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SELFTUNING NONLINEAR CONTROLLER

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Abstract: - This paper deals with application of a self tuning nonlinear control strategy to a boiler drum process for control of water level inside the drum. Basic equations representing the dynamics of boiler drum are solved to form two differential equations. The two differential equations represent changes in steam density and level of water inside the drum. Assumptions are made to reduce the complexity of equations for simulation in Matlab/Simulink.

The above model is made as a SISO system for controlling the level of the drum. A fuzzy logic based set point -weight method (which is stated to be the best and easy to practically implement) is applied to tune standard PID controller to achieve both reduced overshoot and decrease in rise time.

Key-Words: - Fuzzy logic, Selftuning, Modeling, Boiler, Non linear control, PID control

1. Introduction

Boiler drum level control is critical for both plant protection and equipment safety and applies equally to high and low levels of water within the boiler drum. The purpose of the drum level controller is to bring the drum up to level at boiler start-up and maintain the level at constant steam load. A dramatic decrease in this level may uncover boiler tubes, allowing them to become overheated and damaged. An increase in this level may interfere with the process of separating moisture from steam within the drum, thus reducing boiler efficiency and carrying moisture into the process or turbine.

A nonlinear physical model with a complexity that is suitable for model-based control has been presented in Astrom et al (1999). Different models of higher order have been developed. Complex dynamic models are developed by Francis T. Thompson (1967), Liu Changliang et al (2001). These models can be used for synthesis of model based control algorithms and also for developing a real time simulator for testing new boiler control system. Simplified models are developed by F.P.de Mello et al (1991), Kwanty (1971).

PID controllers are particularly suited for pure first- or second-order processes, while industrial plants often present characteristics such as high order, time delays and nonlinearities and so on. In this context, the tuning of the parameters is a crucial issue. Adaptive control technology encompasses a wide range of mathematical and empirical techniques that allow a feedback controller to automatically update not only its next output, but also its entire control strategy to accommodate changes in the behavior of the controlled process. Self-tuning controllers capable of adjusting their own proportional (P), integral (I) and derivative (D) parameters were among the first adaptive controllers available as commercial products.

The aim of this paper is to apply fuzzy logic based setpoint-weight method (which is stated to be the best and easy to practically implement) to a boiler process, which is simulated using the basic boiler dynamics equations.

2. Boiler drum process

The steam generation process can be considered to comprise of 3 distinct stages, viz.

(i) Combustion process, where the fuel is burnt in air and the resulting product gases exit with their thermal energy.

(ii) Heat transfer process, where the thermal energy transfers from hot gases to water takes place.
(iii) Evaporation process, where the water is converted into steam.

The boiler system consists of a combustion chamber, where combustion of fuel takes place. The burning gases pass around a group of vertical tubes. These tubes, called risers, carry a mixture of water and steam. At the top of the risers is the drum, which is a horizontal cylinder, kept about half full of water. The upper part of the drum contains steam. The tubes that leave the bottom of the drum (the down comers) are insulated from the combustion chamber and carry the water down to a mud drum, where mud is separated from the water. Heating the riser tubes with hot flue gas causes the water to circulate and steam to be released in the steam drum. This principle is shown in Fig 1

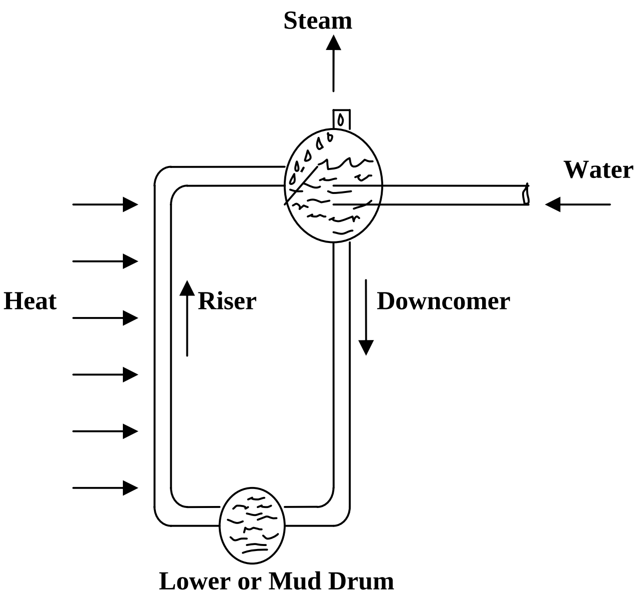

Fig 1: Schematic diagram of boiler drum

The steam that is produced passes from the drum to the super heaters that are located in the combustion chamber. The superheated product steam is then sent to the process, where the energy is returned to the drum where it begins the cycle again.

