World Applied Sciences Journal 34 (7): 922-930, 2016
ISSN 1818-4952

DOI: 10.5829/idosi.wasj.2016.34.7.23760

Effect of Cascade Controller on the Drum Dynamics of CFBC Boiler

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Abstract: An important tool for analyzing the performance of a linear / non-linear system is mathematical modeling. Modeling and simulation of such systems which exists becomes essential. This study investigates performance of circulation system of a CFBC boiler. There exists a non-minimum phase behavior in the boiler drum and is called the swell / shrink and it is predominant in boilers during start-up conditions. Hence it becomes necessary to control the effect of water level in the drum which otherwise leads to unwanted trip. A simple PI-PID controller has been considered as a prelude to achieve optimal start-up and for arresting the swell/shrink phenomenon in the CFBC boilers. Modeling and simulation has been done in Matlab - Simulink environment. The effect of drum pressure, drum level, heat transfer coefficient and steam quality is investigated for change in throttle and change in heat input.

Key words: CFBC boiler · Swell and shrink · Boiler trip · Heat transfer co-efficient · Cascade controller

INTRODUCTION

Drive for Clean and green environment leads to the usage of better quality coal. Availability of low quality coal increased NOx emission led to the development of Circulating Fluidized Bed Combustion (CFBC). In order to meet out the load demand, boiler turbine unit is used and there exists a condition where pressure and level need to be controlled within the operating limits. Several authors have explained several control schemes [1-5]. Among them, the most frequently used one is the three element PID controller. Fuzzy controllers [6, 7] are adopted for drum pressure and level control. Variation in the power demand results in the rapid variation of drum pressure and drum level. Optimal control of drum pressure, temperature and level becomes essential. Increase in power demand increases the load and hence the pressure in the drum decreases due to the increase in load. This results in the swell in the water level. When the operating pressure is low, then the effect swell or shrink is predominant. Hence the level control is taken into consideration.

Drum Boiler Modeling: The CFBC boiler under study [8, 9], has two circulation loops namely the main down comer – water wall loop and the evaporator loop. The feed water in the water wall gets heated up by heat acquired from the furnace Q_{GWW1} and the heat exchanger, Q_{GWW2}. The water is converted into steam and hence a two phase mixture of steam and water exists in both the water walls. The steam collected in the drum passes to the turbine through a series of super heater governed by the throttle valve and it is reheated to increase the heat. From the IP and LP turbine, it passes to the condenser and back to drum through boiler feed pump, HP heaters, flow control station and economizer. The boiler circulation system with its associated boiler feed pump components is shown in Figure1.

The boiler drum has an upper and lower level trip values. For a 210 Mw boiler the upper and lower limits are said to be 175 and -125. The Mass balance and Energy balance (ΔE) equations of steam-water mixture is used for modelling the system. The mass balance (ΔM) equation [1-6] is given by

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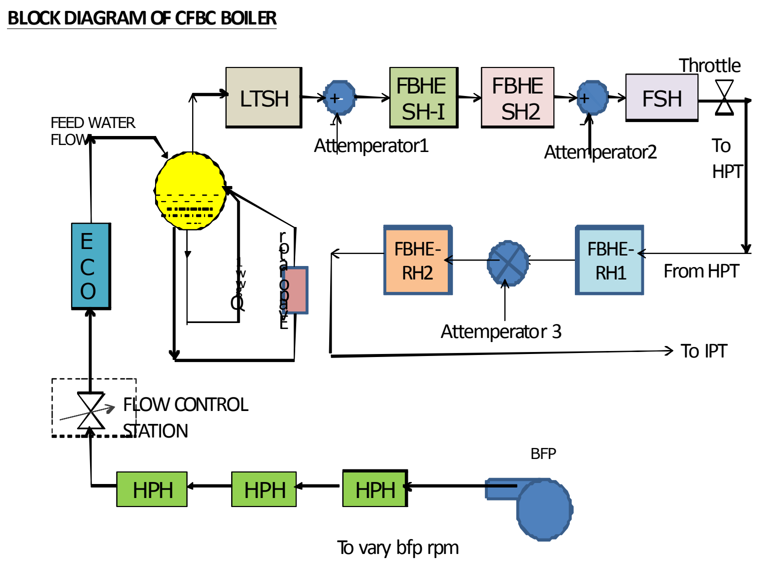

