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반복적 방법을 이용한 화력발전소 과열기 시스템의 온도제어

(A Temperature Control of Thermal Power Plant Superheater System using Iterative Method)

이상혁*, 김주식**

(Sang-Hyuk Lee, Ju-Sik Kim)

요 약

본 논문에서는 반복적 방법을 이용하여 열교환기 시스템의 온도제어를 위한 제어기를 구성하였다. 쌍선형 시스템으로 표현되는 열교환기 시스템에 대하여 최적이론을 적용하기 위하여 반복적 방법이 가능하도록 시스템을 구성하였으며, 상태궤환 제어기의 설계를 위하여 이 시스템의 상태인 증기온도를 추정하기 위한 확장 칼만 필터를 제시하였다. 또한 설계된 제어기를 화력발전소의 과열기 시스템의 온도제어에 적용하였고, 컴퓨터 시뮬레이션을 통하여 추정값이 외부입력의 변동 하에서 상태값에 적절하게 추종됨을 확인하였으며, 출구의 증기온도가 이러한 외부입력의 변동 하에서 주어진 목표치로 추종함을 보였다.

Abstract

In this paper, we construct the controller for the heat exchanger system using iterative method. For applying the linear quadratic control theory to the heat exchanger system which is represented by the bilinear system, we formulate the bilinear system to execute iteration. We also propose Extended Kalman Filter to estimate bilinear system state for the purpose of state feedback controller design. We also apply the iterative controller to the thermal power plant superheater system temperature control, and computer simulation show that the estimated value follows the superheater steam temperature under the variation of the external inputs, and that the output steam temperature is properly maintained.

1. Introduction

This paper consider the problems of steam temperature control of a superheater system with a desuperheater. Among the heat exchanger systems, the superheater system is represented by the bilinear system in thermal power plant. The design problem of controllers for bilinear system has been studied by many authors[1-3]. Most of the obtained results rely on optimization theory, either using quadratic cost criteria or criteria linear in control, specially through the application of Pontryagin's principle leading to bang-bang control or minimizing control time. Cebuhar and Costanza proposed the approximation procedure to show that a wide class of optimal control problems can be

*정회원 : 우송대학교 전자공학과
**정회원 : 충북대학교 전기공학과 제어연구실
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solved for bilinear systems and to explore the ways for practical implementation of these solutions[1]. However, obtaining the optimal solution was not easy because of the nonlinearity in bilinear system[3,4].

Hence, to solve these bilinear system control problems, feedback controllers need for more specific consideration. For the purpose of obtaining the optimal solution in quadratic control, it is required to use closely related Riccati approach in linear quadratic optimization. Hence using the results of Hofer and Tibken's approach, the feedback controller with the iterative method for the bilinear systems control is derived and the proposed iterative controller is applied to the problem of superheater steam temperature control. Whereas Hofer and Tibken considered regulating problem, we formulate the iterative method into the tracking problem.

In the next section, bilinear system variables are defined in order to utilize Riccati equation. We also propose iterative algorithm to obtain the controller for the heat exchanger system. Using these algorithm, we construct bilinear tracking controller. In Section 3, superheater system which is containing deterministic and stochastic disturbance is introduced. Extended Kalman Filter is also proposed. Using Extended Kalman Filter, system variables can be estimated. In Section 4, discussions and simulation are represented. Some conclusions follow in Section 5. As is customary, let $\mathrm{R}^{n\times m}$ denote $n\times m$ real variables.

2. Bilinear Quadratic System

2.1. System variable construction

Consider a particular kind of bilinear system with known disturbance:

$$\dot{x}(t) = Ax(t) + Bu(t) + \langle x(t)N\rangle u(t) + D\xi(t) \tag{1}$$

$$y(t) = Cx(t) \tag{2}$$

where $x(t)\in \mathrm{R}^{n}$, $u(t)\in \mathrm{R}^{m}$, $y(t)\in \mathrm{R}^{r}$ and $\xi(t)\in \mathrm{R}^{q}$ are the state variables, the input variables, the output variables and the known disturbance vectors, respectively;

$$A\in \mathrm{R}^{n\times n},\ B\in \mathrm{R}^{n\times m},\ C\in \mathrm{R}^{r\times n},\ D\in \mathrm{R}^{n\times q},$$

$$\langle x(t)N\rangle \equiv \sum_{j=1}^{n} x_j(t)N_j,\ \ N_j\in \mathrm{R}^{n\times m},\ \ j=1,\cdots,n.$$

To keep an outlet steam temperature $y(t)$ close to y_{ref} over a specified time interval $[0, t^f]$, the quadratic cost functional is given by

$$\begin{aligned} J = &\frac{1}{2}(Cx(t^f) - y_{ref})^T\overline{P}(Cx(t^f) - y_{ref}) \\ &+ \frac{1}{2}\int_0^{t^f}\{(Cx(t) - y_{ref})^T\overline{Q}(Cx(t) - y_{ref}) \\ &+ u(t)^T\overline{R}u(t)\}dt \end{aligned} \tag{3}$$

where t^f is the final time, $\overline{P}$ and $\overline{Q}$ are $r\times r$ positive-semidefinite symmetric matrices, and $\overline{R}$ is an $m\times m$ positive-definite symmetric matrix.