The density of the saturated water in the down comers is greater than the average density of the two-phase mixture in the risers. Natural circulation is dependent upon the difference between these two densities and the height of the drum above bottom headers. Most large steam generator boilers have sufficient natural circulation driving force and are called natural circulation boilers. Some require additional help by pumping the single phase flow and are called controlled or forced circulation boilers.

The most important function of the steam drum is separating the steam from the boiling water. The simplest method is gravity separation. Gravity separation is strongly affected by the difference in steam and water densities. Other separation method is mechanical separation. Mechanical separation is accomplished by fitting the drums with baffles, screens, bent or corrugated plates and centrifugal separators. Centrifugal separators are also called Cyclone or Turbo separators.

Steam drum level control is necessary to add makeup water as steam is delivered into the header and to the associated process equipment. The system should control the drum level at a specific set point while compensating for varying steam demands and drum pressures. For a given volume of steam and blow down leaving the steam drum, an equal amount of water should replace that inventory.

2.1 Process Equations

The simulation is based on the model available in the literature [1]. Each of the 4 subsections of a boiler drum viz the feed water pumps, down comers, water walls and the drum are individually analyzed and the first principle model is obtained.

After solving the mass and energy balance equations, the state equations are given by equ (1) and (2)

$$\frac{dV_{dw}}{dt} = \frac{\frac{W_e}{\rho_{dw}}(1+g) - \frac{W_d}{\rho_{dw}} g - \frac{W_D}{\rho_{dw}} X}{\left[1 + g\left(1 - \frac{\rho_d}{\rho_{dw}}\right)\right]} \tag{1}$$

$$\frac{d\rho_d}{dt} = \frac{-W_e \frac{\rho_d}{\rho_{dw}} + W_d - XW_D\left(1 - \frac{\rho_d}{\rho_{dw}}\right)}{V_{dw} - V_d - \frac{\rho_d}{\rho_{dw}} V_{dw}\alpha_{\rho_{dw}} - \frac{b}{(h_d - h_{dw})} + \frac{b(\rho_d / \rho_{dw})}{(h_d - h_{dw})}} \tag{2}$$

where

$$g = \frac{\rho_d \alpha_{h_d}\left(V_d - V_{dw}\right) + V_{dw}\rho_{dw}\alpha_{h_{dw}}}{\left[V_d - (1-\alpha_{\rho_{dw}})V_{dw}\right](h_d - h_{dw})} - \frac{V_{dw}\alpha_{\rho_{dw}}}{\left[V_d - (1-\alpha_{\rho_{dw}})V_{dw}\right]} \tag{3}$$

$$\alpha_{h_d} = \left[\frac{\partial h_d}{\partial \rho_d}\right]_{sat} = -18.9583 \frac{Btu}{ft^3} \tag{4}$$

$$\alpha_{h_{dw}} = \left[\frac{\partial h_{dw}}{\partial \rho_d}\right]_{sat} = 32.5179 \frac{Btu}{ft^3} \tag{5}$$

$$\alpha_{\rho_{dw}} = \left[\frac{\partial \rho_{dw}}{\partial \rho_d}\right]_{sat} = -2.0132 \tag{6}$$

The state relations

$$\rho_{dw} = -2.0132 * \rho_d + 49.7224 lb / ft^3 \tag{7}$$

$$T_d = 20.5097 * \rho_d + 525.9288^0 F \tag{8}$$

$$P_d = 273.5046 * \rho_d + 539.5794 PSIA \tag{9}$$

$$h_{dw} = 32.5179 * \rho_d + 498.3699 Btu/lb \quad (10)$$

$$h_d = -18.9583 * \rho_d + 1238.9003 Btu/lb \quad (11)$$

are satisfactory for use in the drum and were calculated for saturated steam temperatures between 600 and 650 ^{0}F using data from Keenan and Keyes steam tables.

