Control of the Bed Temperature of a Circulating Fluidized Bed Boiler by using Particle Swarm Optimization

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***Abstract*—Circulating fluidized bed boilers are increasingly used in the power generation due to their higher combustion efficiency and lower pollutant emissions. Such boilers require an effective control of the bed temperature, because it influences the boiler combustion efficiency and the rate of harmful emissions. A Particle-Swarm-Optimization-Proportional-Integrative-Derivative (PSO-PID) controller for the bed temperature of a circulating fluidized bed boiler is presented. In order to prove the capability of the proposed controller, its performances are compared at different boiler loads with those of a Fuzzy Logic (FL) controller. The simulation results demonstrate some advantages of the proposed controller.**

***Index Terms*—particle swarm optimization, bed temperature, fuzzy logic, boiler**

I. Introduction

The demand for electrical energy increases in parallel with the population growth and the rapidly extending industrialization. No storage of electrical energy requires instant production of necessary one. Since the boilers used in thermal power stations for production of steam and electrical energy use fossil fuels, the surfaces of the heater pipes and boilers get covered with a layer of particles which reduces the efficiency and causes the release of harmful gases. So, clean coal technologies are required.

Moving grid boilers used in industry and pulverized coal boilers used for producing electricity have some operational problems. In moving grid boilers, the combustion efficiency is low, because coal particles don't have enough air for combustion. In power stations with pulverized coal boilers, only when high quality coal produces a complete combustion. When low quality coal is used, since of the heat transfer difficulties at the end of the combustion, usually for improving the productivity, an increased coal feed is used, which amplify the greenhouse gas releasing effect. So, actually, the best solution for obtaining clean energy efficiently is to use fluidized bed boilers. In these boilers, fuels with low thermal value can be comfortably used due to the high heat capacity of the bed material.

SO_2 is one of the most harmful gases produced by combustion of fossil fuels. In circulating fluidized bed boilers, this gas is captured because limestone is used and the particles leaving the boiler are returned into the boiler.

So, combustion efficiency increases with rising of bed temperature by providing a good mixture of solid and gas, because carbon burns faster at higher temperatures and at high bed temperature the combustion loss decrease. For maximum capturing of the SO_2 gas, the bed temperature must be kept at an optimum value. Low bed temperature increases the efficiency of the capture of SO_2 by the limestone [17].

Also the bed temperature affects the amounts of other harmful emissions: the NO_x emission increases linearly and the CO emission decreases with rising of the bed temperature, respectively. So, the control of the bed temperature is important for decreasing these emissions and increasing the combustion efficiency [13].

Classical controllers don't react fast enough to the instant changes of the boiler state. In order to achieve a faster response, modern control methods are used.

B. Lixia et al. developed an interesting mathematical model of the bed temperature of the circulating fluidized bed boiler with changing parameters at different boiler loads [1].

P. Fu et al. had controlled the bed temperature with a Fuzzy PID controller by using Lixia's model; they showed that Fuzzy PID controllers are better than classical PID controllers [2].

A.A. Jalali and A. Hadavand had controlled the bed temperature with a H∞ controller by using the same model; they decreased the settling time of the system but overshoots occurred [3]. Overshoots of the bed temperature mean more fuel consumption and more heat energy generation and are not accepted for reasons of the energy efficiency.

In this paper, the use of a Particle Swarm Optimization based PID controller, for increasing the efficiency and stability of the system by eliminating overshoots, is presented. The performances of the proposed PSO-PID controller are compared by simulation with those of a Fuzzy Logic controller.

II. The Bed Temperature Model of a Circulating Fluidized Bed Boiler

Since the dynamic characteristic of the circulating fluidized bed boiler change for different loads, a complex control function is necessary. Eq. (1) shows the mathematical model developed by B. Lixia et al. [1]:

$$G_p(s) = \frac{1-\alpha s}{\left(1+T_p s\right)^2} K_p \exp\left(-\tau s\right) \tag{1}$$

The values of the parameters K_p, T_p and τ depend on the boiler load (Table I), while the recommended value of the parameter α is about 12 [1].

Fig. 1 presents the open loop step response curves for three boiler loads [1]. The curves show that the delay time and the passing stability of the system increase in parallel with increasing boiler load.

