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Application of hybrid fuzzy logic proportional plus conventional integral-derivative controller to combustion control of stoker-fired boilers

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Abstract

Combustion control of an industrial stoker-fired boiler is to provide a continuous supply of steam at the desired condition of pressure. Because no efficient mathematical model of the stoker-fired boiler is available, it would be very hard to design its controller by using any traditional model-based method. Therefore, the most widely used controller for the boiler system is a conventional PID-type controller due to its simple control structure and ease of design. However, control performance of the PID-type controller suffers greatly from high uncertainty and nonlinearity of the system, large disturbances and so on.

This paper presents a hybrid fuzzy logic proportional plus conventional integral-derivative (FUZZY P + ID) controller to improve the control performance yielded by the PID-type controller. The proposed FUZZY P + ID controller is constructed by using an incremental fuzzy logic controller in place of the proportional term in the conventional PID controller. The basic idea of this study is to reduce the parameters of a fuzzy controller to be tuned so that, in comparison with the PID-type controller, only one additional parameter should be adjusted. The proposed hybrid FUZZY P + ID controller is applied to several stoker-fired boilers. In order to demonstrate the effectiveness of the hybrid controller, the real application results on control of the stoker-fired boilers are reported and analyzed.

Keywords: Industrial process control; Engineering; Fuzzy control systems; Hybrid control systems; PID controllers

1. Introduction

Fig. 1(a) shows an industrial stoker-fired boiler which provides a continuous supply of steam at the desired condition of pressure. The basic combustion control scheme in Fig. 1(b) shows that the regulating multiple variables are coal and air flow. The control application design of such units until today has been based

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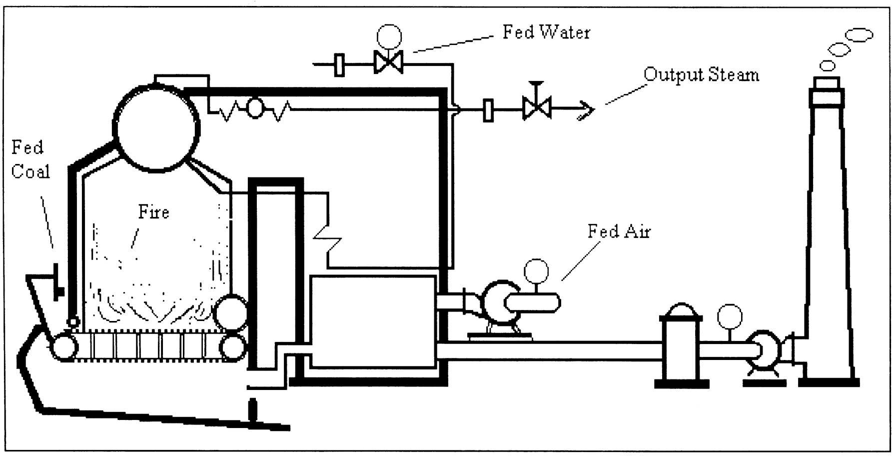
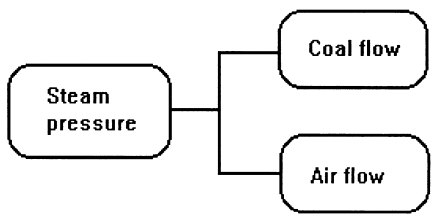


(a)



(b)

Fig. 1. An industrial stoker-fired boiler and its control scheme: (a) An industrial stoker-fired boiler; (b) Combustion control scheme of a stoker-fired boiler.

almost entirely on the skill and intuition of experienced utility boiler control application engineers. The use of what is known as "model-based control" methods to solve the complex and interactive control problems of boiler systems has not been used to any significant extent because of high nonlinearity and uncertainty of the boiler system [6, 9].

At present, conventional PID-type controllers are most widely used in control of industrial stoker-fired boilers due to their simple control structure, ease of design and inexpensive cost. However, these PID controllers cannot yield a good control performance due to high nonlinearity and uncertainty of the boiler systems. Furthermore, when there exists a strong load change or a large disturbance, the PID-type controller might be out of control so that a manual control must be operational.

It was first reported about 20 years ago that a fuzzy logic controller is very suitable for a controlled object with nonlinearity and even with unknown structure [1, 26]. One of the widely used design methods for fuzzy controllers is to define membership functions of linguistic variables and to formulate fuzzy rules by control engineers [3, 12, 17, 22]. Since solid fuels-coal causes a large time lag, it is laborious to find manually fuzzy rules and membership functions during system operation. Another approach for design of the fuzzy controller is to adapt rule base or/and membership functions by self-organizing algorithms or neural network according to previous responses until a desired control performance is achieved [2, 10, 12, 20, 21]. However, this adaptive strategy might not be used for combustion control of a stoker-fired boiler due to its convergent problem.

This paper presents a hybrid fuzzy logic proportional plus conventional integral-derivative controller and its application to the combustion control of a stoker-fired boiler. This controller is constructed by replacing the proportional term in the conventional PID controller with an incremental fuzzy logic controller. The FUZZY proportional (P) term plays an important role in improving an overshoot. The conventional integral (I) term reduces a steady-state error, and the conventional derivative (D) is responsible for the flatness of the step response. The basic idea of this study is to reduce the parameters of a traditional fuzzy controller to be tuned during system operation so that it can be easily accepted by control engineers. In comparison with a PID-type controller, only one additional parameter should be adjusted while implementing the FUZZY P+ID controller. Another motivation for proposing FUZZY P+ID controller is to improve eminently the control performance of the stoker-fired boilers yielded by the PID-type controller.

This paper is organized as follows: In the next section, we present the FUZZY P+ID control scheme and deduce its formulation. In Section 3, we propose an approach to the design of the proposed controller. In Section 4, we apply the proposed Fuzzy P+ID control scheme to several industrial stoker-fired boilers and analyze the real application results.

2. Hybrid fuzzy P+ID controller scheme

Fig. 2(a) shows a PID-type controller and its control signal is easily computed by combining proportional–integral-derivative terms

$$u(t) = K_{\mathrm{P}} e(t) + K_{\mathrm{I}} \int e(t)\,\mathrm{d}t - K_{\mathrm{D}} \dot{y}(t), \tag{1}$$

where K_{P}, K_{I}, and K_{D} are the controller parameters. Its discretized and incremental form is expressed by

$$\Delta u(k) = u(k) - u(k-1) = K_{\mathrm{P}}[e(k) - e(k-1)] + K_{\mathrm{I}} T e(k) - K_{\mathrm{D}} \frac{y(k) - 2y(k-1) + y(k-2)}{T}. \tag{2}$$

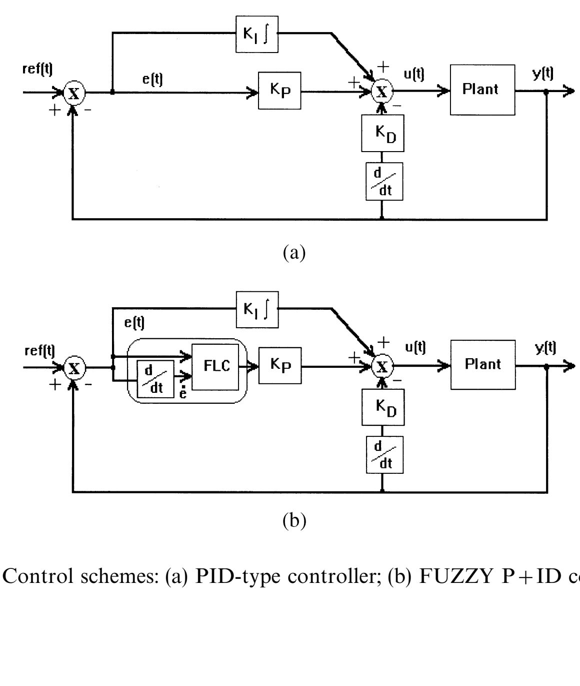


Fig. 2. Control schemes: (a) PID-type controller; (b) FUZZY P+ID controller.