For simulation another useful equation is W_D

$$W_D = \frac{Q_w + W_e(h_e - h_{dw})}{x(h_d - h_{dw})} \quad (12)$$

The state equation obtained is in terms of volume of the drum. Normally the shape of the drum in industry would be a cylinder with two half spheres each at one end enclosing the drum. The following relation is used to convert volume to level based on the physical dimensions of the drum

$$V(h) = l\left[\frac{\pi R^2}{2} + R^2 \sin^{-1}\left(\frac{h-R}{R}\right) + (h-R)\sqrt{2Rh - h^2}\right] + \frac{\pi h^2}{3}[3R - h] \quad (13)$$

The level of water 'h' is computed using Newton Raphson Method iteratively during every sampling instant of the model run.

Assumptions:

- Velocity is negligible at the feed water inlet valve.
- All feed water enters the down comer.
- The total circulating flow (W_D) is constant.
- There is negligible heat transfer along the length of the down comer.

2.2 Nominal Values Of Boiler Drum Variables

Variables	Description	Value	Unit
ρ_d	Density of drum steam	8.221x10^{-5}	Kg/cm^3
ρ_{dw}	Density of water in drum	63.097 x10^{-5}	Kg/cm^3
W_e	Feed water flow	163.5023	Kg/sec
h_e	Enthalpy of feed water	131.97	Kcal/kg
W_d	Steam flow from drum	175.014	Kg/sec
H	Drum level	88.90	cm
P_d	Steam pressure in the drum	176.8	Kg/cm^2
T_d	Saturated steam temperature	354	^{o}C
X	Steam quality	0.95	-
α_{h_d}	Gradient of drum steam enthalpy	-657954.52	Kcal- m^3/Kg^2
$\alpha_{h_{dw}}$	Gradient of water enthalpy at drum conditions	1128547.11	Kcal- cm^3/Kg^2
$\alpha_{\rho_{dw}}$	Gradient of drum steam density	-2.0132	-
V_d	Volume of drum	40185469.46	cm^3
V_{dw}	Drum water volume	20092734.73	cm^3
L	Length of drum	1500	cm
R	Radius of drum	88.9	cm

Table1

3. Design of standard PID controller

Over 60 years ago, Ziegler and Nichols (1942) published a classic paper that introduced the *Continuous Cycling Method* for controller tuning.

PID Controller Settings based on the Continuous Cycling Method is given by

$K_c = Ku/1.7$

$T_i = Pu/2$

$T_d = Pu/8$

where K_u = ultimate gain

P_u = ultimate period

For the Boiler Drum model presented ultimate gain K_u is found to be 0.0008399(Kg/sec)/ cm^3 and ultimate period of sustained cycling P_u is found to be 2 sec. Using the above tuning rules, PID settings were found.

4. PID Tuning With Fuzzy Set-Point Weighting

Based on the comparison done between different methods on fuzzy logic, for the tuning of PID controllers [3], fuzzy set-point weighting technique appears superior to other techniques, as it guarantees in general good performances in the set-point and load disturbance step responses and it requires a modest implementation effort. The controller equation is given by (14)

$$u(t) = K_p e_p(t) + K_d \frac{de(t)}{dt} + K_i \int_0^t e(\tau)d\tau \quad (14)$$

where,

$$e_p(t) = by_{sp}(t) - y(t) \quad (15)$$

e(t) system error;
u(t) control output;
K_p proportional gain;
K_d derivative gain (K_p* T_d)
K_i integral gain (K_p/T_i)
T_d derivative time constant;
T_i integral time constant
b set-point weight

The idea, in a few words, is simply that u(t) has to be increased when the convergence of the process output y(t) to $y_{sp}(t)$ has to be speeded up and decreased when the divergence trend of y(t) from $y_{sp}(t)$ has to be slowed down.

For the sake of simplicity, the methodology is implemented in such a way that the output of the fuzzy module is added to a constant parameter 'W' resulting in a coefficient b (t) that multiplies the set-point [4].

5. Results and Discussion

A boiler drum model [1] is developed using basic dynamic equations. Conventional PID controller is developed using Ziegler-Nichols closed loop method. Fuzzy logic based set point weight tuning is done for the above PID controller.

