Estimation of Unmeasurable Input and States by Applying Fuzzy Control*
(Fuzzy Control for Steam Temperature of a Boiler Heating Surface)

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Previous papers proposed a fuzzy applied observer (FAO) as a solution to the nonlinear estimation problem with unmeasurable input. This paper deals with a steam-temperature control (STC) of a once-through boiler using FAO. The STC consists of a final superheater (FSH), a spray attemperator at the FSH inlet, the FAO and two compensators. One object of compensation is delay in the dynamic behavior of steam temperature and the other is the effect of imbalance between disturbances in heat absorption and steam flow. The former is compensated for by state variable feedback and the latter is compensated for using fuzzy control to deviations in the temperature and the ratio of these two disturbances. Simulations are performed to confirm the control. The results show better control performance due to the suitable fuzzy applied observer compared to the uncompensated case.

Key Words: Observer, Fuzzy Set Theory, Nonlinear Control, Measurement and Control, Fuzzy Applied Observer (FAO), Steam Temperature Control, Estimation, Unmeasurable Input, State Variables, Once-Through Boiler, Final Superheater, Heat Absorption, Simulation

1. Introduction

In a previous paper, the authors proposed an observer which estimates simultaneously state variables and inputs as a solution to the linear estimation problem with unmeasurable inputs[1]. This observer is extended to the nonlinear problem with an unmeasurable input by applying fuzzy control called FAO (Fuzzy Applied Observer). The first and the second reports describe the solution to estimating simultaneously the unmeasurable heat absorption and the state variables, namely enthalpies along the tube length on a boiler heating surface[2]-[4]. This paper deals with the steam-temperature control (STC) for a once-through boiler to improve control by FAO[5].

Almost all boilers commissioned by electric power utility networks in this country in the last decade are coal-fired, super-critical and sliding-pressure-operating once-through boilers. It is quite difficult to control steam temperatures in this type of boiler. The first reason for this difficulty is based on the considerable delay in the dynamic characteristics of the control object. The gain in PID (Proportional, Integral and Derivative) feedback control is, therefore, so restricted that many functions other than the elimination of the steady state deviation do not perform satisfactorily. Consequently, many feed forward actions are employed in the STC. The second reason is that this type of boiler requires so more changes in amount of fuel supply than the constant-pressure-operating boiler as to slide the pressure corresponding to the load in the changing-load operation. As a result, the dynamic characteristics of the control object vary from the norm, and the STC is excessively

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disturbed by great changes in heat absorption on each heating surface. The third reason is that the boiler burns with a large variety of coals with different properties which in turn cause variable performance of the boiler. In addition, the performance variation is accelerated from hour to hour by the fouling of heating surfaces resulting from coal firing. Many mathematical functions have been prepared for the STC to select the adequate characteristic of feed forward action for each boiler's performance and each fouling situation. This makes the STC so complicated and troublesome as to require a lot of time to set up and maintain the functions.

Because the outlet steam temperature of a once-through boiler is determined by how much the feed water is heated, the temperature is ultimately controlled by the ratio of the steam flow rate to the amount heated in steady state. In the transient state, however, this ratio is not effective to control the temperature because of the large delay in the control object. This requires the spray attemperator to be installed in the final superheater inlet to control the temperature deviation. From this situation, a high-performance feedback control with spray attemperator has been adopted to improve the STC by applying FAO to the final superheater. The first improvement is the compensation for the delay in the control object. An example of series compensation has been presented by Sagara et al.[6],[7], while a feedback compensation with state variables[8] is discussed in this paper. Inlet enthalpy, heat absorption and the steam flow rate in the final superheater are considered inputs to the control object. However, state variables can be fed back only to the inlet enthalpy manipulated by the spray attemperator. The other two variables become disturbances to the control object, the effect of which appears in the ratio of heat absorption to steam flow as mentioned above. Based on this consideration, to reduce the effect of disturbances the following compensation applying fuzzy control to deviations in the outlet temperature and the ratio of above two variables is introduced to the STC.