The reason for the popular use of the PID-type controller is that this controller can be designed by adjusting just three controller parameters, K_P, K_I, and K_D. In addition, its control performance can be accepted in many applications. In order to keep this simple structure, we propose a hybrid FUZZY P+ID controller, as shown in Fig. 2(b). It uses an incremental fuzzy logic controller in place of the proportional term; while the integral and derivative terms keep crisp computation

$$\Delta u(k) = u(k) - u(k-1) = K_P^* \Delta u_f(k) + K_I^* T e(k) - K_D^* \frac{y(k) - 2y(k-1) + y(k-2)}{T}, \tag{3}$$

where $\Delta u_f(k)$ is the output of the incremental fuzzy logic controller and (K_P^*, K_I^*, K_D^*) are the parameters of the FUZZY P+ID controller. The most important part in the FUZZY P+ID controller is the FUZZY proportional (P) term because it is responsible for improving an overshoot. The conventional integral (I) term is responsible for reducing a steady-state error if an actual value is close to a reference signal. The conventional derivative (D) term is responsible for the flatness of the step response.

The incremental fuzzy logic controller is a standard one that has two inputs, $e(k)$ and $\dot{e}(k)$, and an output $\Delta u_f(k)$. In this paper, the membership functions of the inputs are defined to be identical, as shown in Fig. 4. In this controller, membership functions (N, Z, P), assigned with linguistic variables, are used to fuzzify physical quantities. For inputs $e(k)$ and $\dot{e}(k)$, we have $(e.n, e.z, e.p)$ and $(\dot{e}.n, \dot{e}.z, \dot{e}.p)$. For the output $\Delta u_f(k)$, we have $(o.n, o.z, o.p)$. The fuzzified inputs are inferred to form a fuzzy rule base which is used to characterize the relationship between fuzzy inputs and fuzzy outputs. The study in [13] states that for some control problems, the semantic information (rule base) of a fuzzy logic controller can be directly defined by human knowledge. Thus, the fuzzy rule base of the incremental fuzzy logic controller is fixed, as shown in Fig. 3.

The response of each fuzzy rule is weighted according to the degree of membership of its input conditions. The inference engine provides a set of control actions according to fuzzified inputs. The commonly used inference engine is the MAX–MIN method. In the rule base shown in Fig. 3, only Zadeh's logical "AND" [24], that is, the MIN operator is used. Since the control actions are described in a fuzzy sense, a defuzzification method is required to transform fuzzy control actions into a crisp output value of the fuzzy logic controller. For the incremental fuzzy logic controller, a widely used defuzzification method is the "center-of-mass" formula [16, 18, 23]

$$\Delta u_f(k) = \frac{\sum\{\text{membership value of input} \times \text{output corresponding to the membership value of input}\}}{\sum\{\text{membership value of input}\}}. \tag{4}$$

e(k) / Δu(k) / ė(k)	N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

Fig. 3. Fuzzy rule base of the incremental fuzzy logic controller.

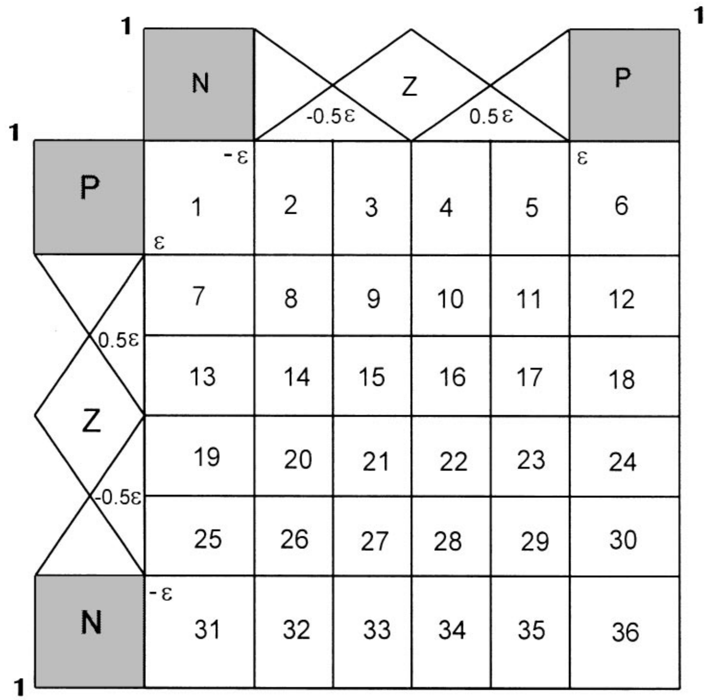


Fig. 4. Membership functions and combined input regions.

According to the defined inputs' membership functions and the fuzzy rule base, we obtain 36 combination regions, as shown in Fig. 4. Therefore, the output of the incremental fuzzy logic controller is expressed by

$$\Delta u_{\mathrm{f}}(k) = \{\Delta u_{\mathrm{f}}^{(1)}(k), \ldots, \Delta u_{\mathrm{f}}^{(i)}(k), \ldots, \Delta u_{\mathrm{f}}^{(36)}(k)\}. \tag{5}$$

Since $\Delta u_{\mathrm{f}}(k) = FLC(e(k), \dot{e}(k))$ is an anti-symmetrical function, that is, $-\Delta u_{\mathrm{f}}(k) = FLC(-e(k), -\dot{e}(k))$, it is easy to obtain the following relationship:

$$\Delta u_{\mathrm{f}}^{(j)}(k) = -\Delta u_{\mathrm{f}}^{(36-j+1)}(k), \quad j = 1, \ldots, 18. \tag{6}$$

We use the methodology proposed in [16, 18] to derive the formulation of the incremental fuzzy logic controller $\Delta u_{\mathrm{f}}(k) = FLC(e(k), \dot{e}(k))$ as follows [14]:

$$\Delta u_{\mathrm{f}}^{(1)}(k) = 0, \qquad e(k) \leqslant -\varepsilon,\ \dot{e}(k) \geqslant \varepsilon, \tag{7}$$

$$\Delta u_{\mathrm{f}}^{(2,3)}(k) = e(k) + \varepsilon, \qquad -\varepsilon \leqslant e(k) \leqslant 0,\ \dot{e}(k) \geqslant \varepsilon, \tag{8}$$

$$\Delta u_{f}^{(4,5,6)}(k) = \varepsilon, \qquad 0 \leqslant e(k) \leqslant \varepsilon,\ \dot{e}(k) \geqslant \varepsilon, \tag{9}$$

$$\Delta u_{\mathrm{f}}^{(7)}(k) = \dot{e}(k) - \varepsilon, \qquad e(k) \leqslant -\varepsilon,\ 0.5\varepsilon \leqslant \dot{e}(k) \leqslant \varepsilon, \tag{10}$$

$$\Delta u_{\mathrm{f}}^{(8)}(k) = \begin{cases} \dfrac{\varepsilon(\dot{e}(k) + e(k))}{3\varepsilon - 2\dot{e}(k)} & \text{if } |-e(k)| \leqslant |\dot{e}(k)|, \\[2ex] \dfrac{\varepsilon(\dot{e}(k) + e(k))}{3\varepsilon + 2e(k)} & \text{if } |-e(k)| > |\dot{e}(k)|, \end{cases} \qquad -\varepsilon \leqslant e(k) \leqslant -0.5\varepsilon,\ 0.5\varepsilon \leqslant \dot{e}(k) \leqslant \varepsilon, \tag{11}$$