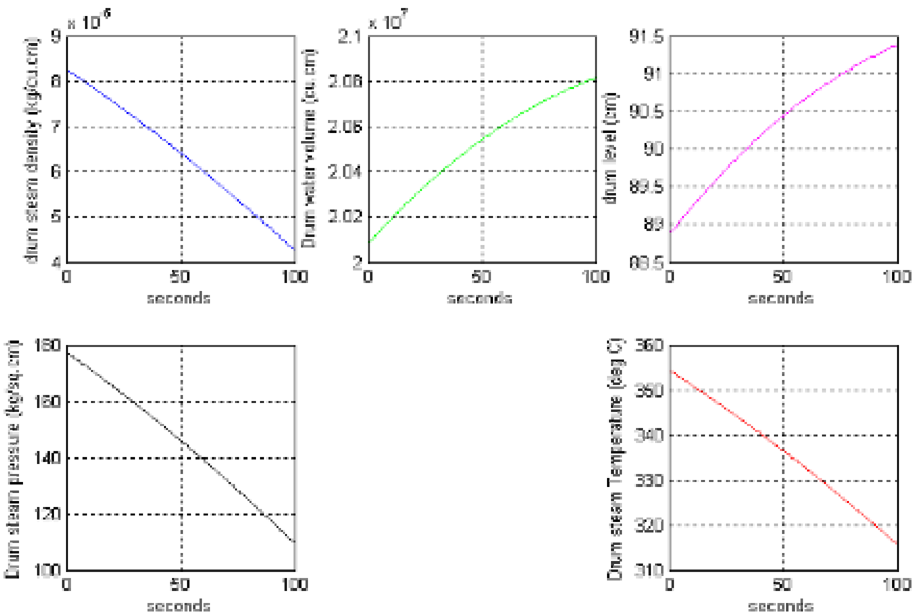

Fig2 Response of boiler drum model for +15% change in feed water flow from nominal value (163.5023 + 24.5253 kg/sec)

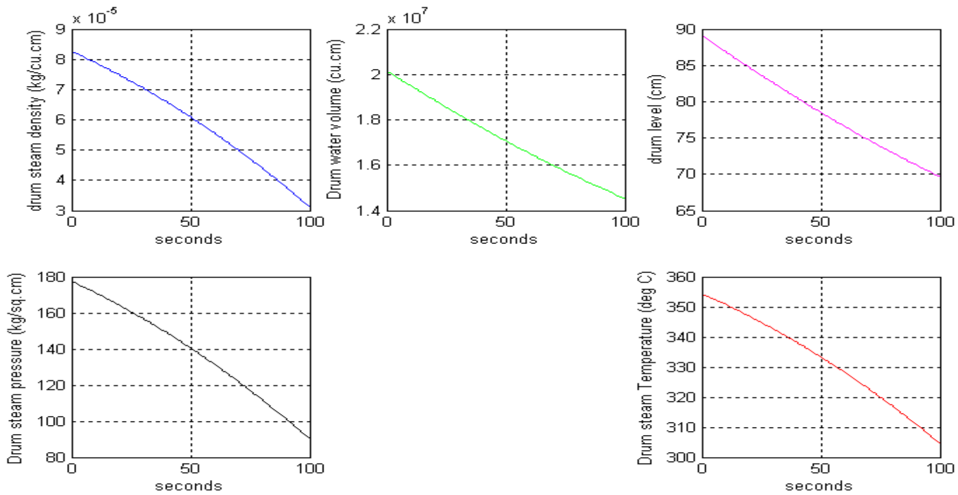

Fig3 Response of boiler drum model for +10% change in steam flow from nominal value (175.01394 + 17.501394 kg/sec)

As shown in Fig2, when the feed water flow increases the drum steam density decreases for a constant heat transferred to the risers. The level of water in the drum increases, the pressure and temperature inside the drum decreases.

As shown in Fig3 when the steam outflow increases the drum steam density decreases for a constant feed water flow and constant heat transferred to the risers. The level of water in the drum decreases. From Fig4 as the heat transferred increases the drum steam density increases for a constant feed water flow. The level of water in the drum decreases, the pressure and temperature inside the drum decreases.