2. Outline of Control Object and Compensations

The control object consists of the final superheater (FSH), the spray attemperator and the related control systems to manipulate the spray in the simulator[9]–[11] of the super-critical pressure, sliding-pressure-operating type once-through boiler used for confirmation of FAO. The model of the control object and of the compensations is illustrated in Fig. 1. In this figure the central part corresponds to the FSH and the spray attemperator, while the related control system manipulating the spray is located on the left side. On the right side of Fig. 1, two compensators are shown in the areas enclosed with dotted and dot-solid lines. A general view of boiler control systems is out of the scope of this study and is not included in Fig. 1. The main action in Fig. 1 involves controlling the temperature difference across the spray, and a target value for the control of spray flow is given by the output of the main controller. The compensations are carried out by adding the outputs of mathematical operations as biases to the target value.

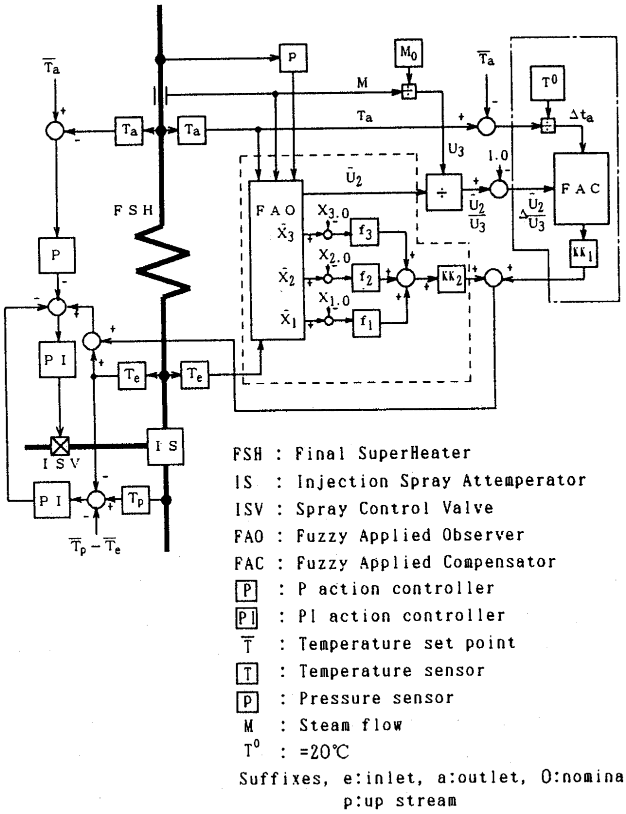


Fig. 1 Model of FSH and control system

3. Delay Compensation by State Variable Feedback

3.1 Examination of the compensation with a linearized system

An examination of the effect of delay compensation by state variable feedback is carried out with a linearized control object. At the same time, the necessity of compensating for disturbance is shown by the influence of the two disturbances mentioned above. No control system except state variable feedback is taken into account in this section. Furthermore, it is assumed that the spray attemperator is modeled to convert the feedback signal into a change in inlet enthalpy. The linearized mathematical model of the heating surface is given by following equations, the details of which are described in a previous paper concerning study of linear system[1].

$$\left.\begin{array}{l}\theta_0=u_1\\ \left.\begin{array}{l}x_i=G\theta_{i-1}\\ \theta_i=x_i+\frac{1}{n}w\end{array}\right\}i=1,2,\cdots,n\\ x_{n+1}=H(u_2-mu_3)\\ y=\theta_n\\ w=x_{n+1}-(1-m)u_3\\ \quad G=1/(Ts+1)\\ \quad H=1/(T's+1)\\ \quad T/T'=K_D/n,\ T=T_s/n\end{array}\right\} \quad (1)$$

All variables in Eq.(1) are normalized deviations. The term n represents the number of divisions along the tube length that approximate the transcendental transfer function obtained as the solution of the distributed system with lumped transfer functions. The term u_1 is the outlet enthalpy of the superheater one step upstream, u_2 is the heat absorption and u_3 is the steam flow rate. The term x_i is the state variable. The terms θ_i, θ_0 and $y=\theta_n$ are enthalpies at the division point, inlet and outlet, respectively. The term m is the power of Reynolds' number in Nusselt's formula for the heat transfer coefficient between the tube wall and the steam, and $m=0.8$. The term T_s is the time constant based on the heat capacity of the tube. The term K_D is the ratio of the increase in steam temperature to the mean temperature difference between the tube and the steam. The term s is the differential operator. The division-point enthalpy θ_i produced from x_i is used as a feedback variable to compensate for the delay.