$$\Delta u_{\mathrm{f}}^{(9)}(k)=\begin{cases}\dfrac{\varepsilon(\dot{e}(k)+e(k))}{3\varepsilon-2\dot{e}(k)} & \text{if } |e(k)+\varepsilon|\leqslant|\dot{e}(k)|,\\ \dfrac{\varepsilon(\dot{e}(k)+e(k))}{\varepsilon-2e(k)} & \text{if } |e(k)+\varepsilon|>|\dot{e}(k)|,\end{cases}\qquad -0.5\varepsilon\leqslant e(k)\leqslant 0,\ 0.5\varepsilon\leqslant\dot{e}(k)\leqslant\varepsilon, \tag{12}$$

$$\Delta u_{\mathrm{f}}^{(10)}(k)=\begin{cases}\dfrac{\varepsilon(2\varepsilon-\dot{e}(k))}{3\varepsilon-2\dot{e}(k)} & \text{if } |-e(k)+\varepsilon|\leqslant|\dot{e}(k)|,\\ \dfrac{\varepsilon(\dot{e}(k)+2e(k))}{\varepsilon+2e(k)} & \text{if } |-e(k)+\varepsilon|>|\dot{e}(k)|,\end{cases}\qquad 0\leqslant e(k)\leqslant 0.5\varepsilon,\ 0.5\varepsilon\leqslant\dot{e}(k)\leqslant\varepsilon, \tag{13}$$

$$\Delta u_{\mathrm{f}}^{(11)}(k)=\begin{cases}\dfrac{\varepsilon(2\varepsilon-\dot{e}(k))}{3\varepsilon-2\dot{e}(k)} & \text{if } |e(k)|\leqslant|\dot{e}(k)|,\\ \dfrac{\varepsilon(2\varepsilon-e(k))}{3\varepsilon-2e(k)} & \text{if } |e(k)|>|\dot{e}(k)|,\end{cases}\qquad 0.5\varepsilon\leqslant e(k)\leqslant\varepsilon,\ 0.5\varepsilon\leqslant\dot{e}(k)\leqslant\varepsilon, \tag{14}$$

$$\Delta u_{\mathrm{f}}^{(12)}(k)=\varepsilon,\qquad \varepsilon\geqslant e(k),\ 0.5\varepsilon\leqslant\dot{e}(k)\leqslant\varepsilon, \tag{15}$$

$$\Delta u_{\mathrm{f}}^{(13)}(k)=\dot{e}(k)-\varepsilon,\qquad e(k)\leqslant-\varepsilon,\ 0\leqslant\dot{e}(k)\leqslant 0.5\varepsilon, \tag{16}$$

$$\Delta u_{\mathrm{f}}^{(14)}(k)=\begin{cases}\dfrac{\varepsilon(e(k)+\dot{e}(k))}{3\varepsilon+2e(k)} & \text{if } |-e(k)+\varepsilon|\leqslant|\dot{e}(k)|,\\ \dfrac{\varepsilon(\dot{e}(k)+e(k))}{\varepsilon+2\dot{e}(k)} & \text{if } |-e(k)+\varepsilon|>|\dot{e}(k)|,\end{cases}\qquad -\varepsilon\leqslant e(k)\leqslant-0.5\varepsilon,\ 0\leqslant\dot{e}(k)\leqslant 0.5\varepsilon, \tag{17}$$

$$\Delta u_{\mathrm{f}}^{(15)}(k)=\begin{cases}\dfrac{\varepsilon(\dot{e}(k)+e(k))}{\varepsilon-2e(k)} & \text{if } |e(k)|\leqslant|\dot{e}(k)|,\\ \dfrac{\varepsilon(\dot{e}(k)+e(k))}{\varepsilon+2\dot{e}(k)} & \text{if } |e(k)|>|\dot{e}(k)|,\end{cases}\qquad -0.5\varepsilon\leqslant e(k)\leqslant 0,\ 0\leqslant\dot{e}(k)\leqslant 0.5\varepsilon, \tag{18}$$

$$\Delta u_{\mathrm{f}}^{(16)}(k)=\begin{cases}\dfrac{\varepsilon(\dot{e}(k)+2e(k))}{\varepsilon+2e(k)} & \text{if } |e(k)|\leqslant|\dot{e}(k)|,\\ \dfrac{\varepsilon(2\dot{e}(k)+e(k))}{\varepsilon+2\dot{e}(k)} & \text{if } |e(k)|\leqslant|\dot{e}(k)|,\end{cases}\qquad 0\leqslant e(k)\leqslant 0.5\varepsilon,\ 0\leqslant\dot{e}(k)\leqslant 0.5\varepsilon, \tag{19}$$

$$\Delta u_{\mathrm{f}}^{(17)}(k)=\begin{cases}\dfrac{\varepsilon(2\varepsilon-e(k))}{3\varepsilon-2e(k)} & \text{if } |-e(k)+\varepsilon|\leqslant|\dot{e}(k)|,\\ \dfrac{\varepsilon(2\dot{e}(k)+e(k))}{\varepsilon+2\dot{e}(k)} & \text{if } |-e(k)+\varepsilon|>|\dot{e}(k)|,\end{cases}\qquad 0.5\varepsilon\leqslant e(k)\leqslant\varepsilon,\ 0\leqslant\dot{e}(k)\leqslant 0.5\varepsilon, \tag{20}$$

$$\Delta u_{\mathrm{f}}^{(18)}(k)=\varepsilon,\qquad \varepsilon\geqslant e(k),\ 0\leqslant\dot{e}(k)\leqslant 0.5\varepsilon. \tag{21}$$

Here, we take the computation of $\Delta u_{\mathrm{f}}^{(8)}(k)$ as an example to explain how $\Delta u_{\mathrm{f}}^{(j)}(k)$ is obtained. In region 8 ($e(k)\in[-\varepsilon,-0.5\varepsilon], \dot{e}(k)\in[0.5\varepsilon,\varepsilon]$) shown in Fig. 5, each of Rules 1, 2, 4, and 5 contributes the output control actions. For Rule 1, we have the input membership function values $e.n=-e(k)/\varepsilon\geqslant 0.5$ and

$\dot{e}.p = \dot{e}(k)/\varepsilon \geqslant 0.5$. Since both the degrees of membership functions $e.n$ and $\dot{e}.p$ change in the same range [0.5, 1.0], the MIN-operation is controlled as follows: If $|-e(k)| \leqslant |\dot{e}(k)|$, $\{e.n \text{ AND } \dot{e}.p\} = \min\{-e(k)/\varepsilon, \dot{e}(k)/\varepsilon\} = -e(k)/\varepsilon$; If $|-e(k)| > |\dot{e}(k)|$, $\{e.n \text{ AND } \dot{e}.p\} = \min\{-e(k)/\varepsilon, \dot{e}(k)/\varepsilon\} = \dot{e}(k)/\varepsilon$. The corresponding output value is $o.z = 0$. For Rule 2, we have the input membership function values $e.z = (e(k) + \varepsilon)/\varepsilon \leqslant 0.5$ and $\dot{e}.p = \dot{e}(k)/\varepsilon \geqslant 0.5$. Obviously, $\{e.z \text{ AND } \dot{e}.p\} = \min\{(e(k) + \varepsilon)/\varepsilon, \dot{e}(k)/\varepsilon\} = (e(k) + \varepsilon)/\varepsilon$, and the corresponding output value is $o.p = \varepsilon$. For Rule 4, we have the input membership function values $e.n = -e(k)/\varepsilon \geqslant 0.5$ and $\dot{e}.z = (-\dot{e}(k) + \varepsilon)/\varepsilon \leqslant 0.5$, and thus $\{e.n \text{ AND } \dot{e}.z\} = \min\{-e(k)/\varepsilon, (-\dot{e}(k) + \varepsilon)/\varepsilon\} = (-\dot{e}(k) + \varepsilon)/\varepsilon$. The corresponding output value is $o.n = -\varepsilon$. For Rule 5, we have the input membership function values $e.z = (e(k) + \varepsilon)/\varepsilon \leqslant 0.5$ and $\dot{e}.z = (-\dot{e}(k) + \varepsilon)/\varepsilon \leqslant 0.5$. In this case, the MIN-operation $\{e.z \text{ AND } \dot{e}.z\}$ is controlled as follows: If $|-e(k)| \leqslant |\dot{e}(k)|$, $\{e.z \text{ AND } \dot{e}.z\} = \min\{(e(k) + \varepsilon)/\varepsilon, (-\dot{e}(k) + \varepsilon)/\varepsilon\} = (-\dot{e}(k) + \varepsilon)/\varepsilon$; If $|-e(k)| > |\dot{e}(k)|$, $\{e.z \text{ AND } \dot{e}.z\} = \min\{(e(k) + \varepsilon)/\varepsilon, (-\dot{e}(k) + \varepsilon)/\varepsilon\} = (e(k) + \varepsilon)/\varepsilon$. The corresponding output value is $o.z = 0$. By the "center of mass" formula (4), we obtain