Fig. 1: Block diagram of circulation system of CFBC boiler

$$W_{eco} - W_{dc1} - W_{dc2} + W_{w1} + W_{w2} - W_s = \frac{d[\rho_s V_s + \rho_w V_w]}{dt} \tag{1}$$

$$\left[W_{eco} * H_{eco} - W_{dc1} * H_{wmn} - W_{dc2} * H_w + W_{w1} * H_{XW1} - W_s * H_s + W_{w2} * H_{xw2} + Q_{GWW1} + Q_{GWW2}\right] = \frac{d[\rho_s V_s H_s + \rho_w V_w H_w]}{dt} \tag{2}$$

where

$$Vdr = Vs + Vw \tag{3}$$

and $H_{xw1} = X_{q1} * H_s + (1-X_{q1}) * H_w$ (4)

$$H_{xw2} = X_{q2} * H_s + (1-X_{q2}) * H_w \tag{5}$$

Similarly, Quality factor X_{q1} and X_{q2} is given by,

$$X_{q1} = \frac{W_{s1}}{W_{dc1}} \tag{6}$$

$$X_{q2} = \frac{W_{s2}}{W_{dc2}} \tag{7}$$

Here in the boiler drum dynamics, the state variables are chosen to be drum pressure, drum level, metal temperature and the quality variation X_{q1}, X_{q2} stated by Mrunalini. K. et.al.[4]. If the heat flux from the combustor is $Qgww_1$ and from evaporator is $Qgww_2$ and heat flux absorbed by the water walls is Qgww, then metal temperature is obtained from the following equation.

$$Q_{GWW2} = M_{WW2} C_{pww_2} \frac{d[Tmww_2]}{dt} \tag{8}$$

The heat required for boiling the water is given by,

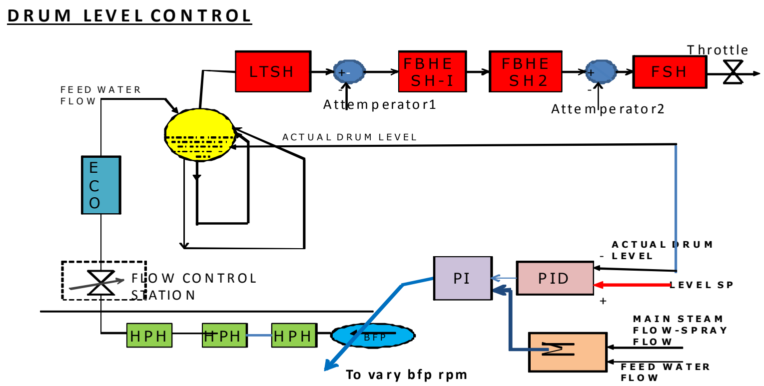

Fig. 2: Level controller for circulation system of CFBC boiler

$$Q_{GWW} = W_S * (H_S - H_{eco}) \quad (9)$$

and the heat flux from the combustor is obtained by,

$$Q_{Gww1} = [Q_{GWW} - Q_{GWW2}] \quad (10)$$

Kg of Steam produced due to the evaporator is $W_{S2} = \frac{Q_{GWW_2}}{[H_S - H_W]}$ (11)

$$W_{S1} = W_s - W_{S2} \quad (12)$$

The density of steam-water mixture in the water walls is given by,

$$\rho_{XW1} = \frac{\rho_W \rho_s}{(1-X_{q1})\rho_s + \rho_W X_{q1}} \quad (13)$$

$$\rho_{XW2} = \frac{\rho_W \rho_s}{(1-X_{q2})\rho_s + \rho_W X_{q2}} \quad (14)$$