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TABLE I
PARAMETER VALUES AT DIFFERENT BOILER LOADS

Parameter	Boiler Load		
	25%	65%	100%
K_p	5	7.5	10
T_p	100	150	200
τ	30	45	60

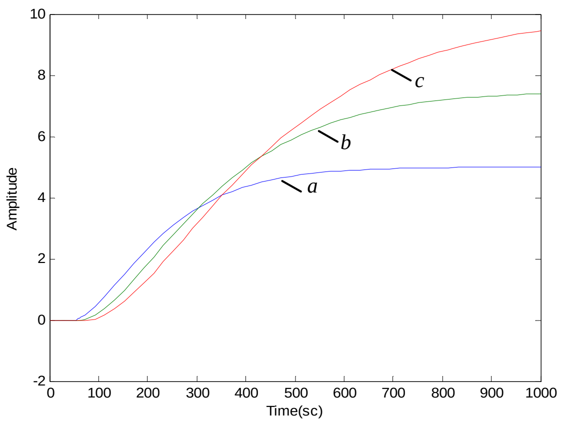

Figure 1 Open loop step responses of the bed temperature model at different boiler loads: *a*) 25% boiler load; *b*) 65% boiler load, c) 100% boiler load [1].

The bed temperature should be controlled for the following reasons: (i) to increase the combustion efficiency, (ii) to have the optimal SO_2 capture, (iii) to prevent the ash agglomeration at the bottom of the combustor chamber, (iv) to decrease the emission of harmful gases such as CO and NO_x, (v) to prevent the melting of the heat exchangers [13].

III. The Particle Swarm Optimization

The Particle Swarm Optimization (PSO) which had been developed by J. Kennedy and R.C. Eberhart in 1995, observing the bird swarms behaviors, is a stochastic optimization technique based on population [5]. It had been designed for solving nonlinear problems and can be used for finding solution to multi-parameter and multi-variable optimization problems [14-17], [19-26], [34-42],.

In PSO technique, particles fly in search space at a certain velocity which is based on flight experiences. The speed and position of the i^{th} particle of swarm x_i at $(t+1)^{th}$ iteration are shown in Eqs. (2) and (3) [8]:

$$v_{iD}^{t+1} = K\left[v_{iD}^{t} + c_1 r_1 \left(p_{iD}^{t} - x_{iD}^{t}\right) + c_2 r_2 \left(g_i^{t} - x_{iD}^{t}\right)\right] \quad (2)$$

$$x_{iD}^{t+1} = x_{iD}^{t} + v_{iD}^{t+1} \quad (3)$$

In the above equations, the following notations have been used: D - dimension of the space used in the optimization problem; r_1 and r_2 - random numbers between 0 and 1; c_1 and c_2 - positive constants which pull the particle local and global best positions, p_i - the best position of the i^{th} particle at the current moment, which is the local best position; g – the best position in the swarm; which is the global best position; K - factor for improving the convergence of optimization, shown in Eq.(4) [9].

$$K = \frac{2}{\left|2-\varphi-\sqrt{\varphi^2-4\varphi}\right|} \qquad \varphi = c_1 + c_2 > 4 \quad (4)$$

For preventing that the particles leave the swarm, the positions and speeds of particles must be limited. The speed values are limited according to determined position values of the particles.

These limits are shown in Eqs. (5) and (6). The algorithm converges to optimal result if appropriate limits for particles are determined [6].

$$v^{\max} = k\, x^{\max} \quad (5)$$

$$v^{\min} = -v^{\max} \quad (6)$$

After determining the initial values for applying the base algorithm of PSO, six steps described below are performed [10 - 12].

Step 1: The speed and position limits for each particle and the values of the parameters used in the update equations (Eqs. (2) and (3)) are determined.

Step 2: The matrix of initial positions and speeds of particles are completed with the initial values, which are random numbers of predetermined ranges.

Step 3: For every particle, the fitness value according to the selected fitness function is determined and compared with the fitness value of the local best position. If the current-position fitness value of the particle is bigger than the fitness value of its local best position, the current particle position and the fitness values are appointed as new local best values.

Step 4: The matrix of the best fitness value of the local best position is compared with the matrix containing fitness value of the global best position. If the best fitness value of the local best position matrix is bigger than the fitness value of the global best position, the position and fitness value of that particle are used as the new global best position and fitness value.

Step 5: The speeds and positions of particles are regenerated according to the update equations (Eqs. (2) and (3)).

Step 6: The evolutionary process is repeated iteratively (from step 3 to step 5). At the end of the iterative process, the obtained global best position is assumed as the solution of the problem.