$$\Delta u_{\mathrm{f}}^{(8)}(k) = \begin{cases} \dfrac{e.n \times o.z + e.z \times o.p + \dot{e}.z \times o.n + \dot{e}.z \times o.z}{e.n + e.z + \dot{e}.z + \dot{e}.z} = \dfrac{\varepsilon(\dot{e}(k) + e(k))}{3\varepsilon - 2\dot{e}(k)} & \text{if } |-e(k)| \leqslant |\dot{e}(k)|, \\ \dfrac{\dot{e}.p \times o.z + e.z \times o.p + \dot{e}.z \times o.n + e.z \times o.z}{\dot{e}.p + e.z + \dot{e}.z + e.z} = \dfrac{\varepsilon(\dot{e}(k) + e(k))}{3\varepsilon + 2e(k)} & \text{if } |-e(k)| > |\dot{e}(k)|, \end{cases}$$

$$-\varepsilon \leqslant (k) \leqslant -0.5\varepsilon,\ 0.5\varepsilon \leqslant \dot{e}(k) \leqslant \varepsilon. \tag{22}$$

By using Eq. (6) and Eqs. (7)–(21) we can obtain $\Delta u_{\mathrm{f}}^{(i)}(k)$ $(i = 19, \ldots, 36)$. In $\Delta u_{\mathrm{f}}(k)$ there exists only parameter ε that should be tuned for designing the FUZZY P+ID controller.

3. Approach to design of the fuzzy P+ID controller

The works in [4, 11, 19, 25] proposed different methods for tuning of the PID control parameters. Because these methods can do without the use of any model of a controlled object, they are still widely used in industrial applications. For example, the most widely used approach to designing a controller of an industrial

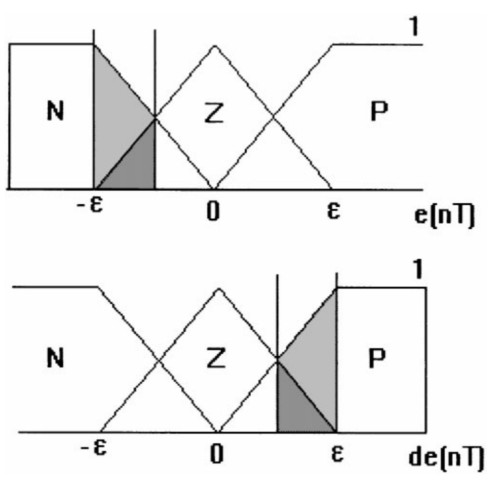


Fig. 5. Control actions in region 8.

stoker-fired boiler is manually to tune a conventional PID-type controller during system operation. The purpose of designing the FUZZY P + ID controller is to improve the control performance of the stoker-fired boilers yielded by the PID controller. Before determining the parameters of the FUZZY P + ID controller, we would like to make the following remarks. In a steady-state stage, we have $\dot{e}(k) \approx 0.0$ and $|e(k)| > |\dot{e}(k)|$. For PID control, it is easy to obtain $\Delta u(k) \approx K_{\mathrm{I}}Te(k)$; while for FUZZY P + ID control, $\Delta u_{\mathrm{f}}^{(15,16)}(k)$ or $\Delta u_{\mathrm{f}}^{(21,22)}(k)$ are activated. Because of symmetry, we only analyze the case of $\Delta u_{\mathrm{f}}^{(15,16)}(k)$. When $\dot{e}(k) \approx 0.0$, $\Delta u_{\mathrm{f}}^{(15,16)}(k) \approx e(k)$. Therefore, it is easy to obtain $\Delta u(k) \approx K_{\mathrm{P}}^{*}e(k) + K_{\mathrm{I}}^{*}Te(k) = (K_{\mathrm{P}}^{*} + K_{\mathrm{P}}^{*}T)e(k)$. This implies that the fuzzy proportional term becomes an additional integral term $K_{\mathrm{P}}^{*}e(k)$, hence the FUZZY P + ID controller can reduce the steady-state error. In this case, we have $e(k)_{\infty} \leqslant 0.5\varepsilon$. Thus, a small steady-state

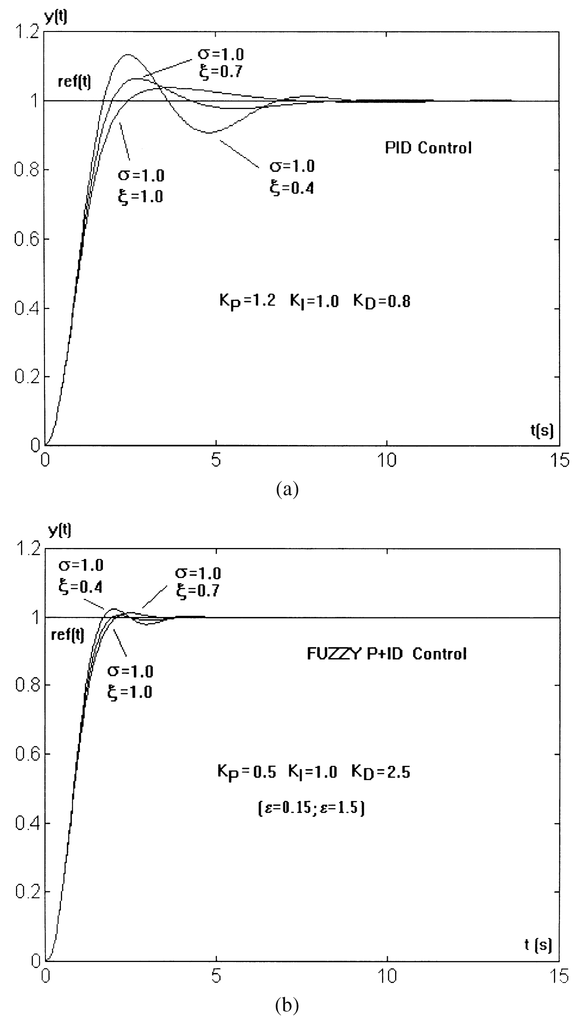
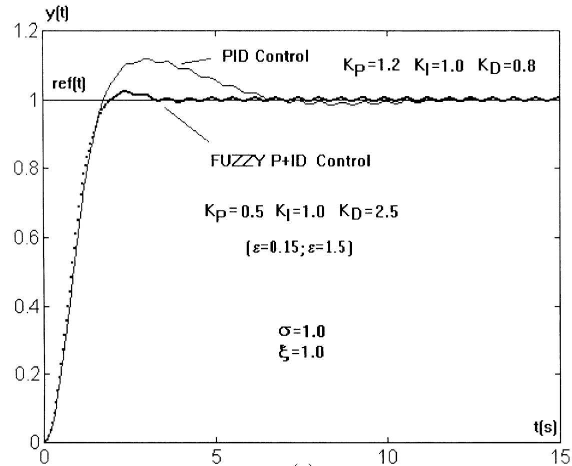


Fig. 6. Time responses of a nonlinear system: (a) PID control; (b) FUZZY P + ID control.