Additional volume rise in the drum is given by

$$V_{Addln} = \frac{1}{(\rho_{XW_1} - \rho_{XWold_1})} * X\,q1 * W_{dc1} + \frac{1}{(\rho_{WX_2} - \rho_{XWold_2})} X\,q2\, W_{dc2} \quad (15)$$

Total volume = $V_w + V_{Addln}$ (16)

From this the level of water in the drum is obtained. The heat transfer co-efficient of the two loops are calculated as mentioned below.

$$HTC1 = \frac{Q_{Gww_1}}{Q} \quad (17)$$

$$HTC_2 = \frac{Q_{GWW_2}}{Q} \quad (18)$$

where heat Q is obtained from [9]

$$Q = 100(Tmww_1 - T_{dr})^{3.57} P_{dr}^{\ 0.86} \quad (19)$$

Drum pressure is obtained from the following expression,

$$\frac{dP_{dr}}{dt} = \frac{\Delta M\,(\rho_W Hw - \rho_s Hs) - \Delta E(\rho_W - \rho_s)}{[[(\rho_{W2} - \rho_{W1})V_W + (\rho_{s2} - \rho_{s1})V_s] - (\rho_W Hw - \rho_s Hs) - (\rho_W - \rho_s)V_W \; [(\rho_{W2} - \rho_{W1})Hw + (H_{W2} - H_{W1})\rho_W + V_s((\rho_{s2} - \rho_{s1})Hs + \rho_s(H_{s2} - H_{s1})]]} \quad (20)$$

Simulation Results: The simulation is done under various operating conditions. The drum pressure and the level depends on heat input from evaporator and furnace, enthalpy of economizer and mass flow rate of steam[10]. The block diagram for controller is shown in Fig. 2 and simulation circuit for level control is given below in Fig. 3.

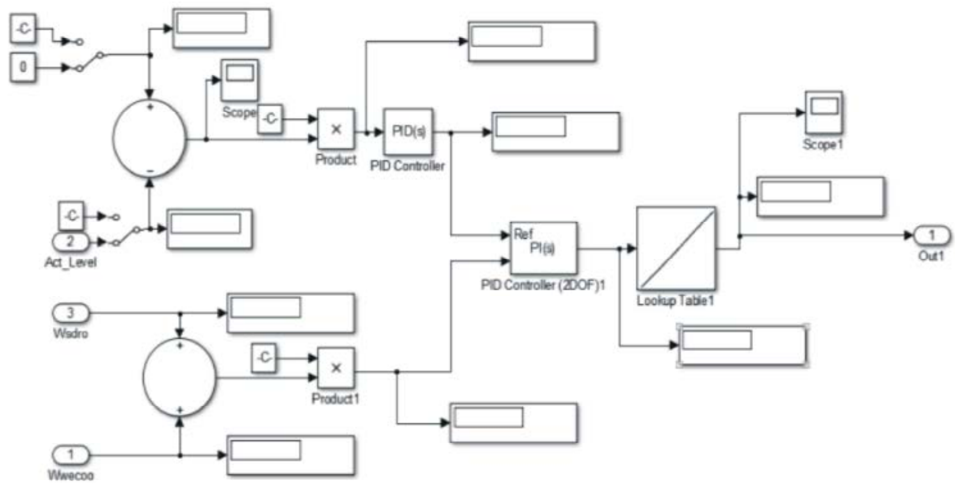

Fig. 3: Drum Level controller - Simulink circuit

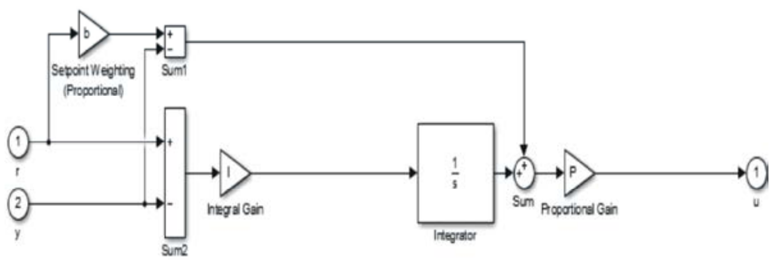

Fig. 4: PI controller - Simulink circuit

Table I: Parameter values of controllers

Parameter	PID controller	PI controller
K_P	0.005	1
K_I	0.00005	0.001
K_d	0.125	-
Set point	-	7.5