Hamiltonian of the problem is defined by

$$\begin{aligned} H(x,u,p) = &\frac{1}{2}\{(Cx(t) - y_{ref})^T\overline{Q}(Cx(t) - y_{ref}) \\ &+ u(t)^T\overline{R}u(t)\} + p(t)^T\{Ax(t) + \langle x(t)N\rangle u(t) \\ &+ Bu(t) + D\xi(t)\} \end{aligned} \tag{4}$$

The necessary optimal condition is obtained by

$$\frac{\partial H}{\partial u} = 0$$

and the optimal control $u^*(t)$ is

$$u^*(t) = -\overline{R}^{-1}(B + \langle x(t)N\rangle)^T p(t) \tag{5}$$

Costate variable $p(t)$ satisfies

$$\frac{\partial H}{\partial x} = -\dot{p}^T \tag{6}$$

(5) and (6) are Euler-Lagrange equations, giving necessary conditions for $u^*(t)$ to minimize J.

The state equation is derived from (1)

$$\begin{aligned} \dot{x}_i(t) = &[Ax(t)]_i - [(B + \langle x(t)N\rangle)\overline{R}^{-1} \\ &\cdot (B + \langle x(t)N\rangle)^T p(t)]_i + [D\xi(t)]_i \end{aligned} \tag{7}$$

and the boundary is restricted to $x(0)$

Executing (6) and taking into account (5), the costate equation is

$$\begin{aligned} [\dot{p}(t)]_i = &-[C^T\overline{Q}Cx(t)]_i - [A^Tp(t)]_i \\ &+ \frac{1}{2}p^T(t)\{N_i\overline{R}^{-1}(B + \langle x(t)N\rangle)^T \\ &+ (B + \langle x(t)N\rangle)\overline{R}^{-1}N_i^T\}p(t) + y_{ref}[C^T\overline{Q}]_i \end{aligned} \tag{8}$$

$p_i(t^f) = [C^T\overline{P}Cx(t^f)]_i - y_{ref}[C^T\overline{P}]_i, \quad i=1,\cdots,n$

where $[\cdot]_i$ is the i-th row of the associated vector.

In order to stay in close proximity to the Riccati approach[2], state and costate equations are rewritten as follows

$$\dot{x}(t) = \tilde{A}x(t) - \tilde{B}\overline{R}^{-1}\tilde{B}^T p(t) + D\xi(t) \quad (9)$$

$$\dot{p}(t) = -\tilde{Q}x(t) - \tilde{A}^T p(t) + y_{ref}C^T\overline{Q} \quad (10)$$

with boundaries restricted to $x(0)$ and $p(t^f) = C^T\overline{P}Cx(t^f) - y_{ref}C^T\overline{P}$.

The time-varying matrices $\tilde{A} = [\tilde{a}_{ij}]$, $\tilde{Q} = [\tilde{q}_{ij}]$ and $\tilde{B}\overline{R}^{-1}\tilde{B}^T$ denote

$$\tilde{a}_{ij} = a_{ij} - \frac{1}{2}[(N_j\overline{R}^{-1}B^T + B\overline{R}^{-1}N_j^T)p(t)]_i \quad (11)$$

$$\tilde{q}_{ij} = [C^T\overline{Q}C]_{ij} - \frac{1}{2}p^T(t)\cdot (N_i\overline{R}^{-1}N_j^T + N_j\overline{R}^{-1}N_i^T)p(t) \quad (12)$$

$$\begin{aligned} &\tilde{B}\overline{R}^{-1}\tilde{B}^T - \frac{1}{2}(\langle xN\rangle\overline{R}^{-1}B^T + B\overline{R}^{-1}\langle xN\rangle^T) \\ &= (B+\langle xN\rangle)\overline{R}^{-1}(B+\langle xN\rangle)^T \end{aligned} \quad (13)$$

$\tilde{a}_{ij}$ and $\tilde{q}_{ij}$ are the i-th row and j-th column element of matrix $\tilde{A}$ and $\tilde{Q}$, respectively.

The above problems are called two-point boundary-value problems, and they are sometimes rather difficult to solve, even with a high speed computer. Notice that the two equations (9) and (10) are coupled since $u(t)$ depends on $p(t)$ through (5). Now, we express $u(t)$ as a combination of a linear state variable feedback plus a term depending on $y_{ref}C^T\overline{P}$. Looking at the boundary restriction $p(t^f)$, it seems reasonable to assume

$$p(t) = S(t)x(t) - y_{ref}C^T\overline{P}, \quad \text{for all } t \le t^f \quad (14)$$

where $S(t)$ is the unknown auxiliary sequence. Using (14), state equation (7) becomes

$$\begin{aligned} \dot{x}(t) = &(\tilde{A} - \tilde{B}\overline{R}^{-1}\tilde{B}^T S(t))x(t) \\ &+ y_{ref}\tilde{B}\overline{R}^{-1}\tilde{B}^T C^T\overline{P} + D\xi(t) \end{aligned} \quad (15)$$