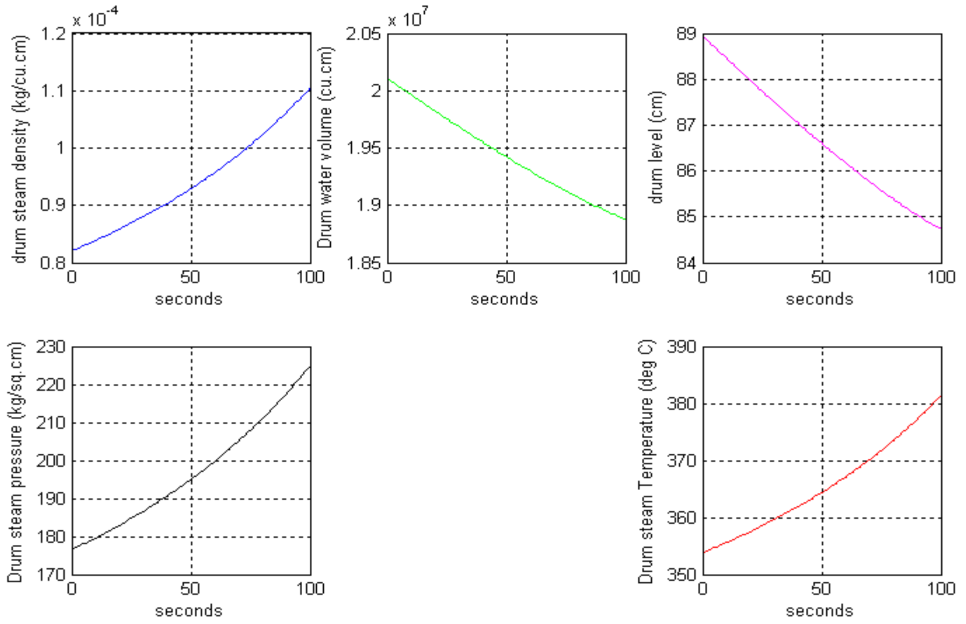

Fig4 Response of boiler drum model for +5% change in heat transferred to risers from nominal value (84570.444 + 4228.5222 kg/sec)

Making steam density constant at 8.221×10^{-5} Kg/cm3 makes the open loop model as a SISO system. The gain of the process changes randomly for changes in setpoint. To control the level of water in the drum, feed water flow is controlled. PID settings were found to be

Ziegler-Nichols	*Kc*	*Ti*	*Td*
PID	*4.9406e-004*	*4.9406e-004*	*1.2351e-004*

Table 2

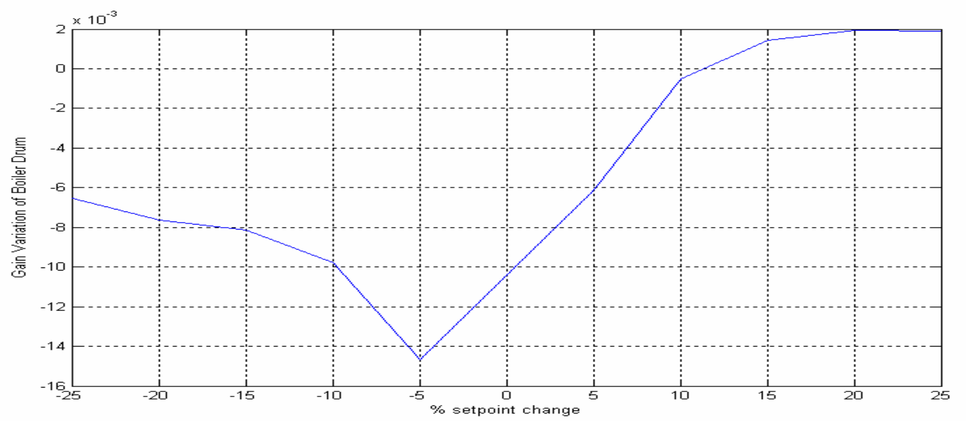

Fig5 Gain variation of the process for variation in setpoint

The rule base designed for FLC [4] based set point weight tuning method is given in table 3.

e/de	NB	NS	Z	PS	PB
NB	NVB	NB	NM	NS	Z
NS	NB	NM	NS	Z	PS
Z	NM	NS	Z	PS	PM
PS	NS	Z	PS	PM	PB
PB	Z	PS	PM	PB	PVB

Table 3

Where

NVB	Negative Very Big	PS	Positive Small
NB	Negative Big	PM	Positive Medium
NM	Negative Medium	PB	Positive Big
NS	Negative Small	PVB	Positive Very Big
Z	Zero		

The two inputs of the fuzzy inference system, the system error and its derivative are scaled by two coefficients in order to match the range on which the membership functions are defined. Five triangular membership functions are defined for each input while nine triangular membership functions over the range are defined for the output, which is scaled by a coefficient

Scaling coefficient for error = 1/ 20092734.73
Scaling coefficient for change in error = 1/ (1.5*10^7)
Scaling coefficient for output = 0.1
W = 0.0320