The feedback is defined in the form of the following equations.

$$\left.\begin{array}{l}\theta_0=u_1-\theta_A\\ \theta_A=\sum_{i=1}^{n}f_i\theta_i\end{array}\right\} \quad (2)$$

The first equation in Eq.(2) represents the model of the spray attemperator. The term f_i is the feedback gain corresponding θ_i. The system of Eqs.(1) and (2) is illustrated in Fig. 2 by a block diagram. From Eq.(1), θ_i can be expressed by the following equation:

$$\theta_i=G^i\theta_0+\frac{1}{n}\sum_{m=0}^{i-1}G^m w,\ i=1,2,\cdots,n \quad (3)$$

The feedback gain is assumed to be:

$$\left.\begin{array}{l}f_i={}_nC_i\left(\frac{1}{\nu}-1\right)^i,\ i=0,1,2,\cdots,n\\ 0<\nu\leq 1\end{array}\right\} \quad (4)$$

Considering $f_0=1$ in Eq.(4), Eqs.(2)~(4) are arranged in the following equation using the definition of G from Eq.(1).

$$\left.\begin{array}{l}\theta_n=\nu^nF^nu_1+\frac{1}{n}\nu\frac{F^{n-1}}{G}\sum_{k=0}F^kw\\ F=1/(\nu Ts+1)\end{array}\right\} \quad (5)$$

In the case of $\nu=1$, Eq.(5) is reduced to the case of

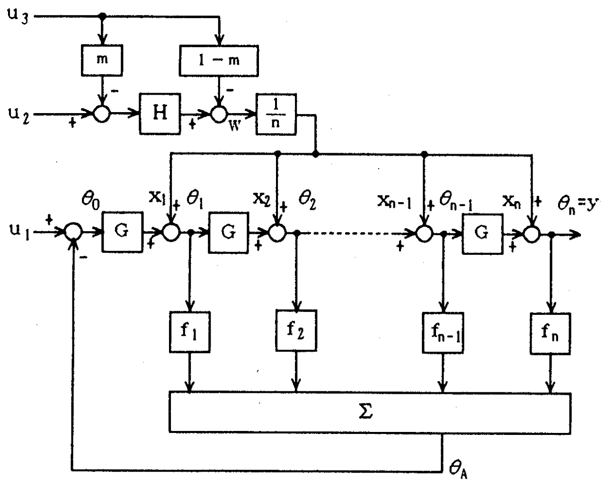


Fig. 2 Block diagram of linearized FSH and state feedback

$i=n$ in Eq.(3) because $f_i=0:\ \forall i$, $F=G$ and $u_1=\theta_0$.

To evaluate the compensation, "delay" is defined as follows. Consider the transfer function P normalized by its steady state gain P^0 and define the delay of P with the following formula.

$$D=\lim_{s\to 0}\frac{1}{s}\left(1-\frac{P}{P^0}\right) \quad (6)$$

Consider the following relation in which D_i represents the delay of P_i,

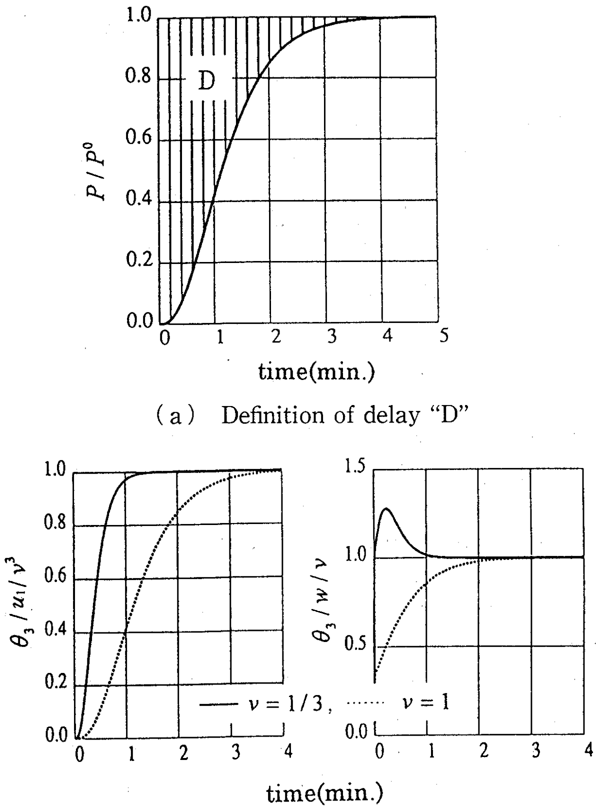
$$P=P_1P_2\cdots\cdots\cdots\cdots P_m \quad (7)$$

then the following equation is obtained.