Next equation is induced by differentiating (14)

$$\begin{aligned} \dot{p}(t) &= \dot{S}(t)x(t) + S(t)\dot{x}(t) \\ &= \dot{S}(t)x(t) + S(t)(\tilde{A}x(t) - \tilde{B}\overline{R}^{-1}\tilde{B}^T(S(t)x(t) \\ &\quad - y_{ref}C^T\overline{P}) + D\xi(t)) \end{aligned} \quad (16)$$

Now, taking into account the costate equation (10), we obtain the relation

$$\begin{aligned} -\dot{S}(t) = &S(t)\tilde{A} + \tilde{A}^T S(t) \\ &- S(t)\tilde{B}\overline{R}^{-1}\tilde{B}^T S(t) + \tilde{Q} \end{aligned} \quad (17)$$

$$\begin{aligned} 0 = &y_{ref}\tilde{A}^T C^T\overline{P} - y_{ref}S(t)\tilde{B}\overline{R}^{-1}\tilde{B}^T C^T\overline{P} \\ &- S(t)D\xi(t) + y_{ref}C^T\overline{Q} \end{aligned} \quad (18)$$

(17) is a matrix Riccati equation, and if $S(t)$ is its solution with final condition $S(t^f)$, then (14) holds for all $t \le t^f$. Since the matrix sequence $S(t)$ is independent of the state trajectory, the Riccati equation can be solved off-line, and $S(t)$ can be stored.

Then, the optimal tracking control becomes

$$\begin{aligned} u(t) &= -\overline{R}^{-1}(B + \langle x(t)N\rangle)^T p(t) \\ &= -\overline{R}^{-1}(B + \langle x(t)N\rangle)^T(S(t)x(t) - y_{ref}C^T\overline{P}) \end{aligned} \quad (19)$$

and the values of $S(t)$ and $x(t)$ are calculated using the relations of (15) and (17)

2.2. Iterative Method

We notice that $\tilde{A}(t)$ and $\tilde{Q}(t)$ are the functions of the costate $p(t)$ and $\tilde{B}\overline{R}^{-1}\tilde{B}^T(t)$ is the function of state $x(t)$. Hence we denote the iteration index (j) by a superscript. For the brevity of the notations, iteration sequences are simplified into

$\tilde{A}(p^{(j)}(t)) = \tilde{A}^{(j)}(t), \quad \tilde{Q}(p^{(j)}(t)) = \tilde{Q}^{(j)}(t)$

and $\tilde{B}(x^{(j)}(t))\overline{R}^{-1}\tilde{B}^T(x^{(j)}(t)) = \tilde{B}^{(j)}\overline{R}^{-1}\tilde{B}^{T(j)}(t)$.

Then the iterative solutions of the state and costate equations are obtained from the following equation

$$\begin{aligned} \dot{x}^{(j+1)}(t) = &\tilde{A}^{(j)}x^{(j+1)}(t) \\ &- \tilde{B}^{(j)}\overline{R}^{-1}\tilde{B}^{(j)T}p^{(j+1)}(t) + D\xi(t) \end{aligned} \quad (20)$$

$$\begin{aligned} \dot{p}^{(j+1)}(t) = &-\tilde{Q}^{(j)}x^{(j+1)}(t) - \tilde{A}^{(j)T}p^{(j+1)}(t) \\ &+ y_{ref}C^T\overline{Q} \end{aligned} \quad (21)$$

and the boundaries are restricted to $x^{(j+1)}(0)$ and $p^{(j+1)}(t^f) = C^T\overline{P}Cx^{(j+1)}(t^f) - y_{ref}C^T\overline{P}$.

We conclude that (20) and (21) are linear time varying system for each iteration step. Hence our problem is to solve the linear time varying system using the Riccati formalism. With the definition of $p(t)$, the solutions of (20) and (21) can be derived from

$$-\dot{S}^{(j+1)}(t)=\tilde{A}^{(j)T}S^{(j+1)}(t)+S^{(j+1)}(t)\tilde{A}^{(j)} -S^{(j+1)}(t)\tilde{B}^{(j)}\overline{R}^{-1}\tilde{B}^{(j)T}S^{(j+1)}(t) +\tilde{Q}^{(j)} \quad (22)$$

$$\dot{x}^{(j+1)}(t)=\tilde{A}^{(j)}x^{(j+1)}(t)-\tilde{B}^{(j)}\overline{R}^{-1}\tilde{B}^{T(j)} \cdot S^{(j+1)}(t)x^{(j+1)}(t) +y_{ref}\tilde{B}^{(j)}\overline{R}^{-1}\tilde{B}^{T(j)}C^T\overline{P}+D\xi(t) \quad (23)$$

where boundary restrictions are $P^{(j+1)}(t^f)=C^T\overline{P}C$ and $x^{(0)}(0)$.