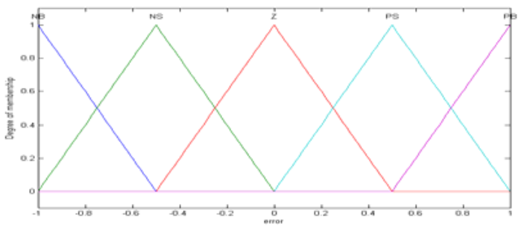

Fig6 Membership functions of the input error of the fuzzy inference system

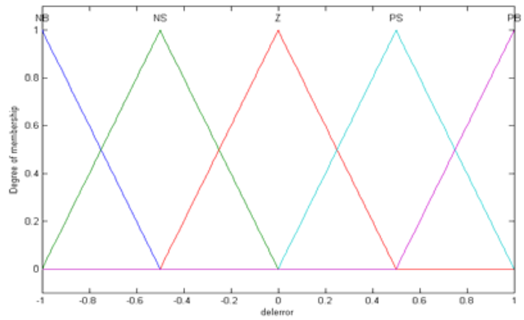

Fig7 Membership functions of the input change in error of the fuzzy inference system

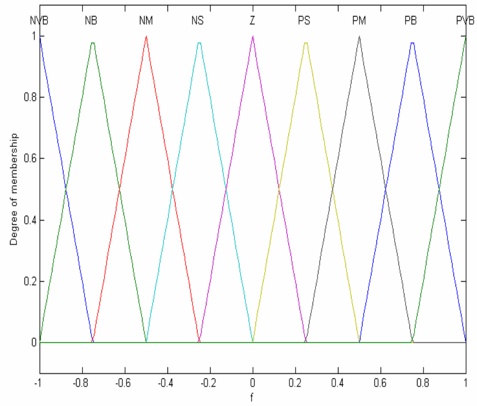

Fig8 Membership functions of the output f of the fuzzy inference system

As shown Fig6, Fig7 and Fig8 five triangular membership functions were chosen for error end change in error and nine membership functions were chosen for factor ‘b (t)’.
From Fig 9 and Fig 11, it can be observed that Fuzzy tuned PID is better than conventional PID. Both the overshoot and rise time are reduced. Corresponding variation in set point weighting factor ‘b (t)’ is shown in Fig 10 and Fig 12.