III.1 The Proposed PSO-PID Controller

The control law of the proposed PSO-PID controller, used for the control of the bed temperature of the circulating fluidized bed boiler, consisting of three control effects (proportional, integral and derivative effects), is presented in Eqs.(7) and (8):

$$m(t) = K_p\, e(t) + K_i \int_0^t e(t)\,\mathrm{d}t + K_d \frac{\mathrm{d}e(t)}{\mathrm{d}t} \quad (7)$$

$$m(t) = K_p \left(e + \frac{1}{T_i}\int_0^t e\,\mathrm{d}t + T_d \frac{\mathrm{d}e}{\mathrm{d}t}\right) \quad (8)$$

Fig. 2 shows the block diagram of the proposed PSO-PID controller.

The control was optimized for three different models obtained for three boiler loads.

A unit step function is applied to the input of the system and the error values are recorded and are entered into optimization software.

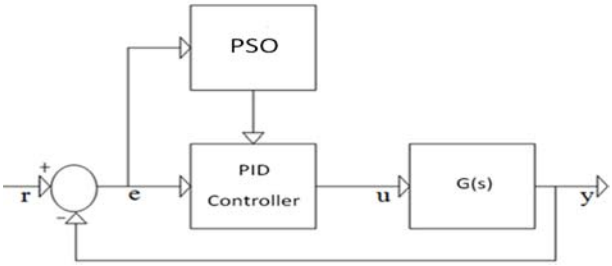

Figure 2 The block diagram of the proposed PSO-PID controller.

The convergence factor *K*, computed by Eq. (4) was used for balancing the local and global search performances.

The chosen value of the coefficients $c_1 = c_2$ was 2.05 [4].

The chosen particle number was 20 and the iteration number for simulation was 50.

In PSO, the fitness function, which affects the settling time and overshoot of the system, is one of the most important parameters.

So, Rosenbrock function, Rastrigrin function and Sum of Error Square function are used in Eqs.(9)-(11) as fitness functions and the best one of them according to simulation results was selected [7].

$$f(x) = \sum_{i=1}^{n} \left[100\left(x_{i+1} - x_i\right)^2 + \left(x_i - 1\right)^2 \right] \tag{9}$$

$$f(x) = \sum_{i=1}^{n} \left(x_i^2 + 10 - 10\cos 2\pi x_i \right) \tag{10}$$

$$SSE = \sum_{k=1}^{q} e_k^2 \tag{11}$$

TABLE II
OPTIMIZED PARAMETER VALUES FOR DIFFERENT BOILER LOADS

Parameter	Boiler load		
	25%	65%	100%
K_p	0.37933	0.4	0.3614
K_i	0.0013206	0.00078248	0.0005
K_d	18.729	30.546	36.7762

In Table II the values of the optimized parameters determined for different boiler loads (25% , 65% , 100% , respecttively) are presented.

IV. Fuzzy Logic (FL) Controller

Fuzzy Logic (FL) controllers were used in a lot of applications, including the control of the bed temperature of boilers [18], [27-33].

The input and output variables of the used FL controller are created by 7 membership functions: NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big). Among these membership functions, NB and PB are *trapmf* (trapezoid membership functions) and the others are *trimf* (triangle membership functions).

IV.1. The Determining of Input and Output Intervals

The input signals are affected by error (*e*) and error change (Δe). The output signal is the control signal *u*. The input and output intervals are shown in Fig. 3.