$$D=\sum_{i=1}^{m}D_i \quad (8)$$

It is obvious from Eq.(6) that the delay D is given by the area enclosed by indicial response of P/P^0 and the unit step function shown in Fig. 3(a). This is an analogy that D is equal to the time constant T if P/P^0 is a first order lag. The value of D may become any positive, zero or negative value. It is easily recognized that if D is positive, P is "delay", and if D is negative, P is "lead". However, if D is zero, it can not be decided whether P is "delay" or "lead". In such a case, this is found out by inferring from Eq.(8) that a part of Eq.(7) is the delay, the remainder is the lead, and as a result the sum of their values of D is zero.

The value of D of each transfer function on the right side of Eq.(5) is calculated from Eq.(6) normalized with P^0 obtained by setting $s=0$. The values of D and P^0 are shown in Table 1. It should be noticed in Table 1 that D for θ_n/w may become any positive, zero or negative value. Here, it is seen that the value of D for θ_n/w is given by the sum of two D terms obtained from transfer functions shown in the right two columns of Table 1. Indicial responses of θ_n/u_1 and θ_n/w for $n=3$ are illustrated in Figs. 3(b) and 3(c), respectively, in the cases of $\nu=1$ and $\nu=1/3$.



(b) Indicial response of θ_3 to u_1 (c) Indicial response of θ_3 to w

Fig. 3

Each response is normalized by the steady state gain P^0.

As mentioned above, it is recognized that both D and P^0 for u_1 are satisfactorily compensated, but the influence of compensation for disturbance w, namely u_2 and u_3, varies with n and ν. Moreover, the overshoot from 1.0 is seen in Fig. 3(c). To suppress the effect of disturbances, another method of compensation is needed.

3.2 Delay compensation applying FAO

The above examination is performed for the linearized control object as well as for the ideal case. In practice, the control object is nonlinear and delays exist in manipulating devices and sensors. The effect of compensation is, therefore, different from that predicted above. From this reason, the delay compensator makes use of the values estimated with FAO, which consist of the mathematical model of the heating surface divided into three, and fuzzy control as described in the first report of this study[2]. FAO estimates the state variables $\hat{X}_{i+3}$, enthalpies $\hat{X}_i$ at division points, and heat absorption $\hat{U}_2$ as the unmeasurable input. These variables are defined by the following equation. A mark ^ over a symbol indicates an estimated value.

Table 1 Static gains and delays of transfer functions in Eq.(6)

	$\frac{\theta_n}{u_1}$	$\frac{\theta_n}{w}$	$\frac{F}{G}$	$\frac{1}{n}\sum_{k=0}^{n-1} F^k$
P^0	ν^n	ν	1	1
D	νnT	$\left(\frac{n+1}{2}\nu-1\right)T$	$(\nu-1)T$	$\frac{n-1}{2}\nu T$

$$\left.\begin{array}{l} X_i=\dfrac{h_i}{h_{a0}-h_{e0}},\ X_{i+3}=\dfrac{T_{mi}}{T_{a0}-T_{e0}} \\ U_1=X_0,\ U_2=\dfrac{Q}{Q_0},\ U_3=\dfrac{M}{M_0},\ t_a=\dfrac{T_a}{T^0} \end{array}\right\} \quad (9)$$

In Eq.(9), h, T_m, Q, M and T represent the enthalpy of steam, the tube temperature, the heat absorption, the steam flow rate and the steam temperature, respectively. The temperature T^0 is the normal value of T. Suffixes e, a, 0 and i designate inlet, outlet, nominal value and the value at the i-th division point counted from the 0 inlet, respectively. The terms X and U are the same variables defined as x and u in first and second reports[2],[3]. However, capital letters are used to avoid confusion with section 3.1. The relationship between these symbols is shown in Table 2. Each division-point enthalpy is fed back based on the same idea described in section 3.1 as a delay compensator. The deviation from the nominal value is used for every feedback value so that the compensator output is zero at nominal operation, and values of f_i from Eq.(4) are used as feedback gains. The output of the compensating operation is connected to the control system in the simulator scaling with KK_2.

