. (2.4), and we are able to get

$$\left[H_c(1-a_m) a_v V_r \frac{d\rho_s}{dp} - a_m H_c (1-a_v) V_r \frac{d\rho_w}{dp} + \rho_s a_v V_r \frac{dH_s}{dp} + \rho_w\right.$$
$$\left.(1-a_m) V_r \frac{dH_w}{dp} - V_r + m_r C_p \frac{dT}{dp}\right]\frac{dp}{dt} + H_c V_r\left[(1-a_m)\rho_s + a_m \rho_w\right]$$
$$\frac{da_v}{da_m}\frac{da_m}{dt} = Q_r - q_{dc} a_m H_c. \tag{2.11}$$

If we take p, V_{wd} and a_m as the state variables, the time derivatives of these variables are given by the Eqs. (2.9)~(2.11), which can be rewritten as

$$e_{11}\frac{dp}{dt} + e_{12}\frac{dV_{wd}}{dt} + e_{13}\frac{da_m}{dt} = Q_r + q_{fw} H_{fw} - q_s H_s$$
$$e_{21}\frac{dp}{dt} + e_{22}\frac{dV_{wd}}{dt} + e_{23}\frac{da_m}{dt} = q_{fw} - q_s$$
$$e_{31}\frac{dp}{dt} + e_{32}\frac{dV_{wd}}{dt} + e_{33}\frac{da_m}{dt} = Q_r - q_{dc} a_m H_c \cdot \tag{2.12}$$

$$e_{21} = V_{st}\left(\rho_s \frac{dH_s}{dp} + H_s\frac{d\rho_s}{dp}\right) + V_{wt}\left(\rho_w\frac{dH_w}{dp} + H_w\frac{d\rho_w}{dp}\right) - V_t + m_t C_p\frac{dT}{dp}$$

$$e_{22} = \rho_w H_w - \rho_s H_s$$

$$e_{23} = (\rho_s H_s - \rho_w H_w) V_r \frac{da_v}{da_m}$$

$$e_{31} = H_c(1-a_m) a_v V_r \frac{d\rho_s}{dp} - a_m H_c(1-a_v) V_r \frac{d\rho_w}{dp} + \rho_s a_v V_r \frac{dH_s}{dp}$$
$$+ \rho_w (1-a_m) V_r \frac{dH_w}{dp} - V_r + m_r C_p \frac{dT}{dp}$$

$$e_{32} = 0$$

$$e_{33} = H_c V_r\left[(1-a_m)\rho_s + a_m \rho_w\right]\frac{da_v}{da_m}$$

3. STEP RESPONSES AND MODEL VALIDATION

To illustrate the dynamic behavior of the model we will simulate responses to step changes in the inputs. One input is changed and the others are kept constant. The magnitudes of the changes are about 10% of the operation point.

Plant parameters are taken as follows: $V_r = 3.355m^3$, $V_{drun} = 10.94m^3$, $V_{dc} = 5.43m^3$, $m_r = 15790kg$, $m_t = 51190kg$. The steam tables were approximated by quadratic approximations in the simulation. We suppose that the temperature of feedwater is 173.7℃.

3.1 Step response of risers, drum and downcomers model

We will select an operating point, which is given at Table 3.1, where step input is started at 50 second.

Table 3.1 Operating point

$p = 4.1926$	$V_{wd} = 7.2245$	$a_m = 0.5332$
$q_s = 4.807$	$q_{fw} = 4.807$	$Q_r = 9999.19$