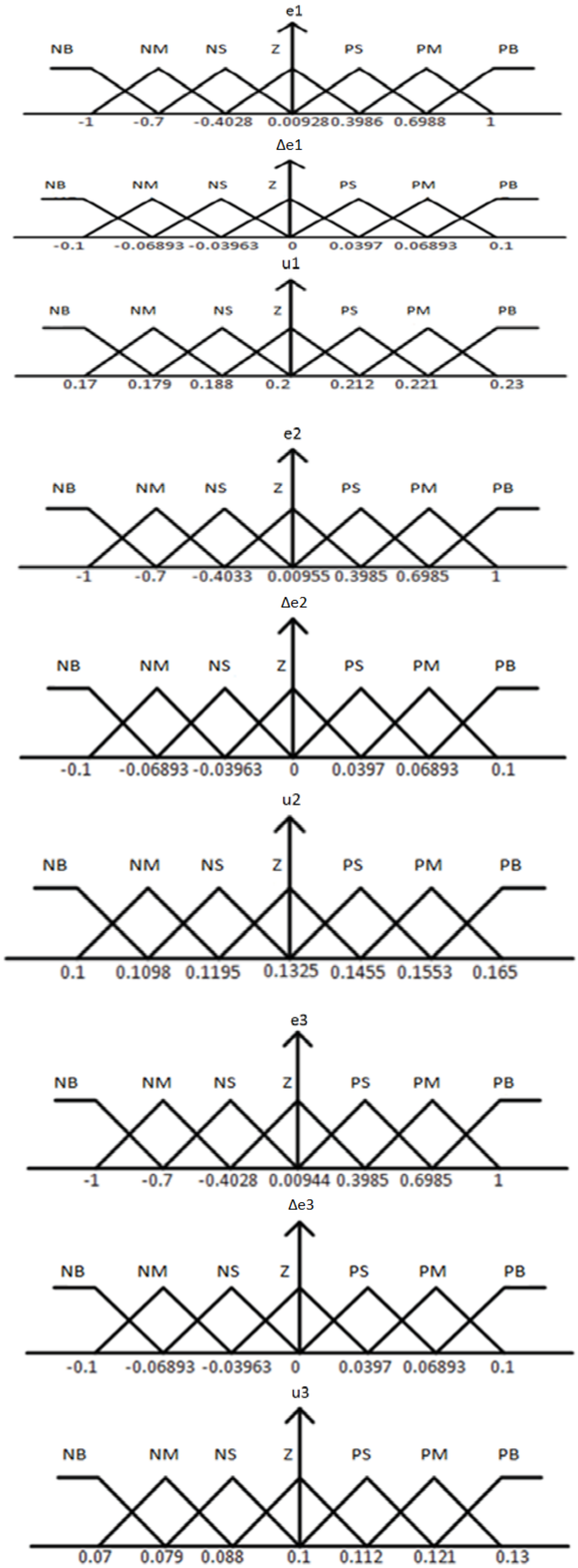

Figure 3 Determining of input and output intervals at 25%, 65% and 100% boiler load, respectively

IV.2. The Extraction of Fuzzy Rules

If the error is PB, it means that the set value is bigger than the measured value. If the error change is PB too, it means that the error value *e* in the i^{th} time interval is bigger than error value e in the $(i\text{-}1)^{th}$ time interval. In this case, the control signal must be PB for decreasing both the error and the change of error. The other rules are determined analogously. The extraction of Fuzzy Rules is shown on Table III.

V. SIMULATION RESULTS

The block diagram shown in Fig. 4 was used for control the system. Simulations are implemented and performed by "Matlab Simulink". The simulation results for the Rosenbrock function are the best ones for all target functions, so, it is used in PSO-PID controller for comparison with the FL controller. During the simulation, a unit step function is used for the desired value. The obtained simulation results for both controllers are shown in Figs. 5-13. Some parameters which belong to the controllers are given in Table IV.

TABLE III
THE EXTRACTION OF FUZZY RULES

Δe \ e	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NB	NM	NM
NM	NM	NM	NM	NM	NM	NS	NS
NS	NS	NS	NS	NS	NS	Z	Z
Z	Z	Z	Z	Z	Z	PS	PS
PS	PS	PS	PS	PS	PS	PM	PM
PM	PM	PM	PM	PM	PM	PM	PB
PB	PB	PB	PB	PB	PB	PB	PB

TABLE IV
COMPARISON OF THE CONTROLLERS

Boiler Load	Parameters	PSO-PID	FL
25%	Maximum Overshoot (%)	-	-
	Settling Time (s)	340	600
65%	Maximum Overshoot (%)	1	-
	Settling Time (s)	325	800
100%	Maximum Overshoot (%)	1,5	-
	Settling Time (s)	385	900