Now we introduce the successive approximation approach[5]. Aganovic and Gajic have developed an optimization algorithm, which is based on the application of the method of successive approximations to the approximative procedure presented in Hofer and Tibken[2]. Applying the procedures of Aganovic and Gajic, (20) and (21) correspond to the following linear quadratic time-varying control problem

$$\dot{x}^{(j+1)}(t)=\tilde{A}^{(j)}x^{(j+1)}(t)+\tilde{B}^{(j)}u^{(j+1)}(t)+D\xi(t)$$

$$J^{(j+1)}=\frac{1}{2}(Cx^{(j+1)}(t^f)-y_{ref})^T\overline{P}(Cx^{(j+1)}(t^f)-y_{ref}) +\frac{1}{2}\int_0^{t^f}\{(Cx^{(j+1)}(t)-y_{ref})^T\overline{Q}(Cx^{(j+1)}(t)-y_{ref}) +u(t)^{(j+1)^T}\overline{R}u^{(j+1)}(t)\}dt$$

The application of the successive approximation technique to the above equation results[5]

$$\dot{x}^{(j+1)}(t)=(A^{(j)}-B^{(j)}P^{(j)})x^{(j+1)}(t) +y_{ref}B^{(j)}C^T\overline{P}+D\xi(t) \quad (24)$$

From the results of Aganovic and Gajic[5], (22) is replaced by

$$\dot{P}^{(j+1)}(t)+\overline{A}^{T(j)}P^{(j+1)}(t)+P^{(j+1)}(t)\overline{A}^{(j)} +\overline{Q}^{(j)}=0 \quad (25)$$

where $\overline{Q}^{(j)}=Q^{(j)}+P^{(j)}B^{(j)}P^{(j)}$, $\overline{A}^{(j)}=A^{(j)}-B^{(j)}P^{(j)}$,

$$\tilde{A}^{(j)}(t)=A^{(j)}(t),\ \tilde{Q}^{(j)}(t)=Q^{(j)}(t),$$

$$\tilde{B}^{(j)}\overline{R}^{-1}\tilde{B}^{T(j)}(t)=B^{(j)}(t).$$

For each iteration, the optimal feedback controller is given by

$$u^{(j+1)}(t)=-\overline{R}^{-1}(B+\langle x^{(j+1)}(t)N\rangle)^T \cdot(P^{(j)}(t)x^{(j+1)}(t)-y_{ref}C^T\overline{P})$$

where matrix $P^{(j+1)}(t)$ is calculated from the Lyapunov equation (25). Hence we confirm that in the bilinear quadratic case the Lyapunov matrix depends on the initial state $x^{(0)}(0)$ in contrast to the linear quadratic problem. This point seems to be natural because of the nonlinearity of the bilinear system.

For the first iteration $j=0$, initial values of the state variables and the costate variables are required to calculate matrices $\tilde{A}^{(0)}$, $\tilde{Q}^{(0)}$ and $\tilde{B}^{(0)}\overline{R}^{-1}\tilde{B}^{(0)T}$. Hence, we consider the linear part of the bilinear system (1)

$$\dot{x}(t)=Ax(t)+Bu(t)+D\xi(t).$$

Then, the matrices $A^{(0)}$, $Q^{(0)}$ and $B^{(0)}$ are calculated by using the solution of

$$\dot{x}^{(0)}(t)=(A-B\overline{R}^{-1}B^TP^{(0)})x^{(0)}(t) +y_{ref}B\overline{R}^{-1}B^TC^T\overline{P}+D\xi(t)$$

and the boundary restriction is to $x(0)$,

$$\dot{P}^{(0)}(t)+AP^{(0)}(t)+P^{(0)}(t)A+\overline{Q}=0,$$

$$P^{(0)}(t^f)=C^T\overline{P}C.$$

With $p^{(0)}(t)=P^{(0)}(t)x^{(0)}(t)-y_{ref}C^T\overline{P}$,

$$u^{(0)}(t)=-\overline{R}^{-1}B^Tp^{(0)}(t)$$

is represented.

From the next iteration steps, $A^{(j)}$, $Q^{(j)}$ and $B^{(j)}$ are calculated by using the solution of

$$\dot{x}^{(j+1)}(t)=(A^{(j)}-B^{(j)}\overline{R}^{-1}B^{(j)^T}P^{(j)})x^{(j+1)}(t) +y_{ref}B^{(j)}\overline{R}^{-1}B^{(j)^T}C^T\overline{P}+D\xi(t),$$

$$\dot{P}^{(j+1)}(t)+A^{T(j)}P^{(j+1)}(t)+P^{(j+1)}(t)A^{(j)}+\overline{Q}^{(j)}=0$$

where boundary are restricted to

$$P^{(j+1)}(t^f)=C^T\overline{P}C \text{ and } x^{(0)}(0)$$

Then, the control law is given by

$$u^{(j+1)}(t)=-\overline{R}^{-1}(B+\langle x^{(j+1)}(t)N\rangle)^T \cdot(P^{(j+1)}(t)x^{(j+1)}(t)-y_{ref}C^T\overline{P}).$$

If the iteration difference of $u^{(j)}(t)$ and $u^{(j+1)}(t)$ has the lower value than the predefined bound, the iteration in this step is terminated.