3.1.1 The steam mass flow rate change

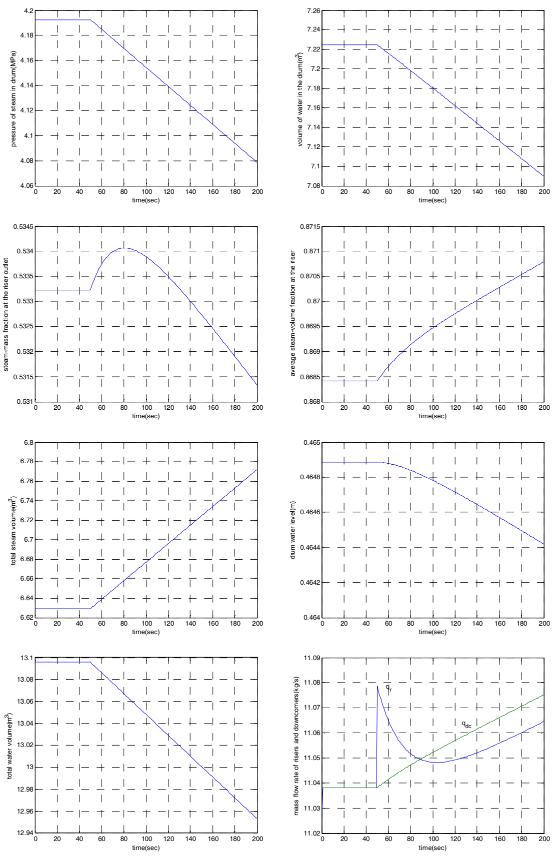

Fig. 3.1 Response to a step change of 0.5 kg/s in steam flow rate

The step response in the steam flow rate is shown in Fig. 3.1. As shown in this figure, if the steam flow rate increases, the steam pressure and drum level decrease. Reversely, if the steam flow rate decreases, the steam pressure and drum water level increase.

3.1.2 The feedwater mass flow rate change

The step response in the feedwater flow rate is shown in Fig. 3.2. As shown in this figure, if the feedwater flow rate increases, the drum water level increases but the steam pressure decreases. Reversely, if the feedwater flow rate decreases, the drum water level decreases but the steam pressure increases.

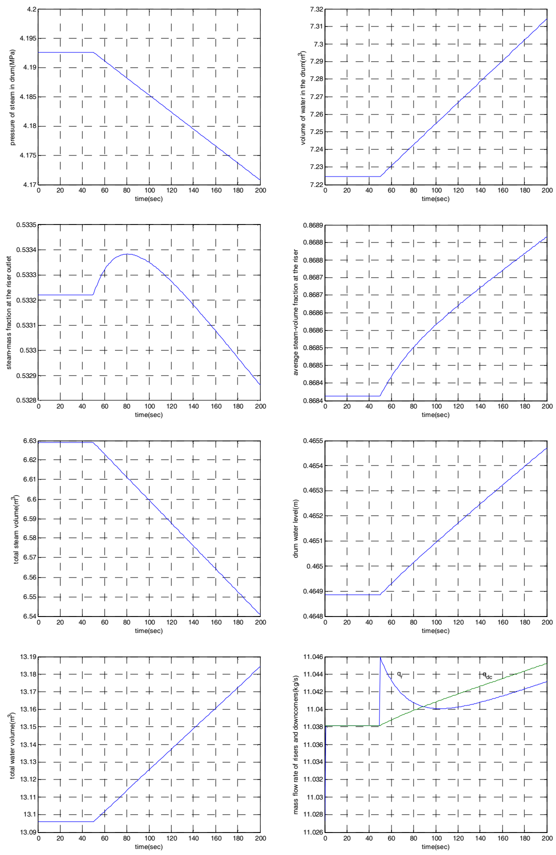

Fig. 3.2 Response to a step change of 0.5 kg/s in feedwater flow rate

3.1.3 The heat flow rate change to the risers

Fig. 3.3 shows the step response in the heat flow rate. As shown in this figure, if the heat flow rate increases, the steam pressure increases, but if the heat flow rate decreases, the steam pressure decreases.

3.2 Model validation

Step response simulation data given in Figs. 3.1~3.3 are shown to be similar to the real data of the boiler. Hence, the model is valid at the operating point. Using this model, we can design a control law and check the performance via some simulations, which will be shown in the next section.