4. Disturbance Compensation with Fuzzy Control

Figure 4 shows the ratio of the estimated heat absorption to steam flow at the final superheater under the load change to the boiler obtained from FAO coupled with the simulator. The boiler load is changed from 100% to 50% rating with a load-change speed of 5%/min. from 20 min. to 30 min. The ratio in Fig. 4 is changed by the load, and the change in the ratio disturbs the final superheater and causes the deviation in the outlet temperature. This fact gave the authors the idea that they could make use of the deviation in the ratio as the disturbance compensator. As a matter of fact, this idea has been realized by adding a functional value of the deviation in the ratio to the spray flow control loop illustrated in Fig. 1. However, it is not easy to find an appropriate nonlinear function for the ratio for a rapid load change between 100% and 50% or 25%.

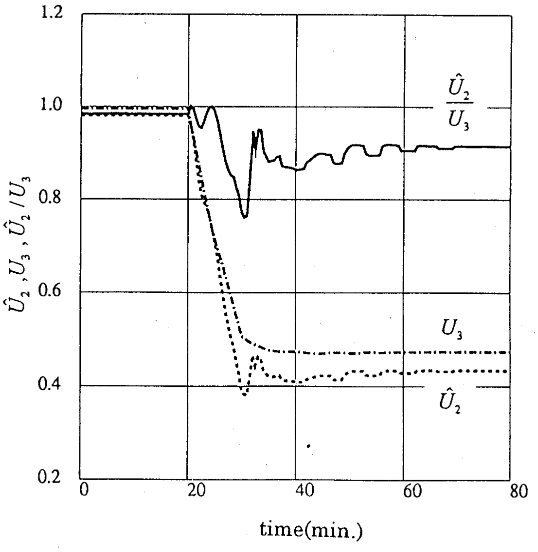


Fig. 4 Ratio of estimated heat absorption to steam flow in load change

Finally the form of the function is composed of fuzzy inferences by following the discussion about FAO[2]. The indication FAC (Fuzzy Applied Compensator) shown in Fig. 1 corresponds to this fuzzy control. Inputs to FAC are the deviation of the outlet steam temperature $\varDelta t_a(=t_a-\bar{t}_a)$ (every value is normalized by T^0), and $\varDelta(\hat{U}_2/U_3)$, the deviation of $\hat{U}_2/U_3$. The FAC is built up by following steps similar to fuzzy control of FAO. That is:

(1) All of antecedent inputs, $\varDelta t_a$, $\varDelta(\hat{U}_2/U_3)$, and consequent output ξ, are normalized to $[-1, 1]$.

(2) $[-1,1]$ is divided into the following 7 discrete fuzzy sets.

$$\left.\begin{array}{l}\text{LN: Large Negative}\\ \text{MN: Medium Negative}\\ \text{SN: Small Negative}\\ \text{ZE: Zero}\\ \text{SP: Small Positive}\\ \text{MP: Medium Positive}\\ \text{LP: Large Positive}\end{array}\right\} \quad (10)$$

Here, $m_A(Y)$ (A is a label from Eq.(10) and Y is an input or output value) represents the grade of input or output belonging to an above fuzzy set, and their membership functions are illustrated in Fig. 5.

(3) A FAM (Fuzzy Associative Memory) bank matrix formulated by the following procedure expresses rules for inference[12].

Consider a rule: IF $\varDelta t_a$ IS I AND $\varDelta(\hat{U}_2/U_3)$ IS J, THEN ξ IS L.

Abbreviate this as (I, J ; L).

Put L into (I, J) entry with considering as I and J as row and column respectively.

The FAM bank matrix is made with facts obtained from following experiences.