3. Superheater Modelling and Construction of Extended Kalman Filter

T_m : metal temperature (℃)

T : steam temperature (℃)

T_i : inlet steam temperature (℃)

T_o : outlet steam temperature (℃)

T_d : spray water temperature (℃)

H_i : inlet steam enthalpy $(kcal/kg)$

H_o : outlet steam enthalpy $(kcal/kg)$

w_i : inlet steam mass flow rate (kg/s)

w_o : outlet steam mass flow rate (kg/s)

w_d : spray water mass rate (kg/s)

Q_{gm} : heat input rate from flue gas to metal $(kcal/s)$

Q_{ms} : heat input rate from metal to steam $(kcal/s)$

V_s : volume of each segment (m^3)

ρ : steam density (kg/m^3)

C_p : superheated steam heat capacitance $(kcal/kg℃)$

C_{pd} : spray water heat capacitance $(kcal/kg℃)$

C_m : superheater tube heat capacitance $(kcal/kg℃)$

α_{ms} : heat transfer rate from metal to steam $(kcal/m^2 s℃)$

α_{gm} : heat transfer rate from gas to metal $(kcal/m^2 s℃)$

M_m : mass of superheater tube (kg)

S_1 : external heating surface (m^2)

S_2 : internal heating surface (m^2)

In the operation of a power plant superheater, exacting demands are made on the steam temperature maintenance at the outlet. For temperature control at the outlet of a superheater, the relevant system state is the temperature pattern along the superheater tube. This is described by a distributed-parameter system, which involves an infinite number of state variables. To derive a simplified model for control purposes, the superheater is divided into segments, and a lumped model is derived, which represents a finite number of intermediate temperatures.

In the interest of simplicity in practical implementation, the observer is constructed based on the lumped model with fewer segments than the superheater model described above.

To describe the distributed parameter nature of the superheater accurately, the superheater is divided into many segments. Each segment is taken as a control volume to be approximated as a simplified single capacitance. Using the control volume approach, a lumped model for each segment is derived as shown in Fig. 1. The steam and the flue gas are separated by a metal tube, which forms a heat-exchange surface.

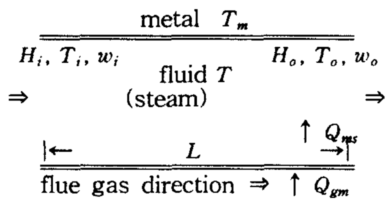


그림1. 열교환기 모델
Fig. 1. Heat exchanger model

Recall that if the velocity of a compressible flow is sufficiently slower than the speed of sound, the flow may be approximated as an incom- pressible one, and consequently $d\rho/dt = 0$. Since the velocity of the steam in the superheater is considerably slower than the sound in the power plant boiler, the approximation can be adopted, and as a consequence, the density of the steam can be excluded from the states. Therefore $w_i = w_o$ is derived. Assuming that the pressure inside the tube is constant, the enthalpy of the steam satisfies the relation $dH = C_p dT$, where C_p is the constant-pressure specific heat. Hence, we conclude that the heat supplied to the following fluid(steam) only increases its enthalpy, $dH = dQ$, where Q denotes the heat. In the above equations, it is assumed that convection is the exclusive heat transfer mode for the superheater. Hence the heat transfer Q_{ms} and Q_{gm} are expressed in terms of the heat transfer rates α_{gm} and α_{ms} and heating surface S:

$$\alpha_{ms}S_1(T_m(l,t)-T(l,t)) = Q_{ms} \tag{26}$$

$$\alpha_{gm}S_2(T_g(l,t)-T_m(l,t)) = Q_{gm} \tag{27}$$

It is also assumed that the heat transfer rates α_{gm} and α_{ms} are constants.

Now, to simulate the profile of superheated steam precisely, it is necessary to divide the superheater into n segments as shown in Fig. 2.

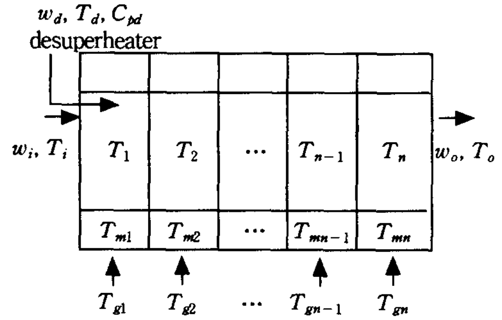


그림 2. 과열기 분할
Fig. 2. Partition of a superheater

In the first segment, the desuperheater is included and system is modified as follows:

$$V_s\rho C_p\frac{dx_1}{dt} = C_pT_iw_i - C_p(w_i+w_d)x_1 + \alpha_{ms}S_1(z_1-x_1)+C_{pd}T_dw_d \tag{28}$$

$$M_mC_m\frac{dz_1}{dt} = \alpha_{gm}S_2(T_{g1}-z_1)-\alpha_{ms}S_1(z_1-x_1) \tag{29}$$

where $x=[x_1, x_2, \cdots, x_n]^T=[T_1, T_2, \cdots, T_n]^T$ and

$$z=[z_1, z_2, \cdots, z_n]^T=[T_{m1}, T_{m2}, \cdots, T_{mn}]^T.$$

In the kth segment, $k=2,\cdots,n$, yield

$$V_s\rho C_p\frac{dx_k}{dt} = C_p(w_i+w_d)(x_{k-1}-x_k)+\alpha_{ms}S_1(z_k-x_k) \tag{30}$$

$$M_mC_m\frac{dz_k}{dt} = \alpha_{gm}S_2(T_{gk}-z_k)-\alpha_{ms}S_1(z_k-x_k) \tag{31}$$