4. CONTROL OF BOILER

In this chapter, we will linearize risers, drum and downcomers model and apply to LQ optimal control using linearized model.

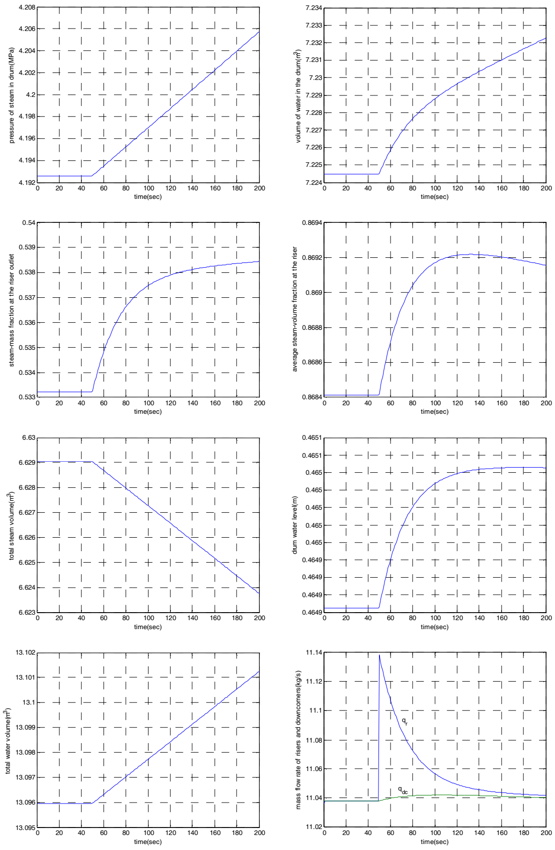

Fig. 3.3 Response to a step change of 100 kJ/s in heat flow rate

4.1 Linearization of risers, drum and downcomers model

If we take

state variables : $x_1 = p, x_2 = V_{wd}, x_3 = a_m$

input variables : $u_1 = q_s, u_2 = q_{fw}, u_3 = Q_r$

output variables : $y_1 = p, y_2 = l, y_3 = q_s$

operating point : $x_1^o, x_2^o, x_3^o, u_1^o, u_2^o, u_3^o, y_1^o, y_2^o, y_3^o$,

where

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}, \quad u = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}, \quad y = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix},$$

then the state equation of nonlinear model : $\dot{x} = f(x,u)$, and the output equation of nonlinear model : $y = g(x,u)$ can be linearized at the operating point as follws:

$$\delta\dot{x} = A\delta x + B\delta u$$
$$\delta y = C\delta x + D\delta u$$

where

$$A = \frac{\partial f}{\partial x}(x^o, u^o), \quad B = \frac{\partial f}{\partial u}(x^o, u^o),$$
$$C = \frac{\partial g}{\partial x}(x^o, u^o), \quad D = \frac{\partial g}{\partial u}(x^o, u^o),$$
$$\delta u = u - u^o, \quad \delta x = x - x^o, \quad \delta y = y - y^o.$$

Table 4.1 is linear model coefficient matrices at operating point of Table 3.1.

Table 4.1 Linearized model around the operating point

A	$\begin{bmatrix} 0.00001982 & 0 & 0 \\ 0.00103049 & 0 & -0.02705983 \\ 0.00179506 & 0 & -0.03950403 \end{bmatrix}$
B	$\begin{bmatrix} -0.00152088 & -0.00029170 & 0.00000087 \\ -0.00168927 & 0.00121701 & 0.00000158 \\ 0.00013685 & 0.00002624 & 0.00000190 \end{bmatrix}$
C	$\begin{bmatrix} 1 & 0 & 0 \\ -0.00371640 & 0.00593877 & 0.03141064 \\ 0 & 0 & 0 \end{bmatrix}$
D	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$

4.2 LQ controller for the boiler control

The structure of the LQ controller used in this paper is shown in Fig. 4.1. This method is used to guarantee the stability and to solve the tracking problem. Following figure describes the general controller including an integrator for the steady state error reduction [6].