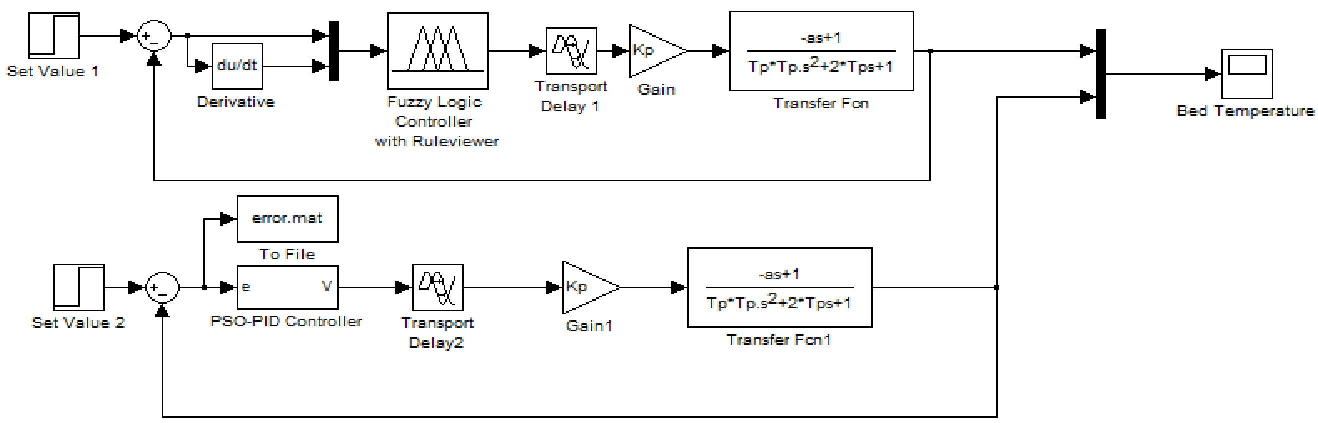

Figure 4 The block diagram of the proposed control

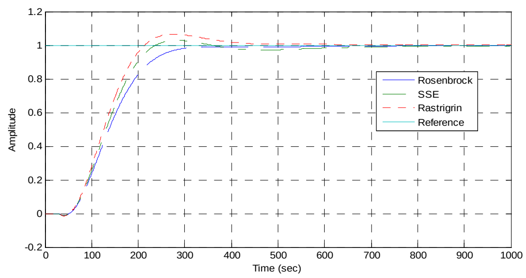

Figure 5 Simulation results of target functions for 25% boiler load

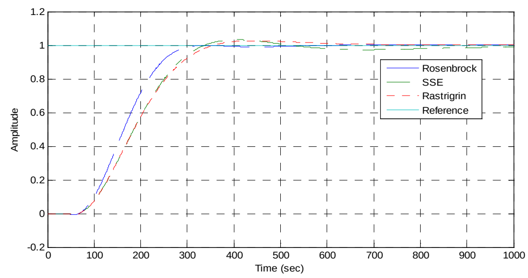

Figure 6 Simulation results of target functions for 100% boiler load

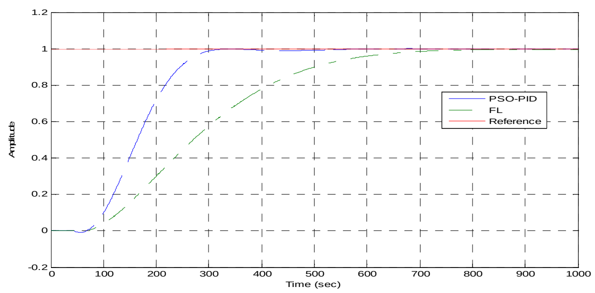

Figure 7 Simulation results of target functions for 65% boiler load

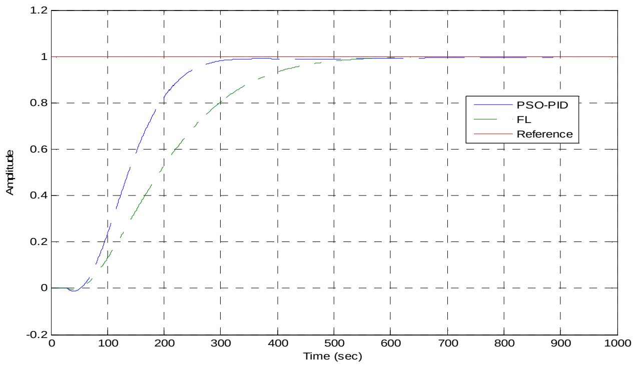

Figure 8 Closed loop step response for 25% boiler load

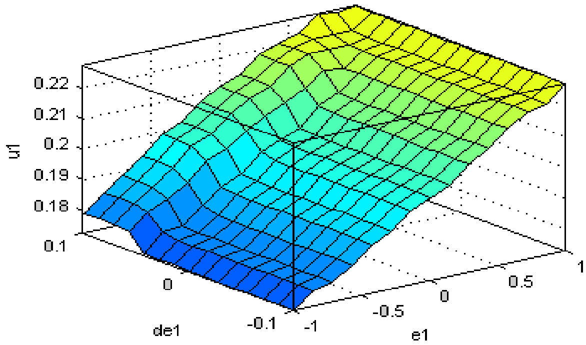

Figure 9 Variation of the parameters $e1$ and $\Delta e1$ of the FL controller with respect to the control signal $u1$ for 25% boiler load