To derive a model for the construction of the observer, the superheater is divided into ν segments. Regarding the metal temperatures z_k, $k=1,\cdots,\nu$, as unknown inputs T_{mk}, $k=1,\cdots,\nu$. After these processes,

$$V_s\rho C_p\frac{dx_1}{dt} = -C_p(w_i+w_d)x_1+\alpha_{ms}S_2(T_{m1}-x_1) + C_pT_iw_i+C_{pd}T_dw_d \tag{32}$$

and in the kth segment, $k=2,\cdots,\nu$,

$$V_s\rho C_p\frac{dx_k}{dt} = C_p(w_i+w_d)(x_{k-1}-x_k)+\alpha_{ms}S_2(T_{mk}-x_k) \tag{33}$$

$$\dot{x}(t)=[\overline{A_0}+\overline{p_1}(t)A_1+\overline{p_2}(t)A_2]x(t) + [B_0+q_1(t)B_1]u(t)+\overline{D}\,\overline{v}(t) \tag{34}$$

where $\overline{p_1}(t)=w_i$, $\overline{v}(t)=[T_{m1}\ T_{m2}\cdots\ T_{m\nu}]^T$,

$\overline{p_2}(t)=w_d$, $q_1(t)=T_i$, $u(t)=[w_d\ w_i]^T$.

The matrices are given by

$$\overline{A_0}=diag[a_1, a_1, \ldots\ldots, a_1],$$

$$A_1=A_2=\begin{bmatrix} -a_2 & 0 & \cdots & \cdots & \cdots & 0 \\ a_2 & -a_2 & \cdots & \cdots & \cdots & 0 \\ 0 & a_2 & -a_2 & \cdots & \cdots & 0 \\ & \cdots & \cdots & \cdots & \cdots & \\ 0 & \cdots & 0 & a_2 & -a_2 & 0 \\ 0 & \cdots & \cdots & \cdots & a_2 & -a_2 \end{bmatrix},$$

$$B_0=\begin{bmatrix} B_{01}^T \\ 0\ 0\ \cdots\ 0 \end{bmatrix}^T, B_1=\begin{bmatrix} 0\ 0\ \cdots\ 0 \\ B_{12}^T \end{bmatrix}^T, \overline{D}=-\overline{A_0},$$

$$B_{01}=[b_1\ 0\ \cdots\ 0]^T, B_{12}=[b_2\ 0\ \cdots\ 0]^T$$

where

$$a_1=-\frac{\alpha_{ms}S_2}{V_s\rho C_p}, a_2=\frac{1}{V_s\rho}, b_1=\frac{C_{pd}T_d}{V_s\rho C_p}, b_2=a_2.$$

Discrete equation of (34) is illustrated by

$$x(k+1)=Ax(k)+Bu(k)+\langle x(k)N\rangle u(k)+D(k) \tag{35}$$

where $B_{01}=[b_1\ 0\ \cdots\ 0]^T$, $B_{12}=[a_2\ 0\ \cdots\ 0]^T$,

$A=I+[A_0+(w_{dn}+w_i(k))A_1]\cdot t_d$,

$B=B_{01}\cdot t_d$, $N=A_1\cdot t_d$,

$D(k)=(B_{01}w_{dn}+T_i(k)B_{12}w_i(k)+\mathrm{Dv})\cdot t_d$,

$u=w_d-w_{dn}$,

with t_d is sampling time, w_{dn} is the nominal value of w_d, and $A\in R^{n\times n}$, $B\in R^{n\times 1}$, $N\in R^{n\times n}$ $D(k)\in R^{n\times 1}$.

Since $D(k)$ contain gas temperature distribution, inlet steam temperature and inlet steam mass flow rate, $D(k)$ can be classified by deterministic component D_0 and stochastic one $D_v(k)$, so we reformulate system (35) as

$$x(k+1) = Ax(k) + Bu(k) + \langle x(k)N \rangle u(k) + D_o + D_v(k) \quad (36)$$

In the superheater, the inlet and outlet steam temperature are usually measured for the purpose of control. Hence, the measurement matrix takes the form, $C_e = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix}$, so measurement equation is

$$z(k) = C_e x(k) + n(k) \quad (37)$$

where $n(k) = \mathrm{N}(0, \mathrm{R_e})$ is white noise process with zero mean and covariance is $R_e \in \mathrm{R}^{2\times 2}$. Assume the inlet and outlet gas temperature variation, ΔT_{g1} and ΔT_{gn} be the uncorrelated with each other $\Delta T_{g1} = \mathrm{N}(0, \sigma_1^2), \Delta T_{gn} = \mathrm{N}(0, \sigma_n^2)$ then unknown input variation ΔD_v is

$$\Delta D_v = \begin{bmatrix} \Delta D_{v_1} \\ \Delta D_{v_2} \end{bmatrix} = \begin{vmatrix} \dfrac{\Delta T_{gn} - \Delta T_{g1}}{d_1} \\ \dfrac{(1+\frac{d_2}{d_1})\Delta T_{g1} - \frac{d_2}{d_1}\Delta T_{gn}}{d_2} \end{vmatrix}$$

$$d_1 = [\{(n-0.5)\Delta l - L\}^2 - (0.5\Delta l - L)^2]d,$$

$$d_2 = (0.5\Delta l - L)^2 d.$$

So $D_v(k)$ can be represented by mean value D_d and variation ΔD_v as follows

$$D_v(k) = D_d \begin{bmatrix} \Delta D_{v_1} \\ \Delta D_{v_2} \end{bmatrix}, \quad D_d \in \mathrm{R}^{n\times 2}.$$