(c)

Fig. 6. (Continued).

error can be achieved by selecting a small ε. In a starting process, the FUZZY P controller outputs a constant control signal, $K_P^*\varepsilon$. If the control parameter ε is too small, a rise time response becomes slow. Besides, the sufficient stability conditions of the FUZZY P+ID controller can be derived by using the bounded-input/bounded-output "small gain theorem" [5, 7]. The following principles are recommended for determining the parameters (K_P^*, K_I^*, K_D^*) of the FUZZY P+ID controller. (1) Reduce the proportional parameter K_P of the PID-type controller; (2) Increase the integral and derivative parameters K_I and K_D of the PID-type controller. Then, a large ε is chosen in the starting process to speed up the rise time; while a small ε is chosen to reduce the steady-state error. For example, we determine the PID-type controller parameters ($K_P = 1.2$; $K_I = 1.0$; $K_D = 0.8$) for the nonlinear plant

$$\ddot{y} + 2.0\xi\omega\dot{y}y + \omega^2 y^2 = \omega^2 u \tag{23}$$

with $\omega = 1.0$ and $\xi = 1.0$. In the following simulation studies, the initial values of the plant $y(0)$, $y'(0)$, and $y''(0)$ are zero, and let the sampling period $T = 0.05$ s. Fig. 6(a) shows time responses for the step control of the nonlinear plant by using the PID-type controller. It can be seen that its control performance is quite satisfactory because the PID controller's parameters are tuned in this case. However, the time responses under this control become worse, when the plant parameters are modified as ($\omega = 1.0$; $\xi = 0.7$) and ($\omega = 1.0$; $\xi = 0.4$). Based on the original PID controller's parameters, we choose the parameters of the FUZZY P+ID controller as ($K_P^* = 0.5$; $K_I^* = 1.0$; $K_D^* = 2.5$). For the parameter ε, we have $\varepsilon = 1.5$ if $|e| > 0.1$ and $\varepsilon = 0.15$ if $|e| \leqslant 0.1$. Fig. 6(b) shows the time responses for the step control of the nonlinear plant by using the FUZZY P+ID controller. It can be seen that the proposed FUZZY P+ID can yield a much better control performance while modifying the plant's parameters. Another demonstration is to add a disturbance $y_{\text{dis}} = 0.2\sin(1.1t)$ to the control system. The time response by the PID-type controller exhibits a large overshoot in the presence of the disturbance; while that by the FUZZY P+ID controller yields a better control performance, as shown in Fig 5(c). This advantage is suitable for improving many industrial plants already controlled by PID-type controllers.

4. Control of a stoker-fired boiler

In a combustion control system of a stoker-fired boiler, the control signals $\Delta u^{\text{coal}}(k)$ and $\Delta u^{\text{air}}(k)$ are computed as follows:

$$\Delta u^{\text{coal}}(k) = K_{\text{P}}^{\text{coal}}\Delta u_{\text{f}}^{\text{coal}}(k) + K_{\text{I}}^{\text{coal}}Te_{\text{pres}}(k) - \frac{K_{\text{D}}^{\text{coal}}}{T}(Press(k) - 2Press(k-1) + Presse(k-2)), \tag{24}$$

$$\Delta u^{\text{air}}(k) = K_{\text{P}}^{\text{air}}\Delta u_{\text{f}}^{\text{air}}(k) + K_{\text{I}}^{\text{air}}Te_{\text{pres}}(k) - \frac{K_{\text{D}}^{\text{air}}}{T}(Press(k) - 2Press(k-1) + Presse(k-2)), \tag{25}$$

where, $e_{\text{pres}}(k)$ is the difference between the desired and actual steam pressure values, $\Delta u_{\text{f}}^{\text{coal}}(k)$ and $\Delta u_{\text{f}}^{\text{air}}(k)$ are the outputs of their incremental fuzzy logic controllers, and ($K_{\text{P}}^{\text{coal}}$, $K_{\text{I}}^{\text{coal}}$, $K_{\text{D}}^{\text{coal}}$) and ($K_{\text{P}}^{\text{air}}$, $K_{\text{I}}^{\text{air}}$, $K_{\text{D}}^{\text{air}}$) are the controller's parameters for coal flow and air flow. The selection of the sampling period, T, is done in two stages: (1) during the loop design, and (2) during the controller design. The empirical rule of Franklin and Powell [8] suggests that the sampling frequency must be from 4 up to 20 times the bandwidth of the closed-loop system. For the controller design, T should be increased to be greater than the sum of the error computation time, the DAC and ADC conversion times, and the zero-order hold delay time. In selecting T, one must have in mind that

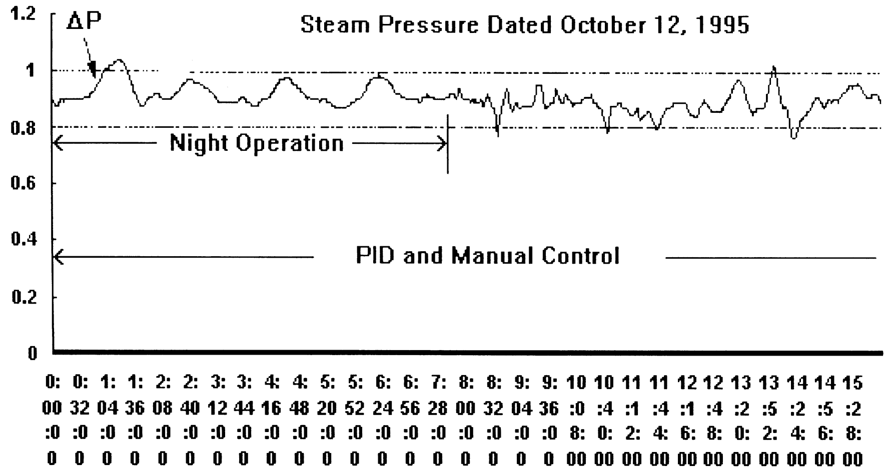
(a) If T is greater, the stability regions are smaller;
(b) large T implies small cost;
(c) large T results in large conversion times of the DAC's and ADC's (i.e., to smaller cost);
(d) small T allows good system performance in the presence of noise.

In accordance with engineer's experience, the sampling period, T, is chosen as 1 s in our boiler control. This control system is applied into several industrial stoker boilers. The control objective is to cause the stoker-fired boilers to provide a desired steam pressure that should be limited to 0.8 and 1.0 units under a change of a steam flow, as shown in Figs. 7–9. We would like to report the real control results of two stoker-fired boilers as follows. One operates in a chemical factory; and the other in a railway station.