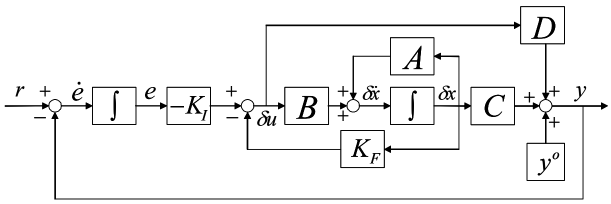

Fig. 4.1 Block diagram of the LQ controller using integration of the error

The augmented state space model including the integrator is as follows:

$$\begin{bmatrix} \delta\dot{x} \\ \dot{e} \end{bmatrix} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix} \begin{bmatrix} \delta x \\ e \end{bmatrix} + \begin{bmatrix} B \\ -D \end{bmatrix} \delta u + \begin{bmatrix} 0 \\ I \end{bmatrix} r + \begin{bmatrix} 0 \\ -y^0 \end{bmatrix},$$

and the LQ cost function is taken as

$$J = \int_0^{t_f} e^T q e + \delta u^T R \delta u dt$$
$$= \int_0^{t_f} \begin{bmatrix} \delta x \\ e \end{bmatrix}^T \begin{bmatrix} 0 & 0 \\ 0 & q \end{bmatrix} \begin{bmatrix} \delta x \\ e \end{bmatrix} + \delta u^T R \delta u dt,$$

where $q^{3\times3}$ and $R^{3\times3}$.

ARE(algebraic riccati equation) is

$$0 = P\begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix} + \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix} P - P\begin{bmatrix} B \\ -D \end{bmatrix} R^{-1} \begin{bmatrix} B \\ -D \end{bmatrix}^T P + Q$$

where

$Q = \begin{bmatrix} 0 & 0 \\ 0 & q \end{bmatrix}$, $Q^{6\times6}$ and $P^{6\times6}$, and the actuator input(controller output) is given by

$$u = u^o + \delta u \,,$$

where

$$\delta u = -R^{-1}\begin{bmatrix} B \\ -D \end{bmatrix} P \begin{bmatrix} \delta x \\ e \end{bmatrix} = -K_F \delta x - K_I e \,,$$

$$K = R^{-1}\begin{bmatrix} B \\ -D \end{bmatrix} P \begin{bmatrix} \delta x \\ e \end{bmatrix} = \begin{bmatrix} K_F \\ K_I \end{bmatrix}^T, K^{3\times 6}, \;\; K_F{}^{3\times 3} \text{ and } K_I{}^{3\times 3}.$$

The most important performance objective of the boiler is to get quantity of steam under demanded temperature and pressure conditions. Note that the steam mass flow rate is an input and at the same time output of system. Design parameters are tuned to satisfy these objectives as follows:

$$q = \begin{bmatrix} 200 & 0 & 0 \\ 0 & 50 & 0 \\ 0 & 0 & 400 \end{bmatrix}, \; R = \begin{bmatrix} 100 & 0 & 0 \\ 0 & 20 & 0 \\ 0 & 0 & 0.00001 \end{bmatrix}$$

The following limit constraints of an actuator exist for the three element control variables :

$$0 \le u_1 \le 16(kg/s), -0.35 \le \dot{u}_1 \le 0.35$$
$$0 \le u_2 \le 16(kg/s), -0.9 \le \dot{u}_1 \le 0.9$$
$$0 \le u_3 \le 35000(kJ/s), -1000 \le \dot{u}_3 \le 1000.$$

The reference input r ($p = 4.5, l = 0.4649, q_s = 5.5$) is commanded at 100 second at nonlinear boiler model operating at trim point. As shown in Fig. 4.2, although the controller output differ from the actuator output, the controller gives good tracking performance.