Based on the open loop response and using the Ziegler-Nichols method, the parameters of PID controller - K_P, K_I, K_D gain values are obtained.

$$u(t) = K_P \left[e(t)+ \frac{1}{T_i}\int_0^t e(t)dt + Td\frac{de(t)}{dt}\right] \tag{18}$$

where u(t) is the control variable, e(t) is the error signal and K_P, K_I and Kd the proportional, integral and derivative gain. The fine tuned parameter values of P, PI and PID controller are tabulated in Table I.

The set point weight for the cascade PI controller is obtained from the compensator formula and is shown in Fig. 4.

$$P[(br - y) + I\frac{1}{s}(r - y)] \tag{19}$$

where 'b' is set point weight, 'r' is the reference signal and 'y' is the actual signal.

Table II: Steady state data for a change in load

Parameter		Unit	Load (in%) 100% load	70% load	50%load
Drum Pressure	P_{dr}	Kg/cm^2	146.72	136.38	131.10
Steam flow rate	W_s	Kg/sec	99.02	72.13	54.95
Feedwater temperature	T_{eco}	°C	318	302	290
Heat from the combustor	Q_{GWW1}	Kcal/sec	21175	19647.92	15867.29
Heat from the evaporator	Q_{GWW2}	Kcal/sec	6615.8	2985.3	2274.39

The operational and steady state data for change in load is given below in the Table II.

10% Change in Throttle: When the demand increases, the throttle opening is increased so that the pressure in the drum decreases. Additional latent heat is required to increase the steam. Hence the volumetric flow of feed water has to increase. But the level in the drum increases instantly and then decreases gradually. This is due to the 'swell' phenomenon.

When the demand decreases, the throttle opening is decreased further and hence the pressure in the drum increases. The volumetric flow of feed water has to

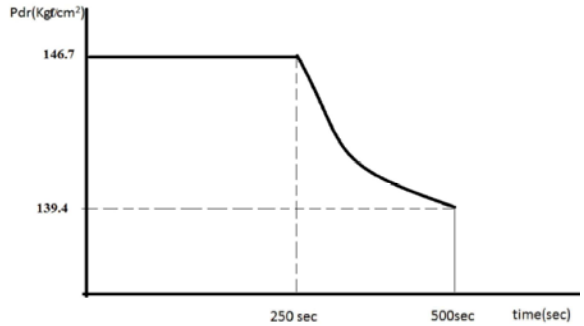

Fig. 5: Effect of drum pressure of circulation system of a CFBC boiler

decrease. But the level of water in the drum decreases instantly and then it increases gradually. This is due to the 'Shrink' phenomenon.

But this is predominant only with lower operating pressure. However, the 'Swell and Shrink' can be controlled by means of a closed loop system. The simulation is done for 500 seconds and a step input disturbance is given at 250 seconds. Based on the Fig. 5, the transfer function is obtained [1].

Ws changes from 99.02 to 106.67. Hence change in Ws(t) is given by R=7.65;

$\Delta Ws(s) = \frac{7.65}{s}$

Assume $\frac{\Delta Pdr(s)}{\Delta Ws(s)} = \frac{-K}{s}$

$\Delta Pdr(s) = \Delta Ws(s) * \frac{-k}{s} = -\frac{-7.65}{s} * \frac{-k}{s} = -7.65\frac{-k}{s^2}$

Hence $\Delta Pdr(t) = -7.65kt$

When t1= 250 sec, Pdr(t1)=146.7; and t2= 500 sec, Pdr(t2)=139.4 ΔPdr(t)= 7.3; t= t2-t1

t=250-500= -250 sec

$k = \frac{\Delta Pdr(t)}{-7.65*t} = \frac{7.3}{-7.65*(-250)} = 0.003817$

Transfer function of $\frac{\Delta Pdr(s)}{\Delta Ws(s)} = \frac{-K}{s} = \frac{-0.003817}{s}$

The response of drum pressure and level is given below for a disturbance in throttle valve. When the throttle position is increased, the pressure in the drum decreases and mass flow rate of steam increases. Initially there is an increase in the steam quality and then there it decreases.