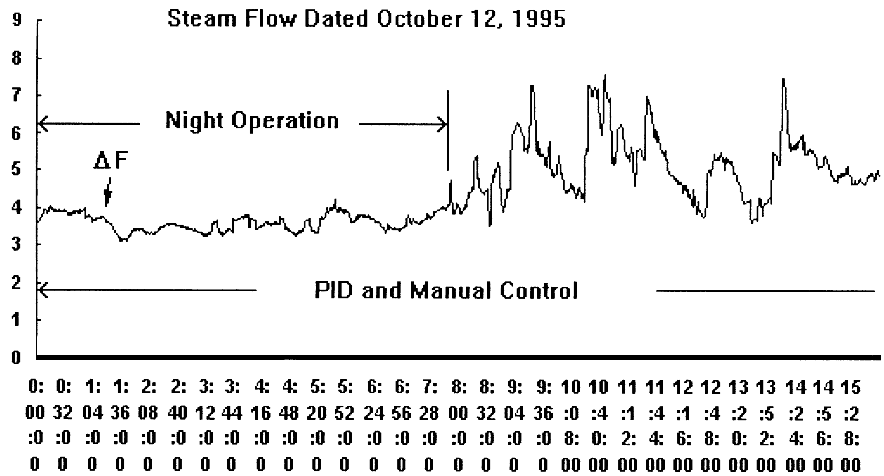
The boiler at the chemical factory provides the power for machines, canteens and so forth. PID-type control of the stoker-fired boiler at the chemical factory was switched off, and the proposed FUZZY P+ID controller came into operation on 13 October 1995. In order to demonstrate the control performance of the FUZZY P+ID controllers, we plot some of the recorded data on steam pressures, steam flows (loads of the steam pressures), fed coal and fed air flows from 12–14 October in Figs. 7–9. Because no same situation during a stoker-fired boiler operation could be repeated, in the real operation, it is difficult to provide a performance measure for the PID-type and the FUZZY P+ID controllers under the same condition. However, we try to verify the effectiveness of the FUZZY P+ID controller in the following aspects.

First, the original control strategy is combined by PID-type and manual control operations and the controller's parameters are adjusted under a small steam flow change. If a load, i.e., a steam flow change is large, the PID-type controller must be switched off and the manual control put in operation. Figs. 7 and 8 show that there are about 20 times of manual control operations 40 h before FUZZY P+ID control operation. Consequently, such manual control operations make operators very nervous. However, no manual control operation is used after the FUZZY P+ID control. This result shows that the FUZZY P+ID controller makes the combustion control system more automatic.

Second, we observe a steam flow change, ΔF, and measure an induced steam pressure change, ΔP, under both PID-type control and FUZZY one. Then, we define the coefficient, $\delta = \Delta\text{P}/\Delta\text{F}$, to measure control performance. The smaller the coefficient δ is, the more robust the load change of the



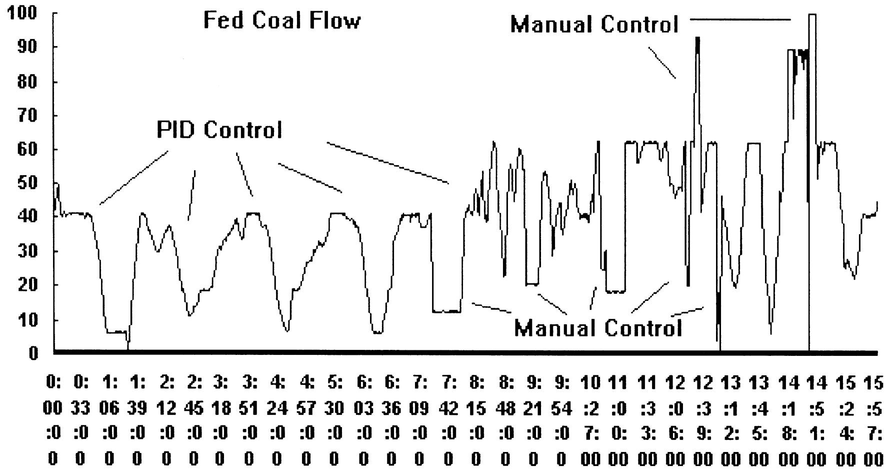
(a)



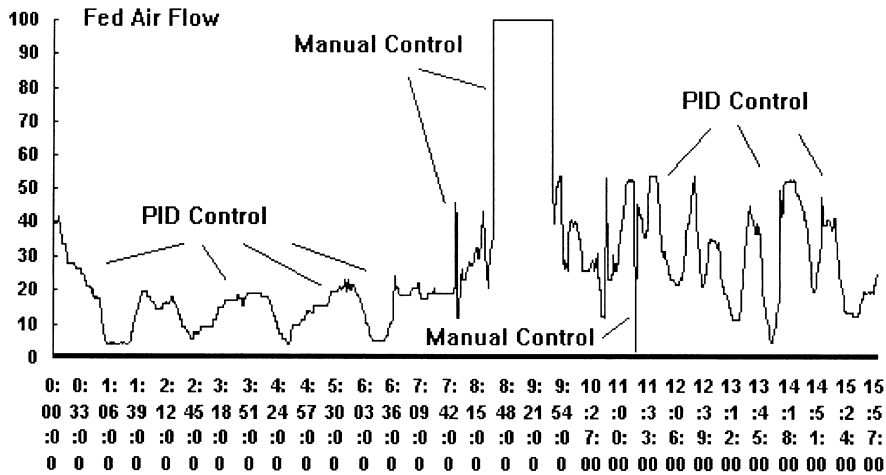
(b)

Fig. 7. PID and manual control on 12 October 1995. (a) steam pressure; (b) steam flow; (c) fed coal flow; (d) fed air flow.

control system is. Fig. 7(a) and (b) show the steam pressure and the steam flow changes of 12 October yielded by PID control; while Fig. 9(a) and (b) show those of 14 October yielded by FUZZY P+ID control. Although the steam flow changes of both days are different, their change tendencies are similar. During night operation many power machines are shutdown, so the required steam flow is rather low and its change is quite small so that PID-type control is effective. As mentioned above, however, PID-type control is often replaced by manual control due to large steam flow changes during day operation. Therefore, we can only take night operations to compare the control performance of FUZZY P+ID control and full PID-type control. We can approximately obtain $\delta_{(\mathrm{PID})} = 1.3$ in Fig. 7(a) and (b); while we can obtain $\delta_{(\mathrm{FUZZY\ \ P+ID})} = 0.38$ in Fig. 9(a) and (b). When the applied steam flow changes violently, even under manual



(c)

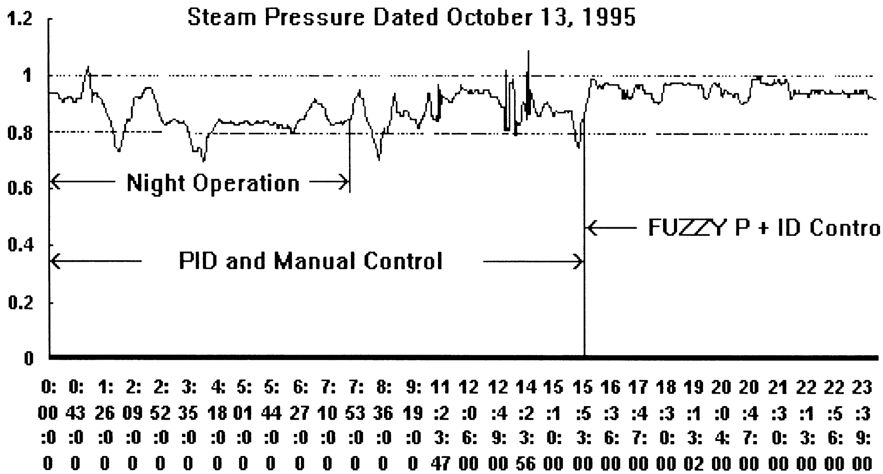


(d)

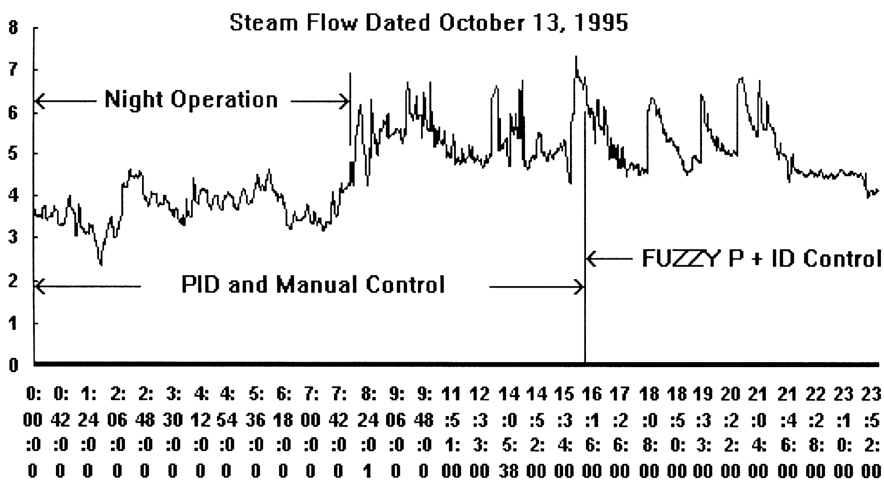
Fig. 7. (Continued).

control, the steam pressure may go over its limit range, as shown in Figs. 7(a) and 8(a). After the FUZZY P + ID controller is in operation, however, it can be seen that the steam pressure keeps in its limit region and its change becomes smoother, as shown in Figs. 8(a) and 9(a).