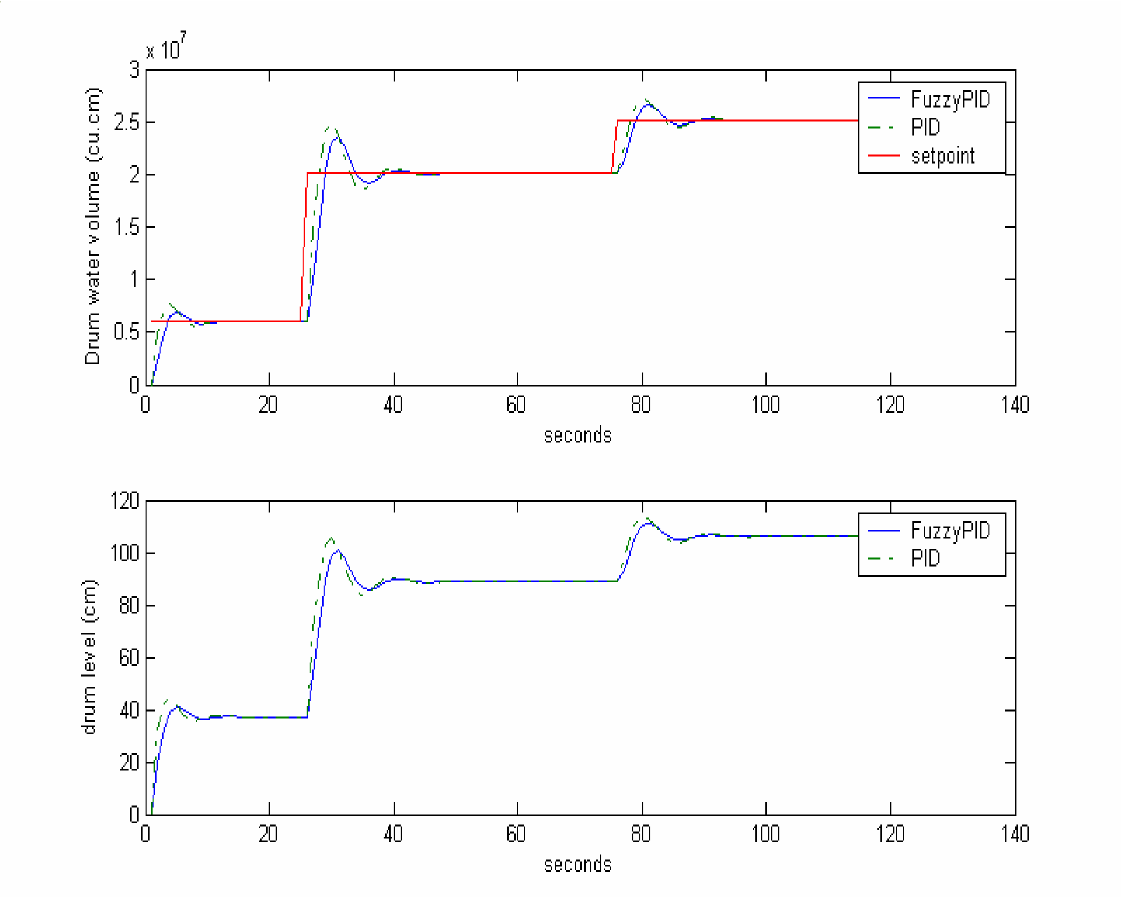

Fig 9 A step change of + 25% is applied at 75th instant for the feed water flow.

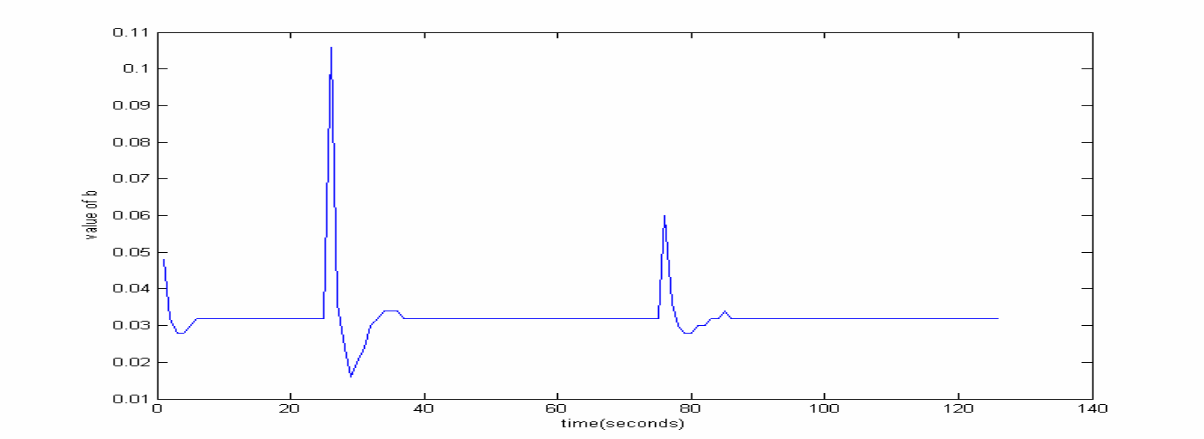

Fig10 Setpoint Weighting factor variation 'b'