Variance of $D_v(k)$, Q is represented as

$$Q = \mathbf{E}\left\{ D_d \begin{bmatrix} \Delta D_{v_1} \\ \Delta D_{v_2} \end{bmatrix} [\Delta D_{v_1} \ \Delta D_{v_2}] D_d^T \right\}.$$

Deterministic disturbance D_0 be measurable, therefore can be compensated as

$$D_{dk} = -(A + Nu(k))^{-1} D_0(k)$$

$$\hat{x}(k) = \bar{x}(k) - D_{dk}$$

where $\bar{x}(k)$ is estimated value and $\hat{x}(k)$ is Kalman filter state.

Linearized model coefficient is constructed as

$$f(x(k), u(k)) = Ax(k) + \langle x(k)N \rangle u(k) + Bu(k) \quad (38)$$

$$F(\hat{x}(k)(+)) = \left[\frac{\partial f(x(k), u(k))}{\partial x(k)} \right]_{x(k) = \hat{x}(k)_{(+)}} = A + Nu(k) \quad (39)$$

Using the Extended Kalman Filter theory[10], steam temperatures are estimated following measurement and time update equations.

Measurement update equation:

$$\hat{x}(k+1)_{(-)} = (A + Nu(k))\hat{x}(k)_{(+)} + Bu(k)$$

$$P(k+1)_{(-)} = (A + Nu(k))P(k)_{(+)}(A + Nu(k))^T + Q$$

$$K(k+1) = P(k+1)_{(-)} C_e^T (C_e P(k+1)_{(-)} C_e^T + R_e)^{-1}$$

Time update equation:

$$\hat{x}(k+1)_{(+)} = \hat{x}(k+1)_{(-)} + K(k+1) \cdot \{z(k+1) - C_e(\hat{x}(k+1)_{(-)} + D_{dk})\}$$

$$P(k+1)_{(+)} = \{I - K(k+1)C_e\}P(k+1)_{(-)}.$$

In this paper, we divide the superheater into 5 segments, and construct an Extended Kalman Filter when the gas flows in parallel with the fluid inside.

4. Simulation

Computer simulations were performed to verify the performance of the proposed controller. It is shown that the estimated value follows the steam temperature under the variation of inlet steam temperature and flue gas temperature, and that the proposed controller maintains the outlet steam temperature properly. Superheater is approximated as a system with states consisting of 20 steam temperatures. Whereas in the interest of simplicity in implementation, the state model for the observer is derived by decomposing the superheater into 5 segments, The following values obtained from an actual superheater specification were used in the simulation[6]:

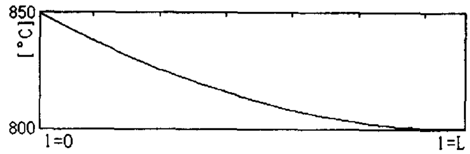
$$L = 32.8(m), \ a_1 = -0.49, \ a_2 = 2.08\times 10^{-3},$$

$$b_1 = 0.24, \ d = 0.49.$$

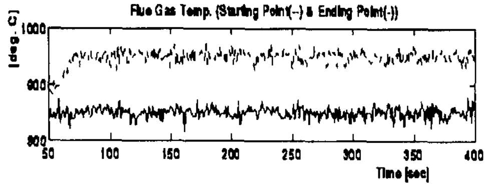
In equation (3), the input weighting matrix $\overline{R}$ is taken to be I, and the state weighting matrices $\overline{P}$ and $\overline{Q}$ are taken to be $5I$. Those weighting matrices are used in the state feedback controller

(34). Superheater system is assumed to be 100% BMCR operation, so Extended Kalman Filter is used to estimate system state by linealizing in operating point. In the simulation, bound satisfying iteration difference of $u^{(j)}(t)$ and $u^{(j+1)}(t)$ is 0.01. Total simulation time is 400 (s), iteration time is 1 (s) and sampling time is 0.1 (s). Since we assumed normal operation, we simulate from 50 (s).