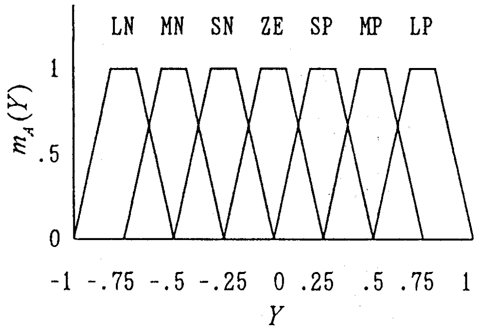


Fig. 5 Fuzzy sets and membership functions

① If $\varDelta t_a$ is ZE and $\varDelta(\hat{U}_2/U_3)$ is LN, $\varDelta t_a$ can be predicted to be LN in a short time. Then it is desirable to decrease the spray flow rate considerably; that corresponds to output ξ in this case. Namely,

(ZE, LN ; MN)

② If $\varDelta t_a$ is LN and $\varDelta(\hat{U}_2/U_3)$ is LN, $\varDelta t_a$ can be predicted to drop on a large scale. Then the spray flow rate (ξ) should be reduced further. Namely,

(LN, LN ; LN)

③ If $\varDelta t_a$ is LP and $\varDelta(\hat{U}_2/U_3)$ is LN, then it is desirable that the spray flow rate (ξ) holds the value SP or as it is. Namely,

(LP, LN ; SP)

④ If $\varDelta(\hat{U}_2/U_3)$ is positive, the rules are the opposite of those of ①, ②, and ③.

⑤ When $\varDelta(\hat{U}_2/U_3)$ is ZE, it means that the balance is kept between $\hat{U}_2$ and U_3. If the balanced state between $\hat{U}_2$ and U_3 continues, $\varDelta t_a$ will be ZE after a while. Therefore, the spray flow rate (ξ) may be determined with respect to the value of $\varDelta t_a$.

The FAM bank matrix determined by the above procedure is shown in Eq.(11).

		$\varDelta\frac{\hat{U}_2}{U_3}$						
		LN	MN	SN	ZE	SP	MP	LP
$\varDelta t_a$	LN	LN	LN	MN	MN	MN	SN	SN
	MN	LN	MN	MN	SN	SN	SN	ZE
	SN	MN	MN	SN	ZE	SN	ZE	SP
	ZE	MN	SN	ZE	ZE	ZE	SP	MP
	SP	SN	ZE	SP	ZE	SP	MP	MP
	MP	ZE	SP	SP	SP	MP	MP	LP
	LP	SP	SP	MP	MP	MP	LP	LP

(11)

(4) The inference process is made up with a minimum to secure compatibility of antecedents, a product to produce shapes of consequent fuzzy sets, and a sum to form the combined output fuzzy set as given by Eq.(12).

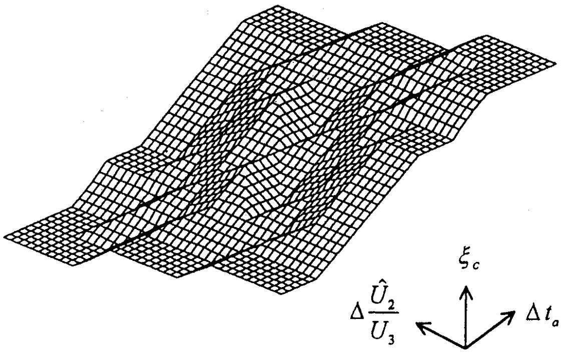


Fig. 6 Control surface of fuzzy control

$$\left.\begin{array}{l}\overline{m}(\xi)=\sum_L \overline{m}_L(\xi),\\ \overline{m}_L(\xi)=(m_I(\varDelta t_a)\wedge m_J(\varDelta(\hat{U}_2/U_3)))m_L(\xi)\\ I,J,L\in\left\{\begin{array}{l}LN,MN,SN\\ ZE,SP,MP,LP\end{array}\right\}\end{array}\right\}\quad(12)$$

$(m_I(\varDelta t_a), m_J(\varDelta(\hat{U}_2/U_3))\,;\, m_L(\xi))$ shows the grade of fuzzy set $(I, J\,;\, L)$ corresponding to $(\varDelta t_a, \varDelta(\hat{U}_2/U_3)\,;\, \xi)$.