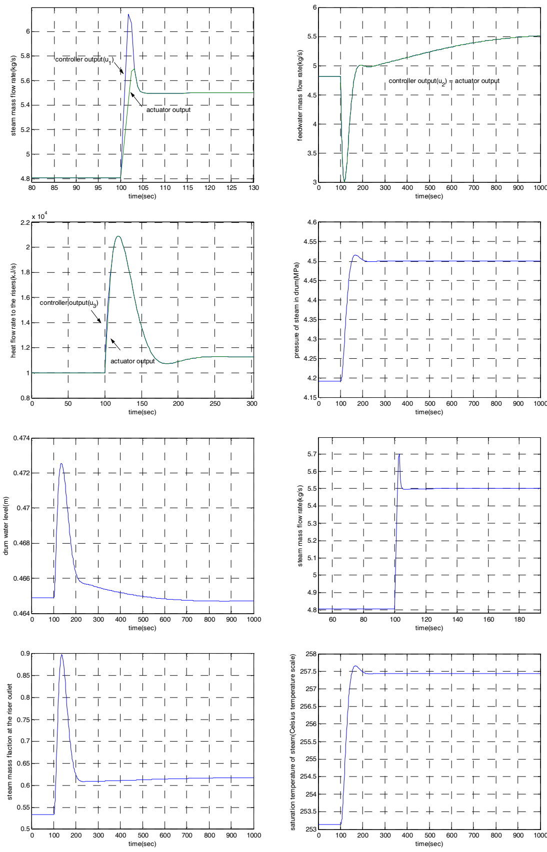

Fig. 4.2 Simulation results of nonlinear model using LQ controller using integration of the error

5. CONCLUSIONS AND REMARK

So far, we have proposed a boiler including model risers, drum and downcomers. And we have also derived a linearized model at an operating point. Using linearized model, a LQ controller is using integration of the error, and applies it to nonlinear model.

Since the model is derived by DM method, each variable and parameter has the physical meaning. Thus we can evaluate a system safety with this information. For example, steam-mass fraction a_m must not exceed 1. Then, if it exceeds 1 in certain cases(e.g., when energy supplied at q_{fw} is much excessively), that is a contradiction. In fact, it means to generate superheated steam in the riser that a_m exceeds 1 in the simulation. This is very dangerous situation because the temperature is able to increase highly than durability -temperature of system.

Using the model derived, we will design various controllers at other operating points for application in a wide operating range to apply AWBT(anti windup bumpless transfer) [7]. And we are to add an other modules of the boiler(e.g., superheater etc.) and connect them.

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APPENDIX:

p : pressure of steam in drum(MPa)

t : time

ρ_s, ρ_w : the specific density of steam, water and feedwater(kg/m^3)

H_s, H_w, H_{fw} : the specific enthalpy of steam, water and feedwater(kJ/kg)

H_c : the specific enthalpy of condensation (= $H_s - H_w$)

V_{wt}, V_{st} : the total volume of water and steam in the risers, drum and downcomers(m^3)

V_t : the total volume of the risers, drum and downcomers(= $V_{wt} + V_{st}$)

m_t : the total mass of the risers, drum and downcomers(kg)

m_r : the mass of the risers(kg)

C_p : the specific heat of the metal($kJ/kg^{\circ}C$)

T : the temperature of metal($^{\circ}C$) (=the temperature of the steam and the water in the risers, drum and downcomers)

Q_r : the heat flow rate to the risers(kJ/s)

q_s : the steam mass flow rate(kg/s)

q_{fw} : the feedwater mass flow rate(kg/s)

V_{drum} : the volume of the drum(m^3)

V_r, V_{dc} : the volume of the risers and downcomers(m^3)

V_{wd} : the volume of water in the drum (m^3)

a_v : the average steam-volume fraction in the flow at the riser

a_m : the steam-mass fraction in the flow at the riser outlet

q_r : the mass flow rate of the risers(kg/s)

q_{dc} : the mass flow rate of the downcomers(kg/s)

l : the drum water level(m)

A : the wet surface of the drum(m^2)

k : the friction coefficient of the downcomer