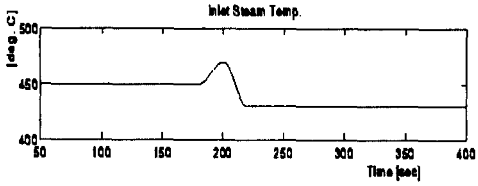
The initial flue gas temperature profile for the parallel flow arrangement is illustrated in Fig.3(a), where the flue gas temperatures at $l=0$ and $l=L$ are 850 (℃) and 800 (℃), respectively. The initial flue gas temperature profile is approximated as a second-degree polynomial. In the simulation, flue gas temperatures at $l=0$ and $l=L$ vary in time independently, and inbetween the temperature distribution changes smoothly according to the variation of the flue gas temperatures at $l=0$ and $l=L$. Fig. 3(b) illustrates the flue gas temperature variations at $l=0$ and $l=L$, where the upper part represents the temperature variation at $l=0$ and the lower part represents the temperature variation at $l=L$. The inlet steam temperature variation is a known external input. Fig. 3(c) shows the inlet steam temperature variation. As shown in Fig. 3(c), the inlet steam temperature changes before and after at 200 (s). Variation of the inlet steam mass flow rate is shown in Fig. 3(d). The inlet steam mass flow rate decreases and increases linearly from 320 (s) to 330 (s) and from 330 (s) to 340 (s). With the specified initial conditions and temperature variations, it has been checked how the observer estimates the superheater steam temperature. The first and the fourth states in the observer geometrically correspond to the fourth and the sixteenth steam states of the superheater model partitioned into 20 segments. They are compared in Fig. 4. In Fig. 4, it can be seen that the estimate follows the true value very closely, even though a small offset can be noticed, which results from the crude dividing scheme for the observer model and the appro- ximation of the flue gas temperature.



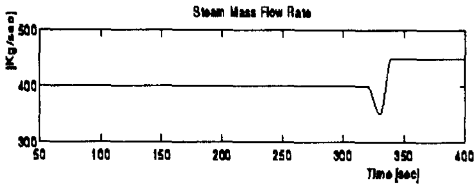
(a) distribution of initial flue gas temperature.



(b) flue gas temp.



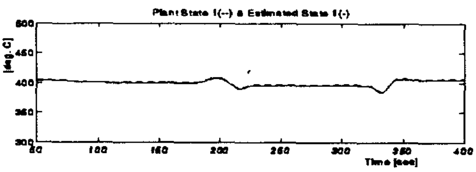
(c) inlet steam temp.



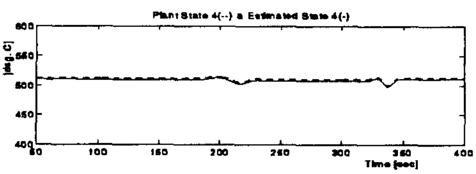
(d) steam mass flow rate

그림 3. 외부입력

Fig. 3. External input



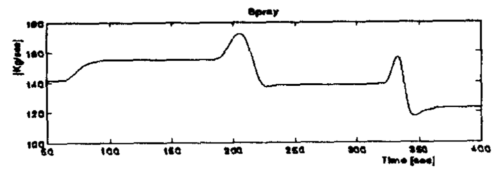
(a) plant and estimated state 1



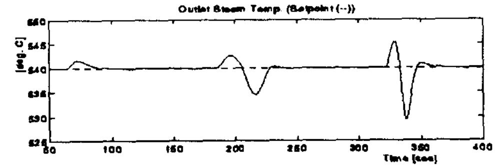
(b) plant and estimated state 4

그림 4. 추정상태

Fig. 4. Estimated state



(a) spray water mass rate



(b) outlet steam temp.

그림 5. 입력 및 출력
Fig. 5. Input and output

Fig. 5(a) shows the spray water mass rate. It can be seen that the spray water mass rate changes against the variation of the inlet steam temperature and steam mass flow rate. The outlet steam temperature is shown in Fig. 5(b). The changes of the inlet steam temperature and steam mass flow rate cause the outlet steam temperature to change after 5~6 (s) by about one-fifth of the inlet steam temperature change. As shown in Fig. 5(b), the superheater outlet temperature is properly maintained at 540(℃) under the changes of inlet steam temperature, inlet mass flow rate and flue gas temperature. In this paper, we assume the stochastic unknown input changes with $\Delta T_{g1} = \mathrm{N}(0,2)$, $\Delta T_{gn} = \mathrm{N}(0,2)$. System also has measurement noise with $n(k) = \mathrm{N}(0,1)$.

5. Conclusion

In this paper, we proposed the temperature controller for the heat exchanger system using iterative method. With this controller, we apply to the superheater system. Uncertain information about gas temperature distribution was regarded as white noise process, and applied to the Extended Kalman Filter. We show that the superheater outlet temperature is properly maintained by a tracking controller based on the Extended Kalman Filter under the variation of inlet steam mass flow rate, inlet steam temperature and flue gas temperature.

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◇ 저자소개 ◇

이 상 혁(李相赫)
1988년 충북대학교 전기공학과 졸업, 1991년 서울대학교 대학원 전기공학과 졸업(석사), 1998년 동대학원 전기공학과 졸업(박사), 1996년~1999년 (주)하우 책임연구원, 1999년~현재 우송대학교 전자공학과 강의전담교수

김 주 식(金周植)
1992년 충북대학교 전기공학과 졸업, 1994년 동대학원 전기공학과 졸업(석사), 1998년 동대학원 전기공학과 졸업(박사)