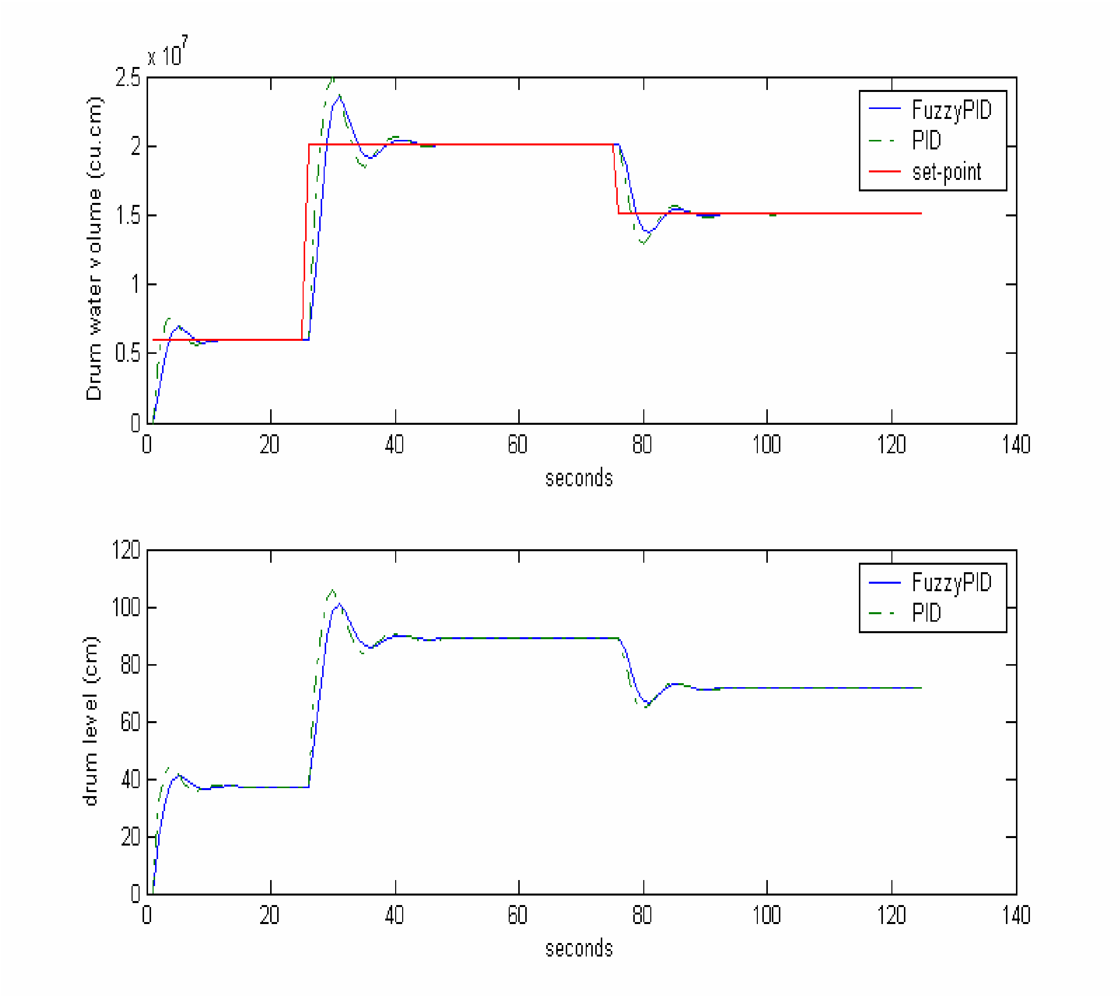

Fig11 A step change of - 25% is applied at 75th instant for the feed water flow.

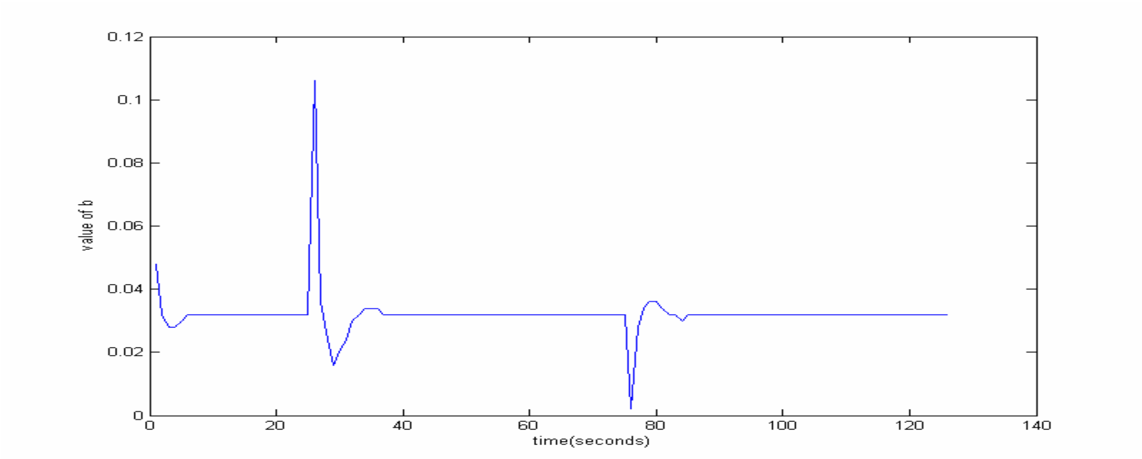

Fig12 Setpoint Weighting factor variation ‘b’

6. CONCLUSION

In this paper, fuzzy setpoint weighting method of tuning PID parameters is applied to a boiler drum process described by basic dynamic equations. The approach has been effective in set point tracking while the load disturbance attenuation performances are obtained by the use of Ziegler-Nichols tuning rules. Higher performances can be obtained by tuning of fuzzy membership functions using genetic algorithms and also by selecting different scaling factors for different setpoint changes [5].

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