(5) The calculation of output is made by defuzzification to obtain the centroid of the combined output fuzzy set $\overline{m}(\xi)$. The centroid is easily calculated as shown in the following because every membership function $m_A(Y)$ is the same in shape and is as symmetric as the centroid itself.

$$\left.\begin{array}{l}\xi_c=\dfrac{\sum_L \omega_L\delta_L s_L}{\sum_L \omega_L s_L}\\ \omega_L=(m_I(\varDelta t_a)\wedge m_J(\varDelta(\hat{U}_2/U_3)))\\ I,J,L\in\left\{\begin{array}{l}LN,MN,SN\\ ZE,SP,MP,LP\end{array}\right\}\end{array}\right\}\quad(13)$$

The terms δ_L, s_L are centroid and the area of $m_L(\xi)$ in Eq. (12).

(6) The set $(\varDelta t_a, \varDelta(\hat{U}_2/U_3)\,;\, \xi_c)$ obtained by calculating ξ_c with respect to $\varDelta t_a$ and $\varDelta(\hat{U}_2/U_3)$ in the domains of $|\varDelta t_a|\leq 1$ and $|\varDelta(\hat{U}_2/U_3)|\leq 1$ makes a surface in 3-dimensional space. When a varying set $(\varDelta t_a, \varDelta(\hat{U}_2/U_3))$ is given, a trajectory mapped by fuzzy inference is on this surface. That is, the control action with fuzzy inference is displayed on this control surface. Figure 6 is an illustration of this example. The output ξ_c is added to the control system of the simulator by scaling with KK_1 similar to delay compensation.

5. Evaluation of Control Performance by Simulation

Now the evaluation of two compensators, delay and disturbance, is carried out by simulations with load changes for the final superheater with FAO. No modifications are made to the configuration or to

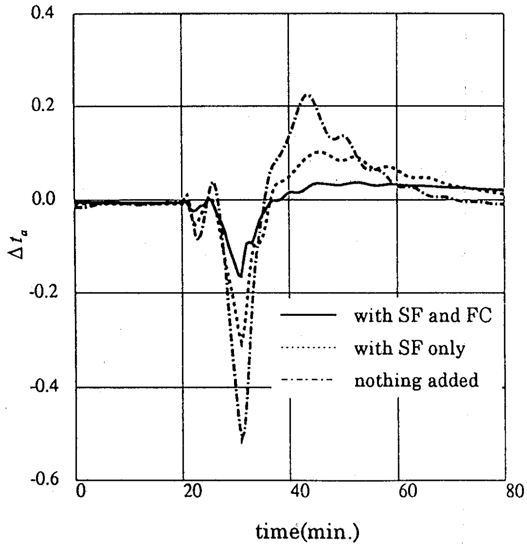


Fig. 7 Normalized temperature deviations st FSH outlet

parameters such as gains of the control system in the simulator for attaching compensators.

Parameters of the compensators are set for simulations as follows:

① $n=3$, $\nu=1/3$, then by Eq. (4) feedback gains are

$f_1=6$, $f_2=12$, $f_3=8$

② Scaling gains for delay and disturbance compensations are

$KK_1=0.45$, $KK_2=0.01$

③ Nominal and normal values of enthalpy and temperature are

$h_{a0}-h_{e0}=217.8$ kJ/kg, $T_{a0}-T_{e0}=68.5$°C

$T^0=20$°C

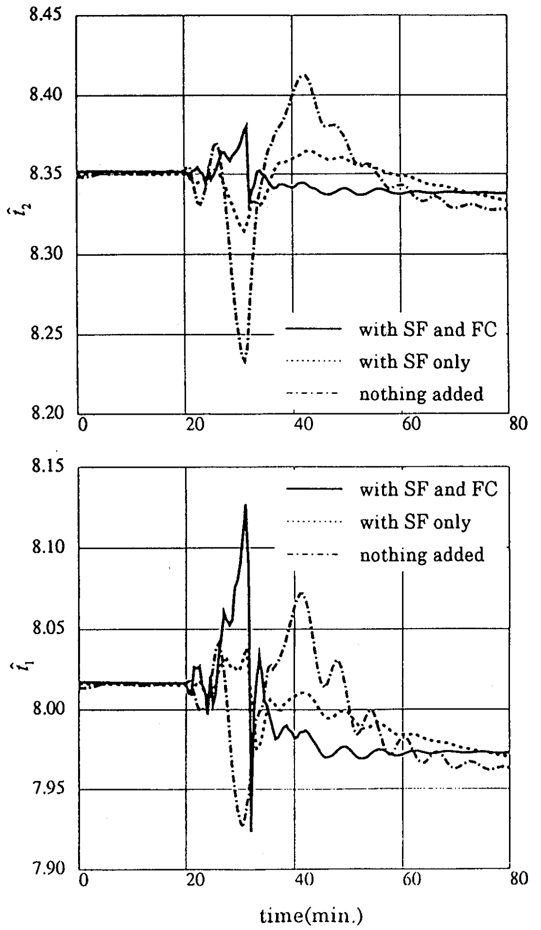
The temperature T^0 is determined to be $-20\leq\varDelta T_a\leq 20$ for $-1\leq\varDelta t_a\leq 1$, where $\varDelta T_a$ is the deviation in outlet steam temperature. The load change for the boiler is the same as in Fig. 4 and ranges from 100% to 50% by the load-change speed of 5%/min.