The FUZZY P + ID controller for the boiler at the chemical factory is tuned in case of a small variation to around the reference pressure value. However, these controller's parameters may not be suitable for other operation processes, for example, the transient responses during power recovery, since this dynamic behavior is quite different from one in the steady-state operation. The behavior-based modeling approach is used to deal with this problem [13]. In doing it, a neural network is used to perceive dynamic behavior. Then, the corresponding parameters of the FUZZY P + ID controller are fired based on the dynamic behavior. Finally,



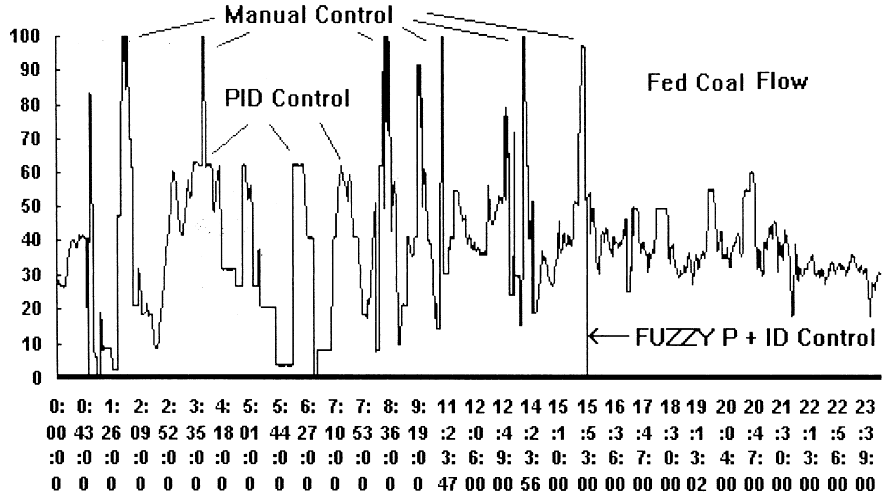
(a)



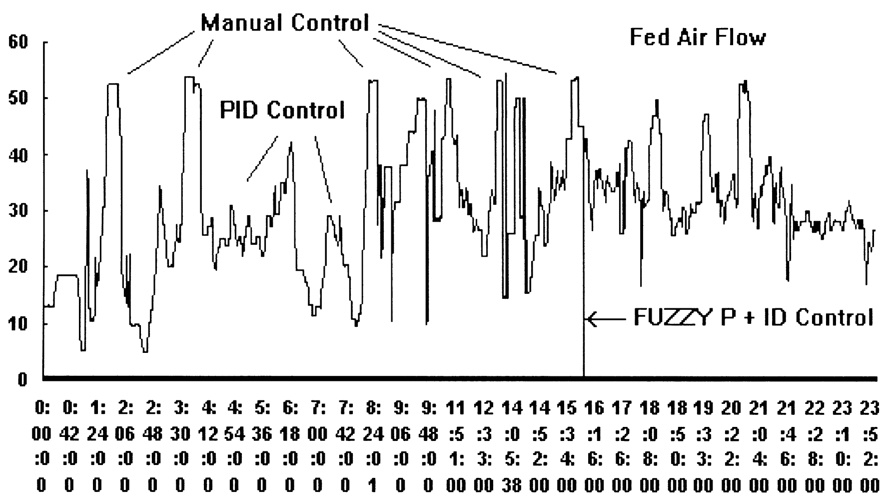
(b)

Fig. 8. PID control switch off and FUZZY P + ID control switch on: (a) steam pressure; (b) steam flow; (c) fed coal flow; (d) fed air flow.

we take an extreme example of power shutdown during boiler operation at the railway station to demonstrate the effectiveness of the FUZZY P + ID controller. On 26 December 1995, there were two power shutdowns due to short-time accidents. Fig. 10 shows the recorded data of the steam pressure and the steam flow of this day. It can be seen that the steam pressure and flow go down rapidly due to no fuel supply during the power shutdown. According to previous experience, the PID controller should be out of control in a transient response stage after a power recovery. Even though manual control is in operation in this case, it is difficult to obtain a desired transient response. By using the FUZZY P + ID controller, the steam pressure runs to its desired value very fast without an overshoot after power recovery.



(c)

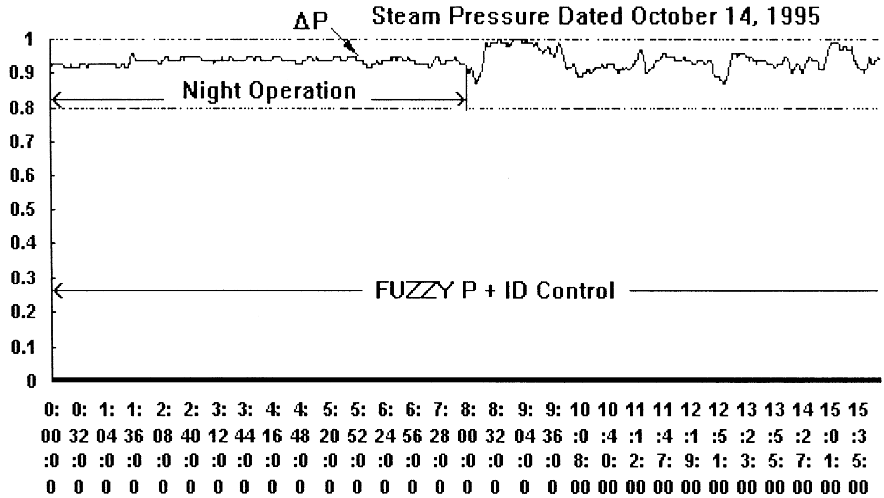


(d)

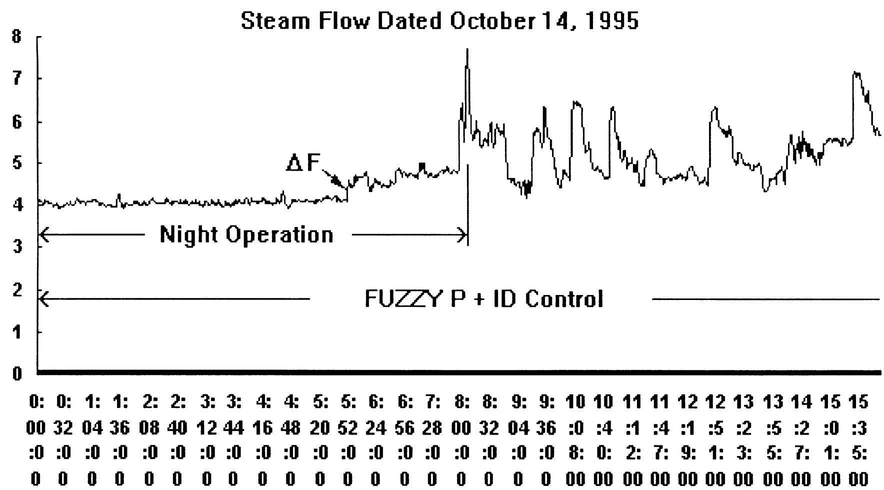
Fig. 8. (Continued).