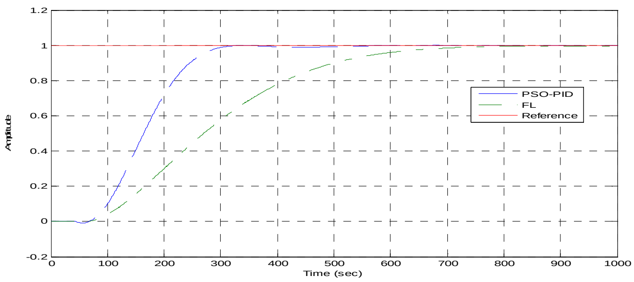

Figure 10 Closed loop step response for 65% boiler load

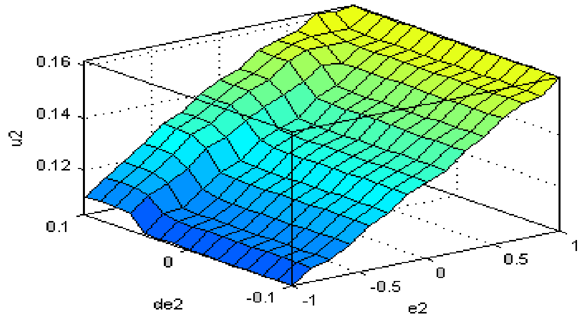

Figure 11 Variation of the parameters $e2$ and $\Delta e2$ of the FL controller with respect to the control signal $u2$ for 65% boiler load

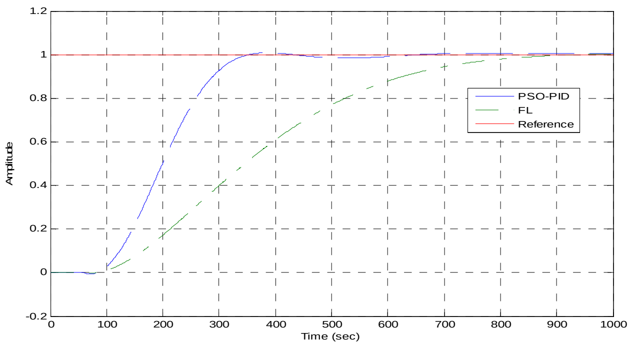

Figure 12 Closed loop step response for 100% boiler load

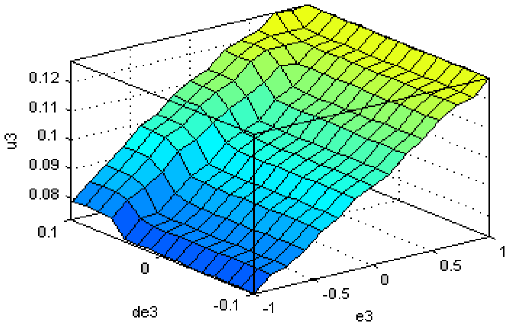

Figure 13 Variation of the parameters $e3$ and $\Delta e3$ of the FL controller with respect to the control signal $u3$ for 100% boiler load

VI. CONCLUSIONS

In this paper, a simulation based comparative study of the performances of a Particle Swarm Optimization Proportional-Integrative-Derivative (PSO-PID) controller and a Fuzzy Logic (FL) controller was presented. Both controllers were used for controlling the bed temperature into a circulating fluidized bed boiler at three boiler loads. Both controllers and the boiler system were designed with Matlab. The simulation results suggest that the proposed PSO-PID controller has considerably better performances than the FL controller.The simulation results suggest that the proposed PSO-PID controller has considerably better performances than the FL controller.

In FL controller overshoot is decreased by determining fuzzy rules and membership functions by experience but settling time in FL controller is longer. Although the algorithm of Particle Swarm Optimization is simple, it is more effective and it doesn't need experience like Fuzzy Logic.

Settling time and overshoot must be minimized in controlling bed temperature of circulating fluidized bed boiler. Reduced settling time significantly reduces energy generating costs, providing economical benefits to both the management and the consumer. Also corrosions of the machines used in the system can be prevented by lowered overshoot of the bed temperature.

Settling time and overshoot are decreased very much by using error values in Rosenbrock function as fitness function in PSO-PID. So, austerity from fuel and heat energy is provided. Therefore combustion efficiency will increase at the boiler and the emission of harmful chemical gases will decrease. Equipment used in power plants will be able to work for longer time by showing less corrosion. So maintenance and revision costs will decrease.

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