The results of the simulation are illustrated in Figs. 7 and 8. Figure 7 shows the steam temperature deviation $\varDelta t_a$ at the final superheater outlet, and Fig. 8 also shows normalized division-point temperatures $\hat{t}_i$, $i=1, 2$ transformed with the following equation from division-point enthalpies $\hat{X}_i$, $i=1, 2$ estimated by FAO.

$$\hat{t}_i=\frac{1}{T_{a0}-T_{e0}}tph(p, \hat{X}_i(h_{a0}-h_{e0}))\quad(14)$$

where tph is the function calculating temperature from pressure and enthalpy.

In these figures, results of three cases are plotted



SF and FC stand for same meaning in Fig. 7

Fig. 8 Estimated normalized temperatures at division points i=1, 2 in FAO

for comparison; the first is the case with no added compensations, the second is the case of only delay compensation, and the last is the simultaneously compensated case with both delay and disturbance. It is quite obvious from Fig. 7 that the deviation in the outlet steam temperature that appeared in the early period of load change is suppressed to 60% by delay compensation and to 33% by the combination of delay and disturbance compensations compared with that of no compensations. Furthermore, Fig. 8 suggests a dynamical relationship in how division-point temperatures respond to the suppression of the outlet steam temperature deviation.

6. Conclusions

The authors discussed the problem of improving the performance of the feedback system for the steam temperature control by compensating the delay and the effect of disturbances by applying FAO to the final superheater of the super-critical and sliding-pressure-operating type once-through boiler. FAO is proposed as a nonlinear observer estimating state variables and heat absorption that is an unmeasurable input to the boiler heating surface.

Table 2 Symbols of variables

	State variable	Enthalpy at division point	Inputs
Eq.(1)	x_i	$\theta_i = \frac{\Delta h_i}{h_{a0} - h_{e0}}$	$u_1 = \theta_0$ $u_2 = \frac{\Delta Q}{Q_0}$ $u_3 = \frac{\Delta M}{M_0}$
1st Report(2)	$x_{n+i} = \frac{T_{mi}}{T_{ao} - T_{eo}}$	$x_i = \frac{h_i}{h_{ao} - h_{eo}}$	$u_1 = x_0$ $u_2 = \frac{Q}{Q_0}$ $u_3 = \frac{M}{M_0}$
Eq.(9)	$X_{n+i} = \frac{T_{mi}}{T_{ao} - T_{eo}}$	$X_i = \frac{h_i}{h_{ao} - h_{eo}}$	$U_1 = X_0$ $U_2 = \frac{Q}{Q_0}$ $U_3 = \frac{M}{M_0}$

The delay compensation is performed with feeding back deviations in three division-point enthalpies estimated by FAO. The disturbance compensation is also carried out by fuzzy control, in which inputs are deviations of the outlet steam temperature and the ratio of heat absorption to steam flow rate. Every compensation is added as bias to the target value of the spray flow control system.

As a result, in spite of the simplicity of the compensation, this method effectively suppresses the temperature deviation seen in the rapid load changes. From the results, it is suggested that the performance of feedback systems in STC can be improved much more by applying FAO to all heating surfaces of the boiler.

The sensitivity of FAO to the change of plant characteristics is kept at a lower level as mentioned in the second report in this study(3). In this respect, the authors expect to obtain similar results without special field test such as system identification when applying FAO to actual problems. Moreover, the authors also expect that no modifications will be required in functions and parameters of the control system for the variation in fuels and the seasoning of the boiler itself.

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