5. Conclusions

The structure of the proposed FUZZY P+ID controller is very simple since it is constructed by replacing the proportional term in the conventional PID controller with an incremental fuzzy logic controller. This control strategy is applied to combustion control of several stoker-fired boilers. The real operation results show that the FUZZY P+ID controller is more efficient and robust than the PID-type controller.



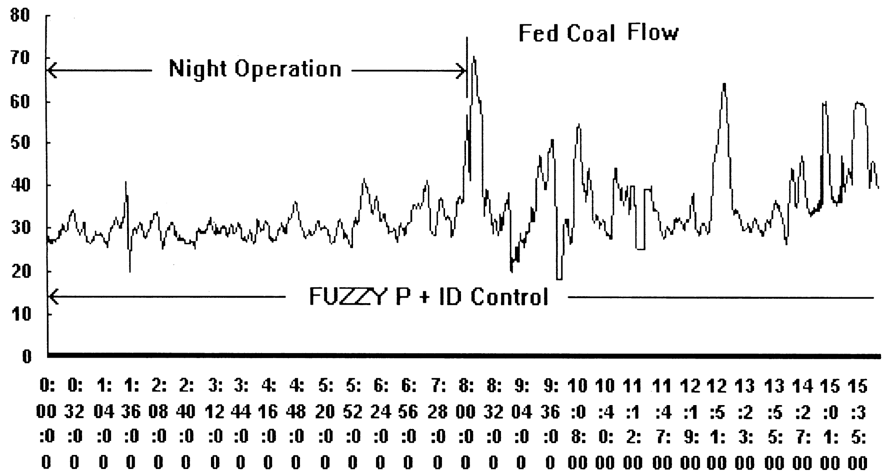
(a)



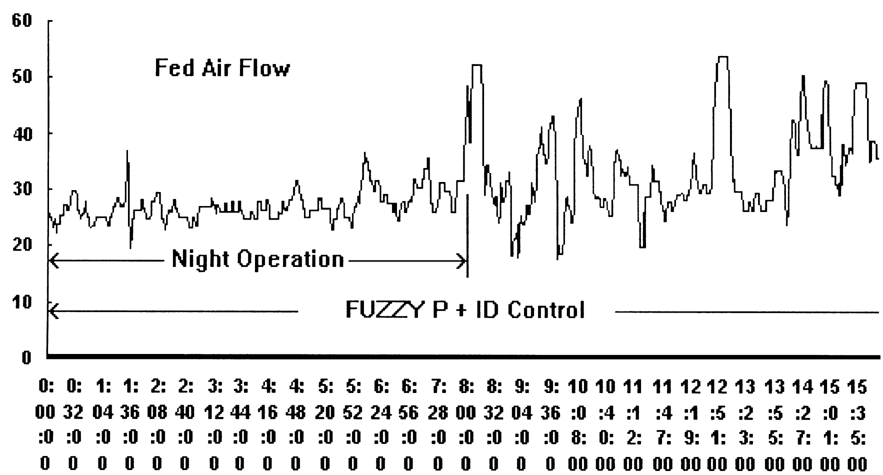
(b)

Fig. 9. FUZZY P + ID control on 14 October 1995: (a) steam pressure; (b) steam flow; (c) fed coal flow; (d) fed air flow.

Since the combustion systems of the stoker-fired boilers have a large time lag and controllers' parameters are tuned during the boiler's operation, engineers hope that a few parameters of the controller should be adjusted. For this reason, the fuzzy inference rules of the proposed FUZZY P + ID controller are only 3×3 in dimension so that only one additional parameter, ε, should be adjusted for implementing the FUZZY P + ID controller. Therefore, this FUZZY P + ID controller is practical for improving control performance of an industrial plant which is already controlled by a conventional PID-type controller. Besides, the bounded-input/bounded output stability of the proposed FUZZY P + ID controller can be proved by using "small gain theorem" [14]. In fact, the stability analysis for the boiler system controlled by the PID-type controller is very difficult due to the lack of an appropriate model.



(c)



(d)

Fig. 9. (Continued).

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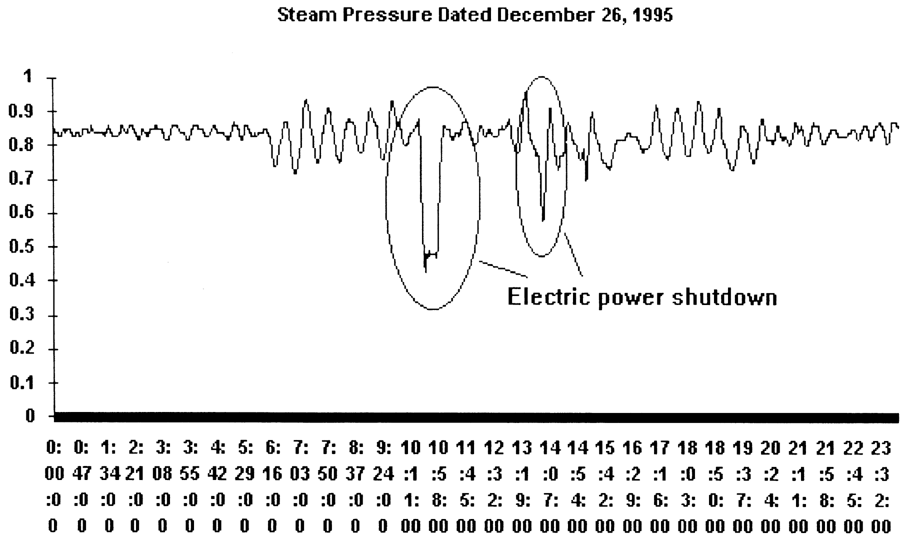
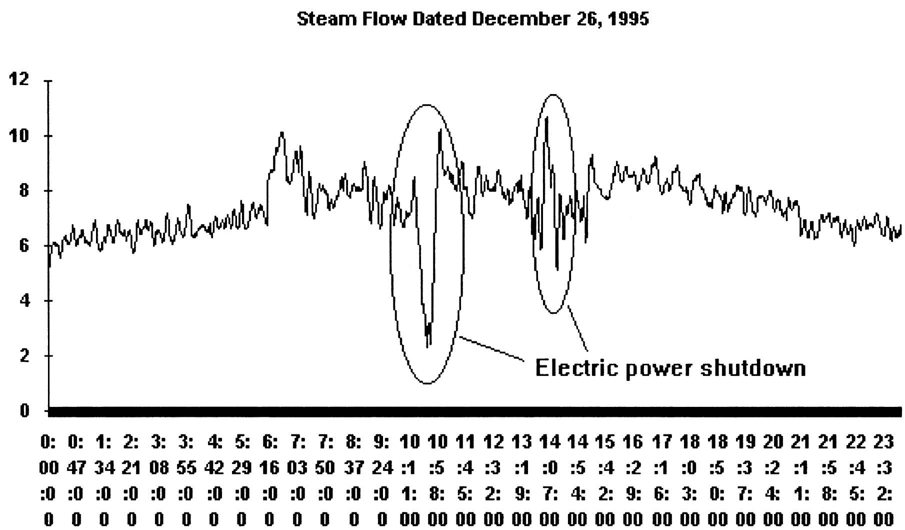


(a)



(b)

Fig. 10. FUZZY P+ID control with power shutdown on 26 December 1995 at a railway station: (a) steam pressure; (b) steam flow.

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