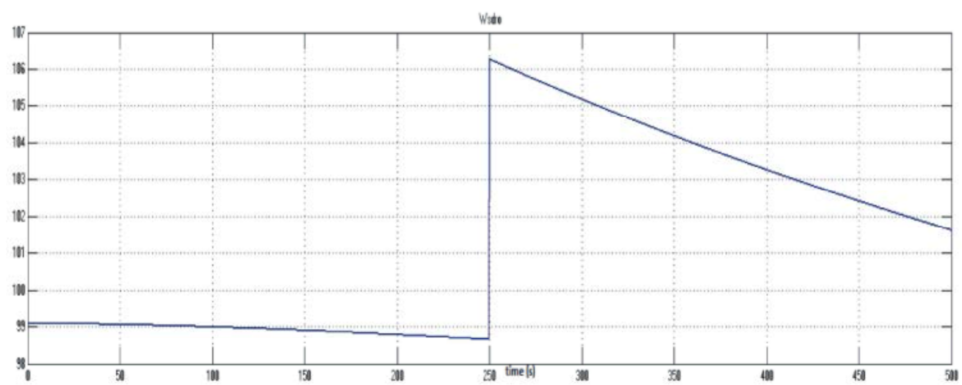

Fig. 6: Response of Ws for a step change in throttle

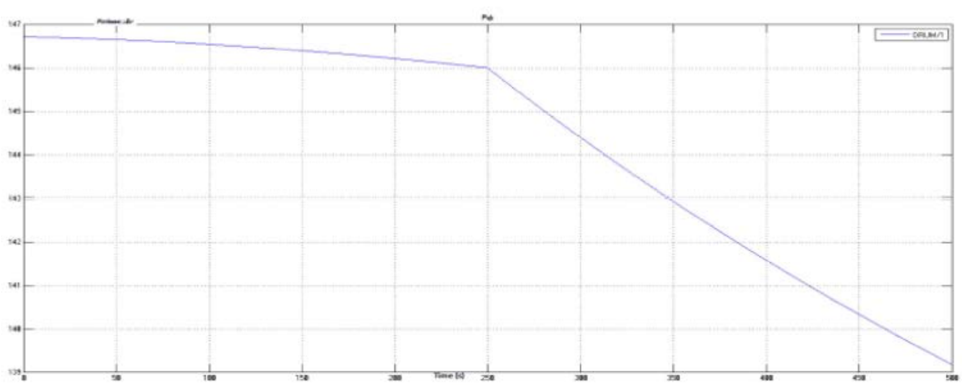

Fig. 7: Response of P_{dr} for a step change in throttle

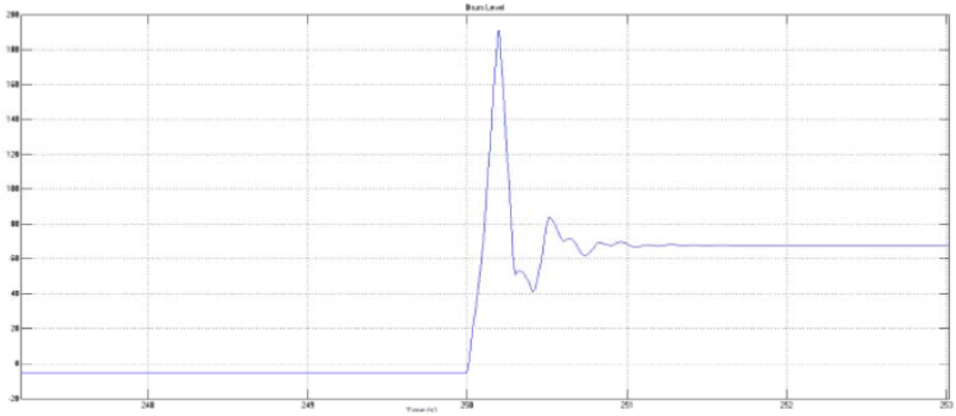

Fig. 8: Response of drum level for a step change in throttle

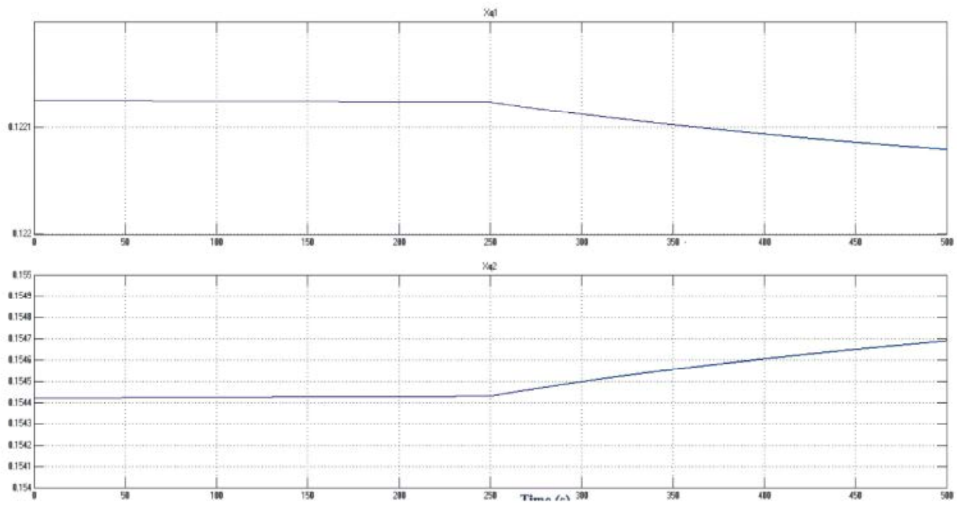

Fig. 9: Open loop response of X_{q1} and X_{q2} for a step change in throttle

The steam quality X_{q1} and X_{q2} increases initially and then it decreases when the throttle is increased. When a PID controller is introduced, the steam quality increases and then it decreases when a disturbance is introduced and it settles at a steady state value. Similarly the heat transfer co-efficient increases for an increase in throttle [6].

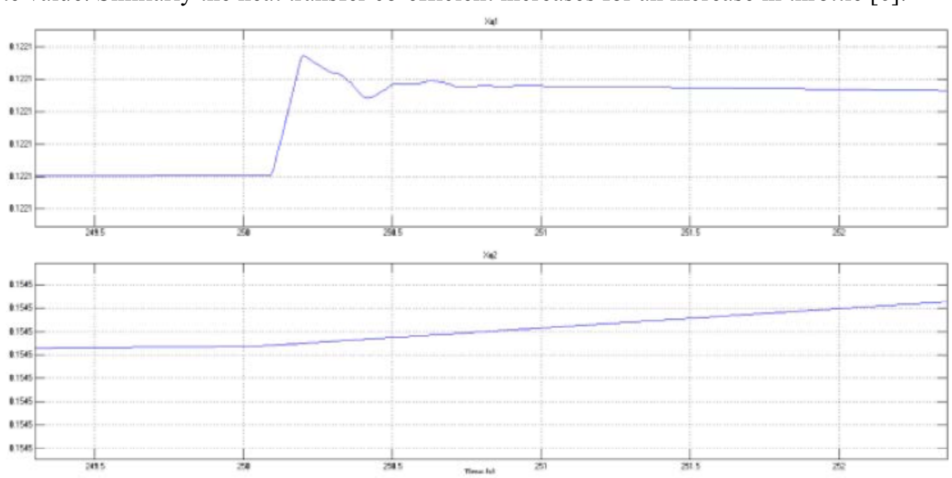

Fig. 10: Response of X_{q1} and X_{q2} for a step change in throttle with 3 element PID controller

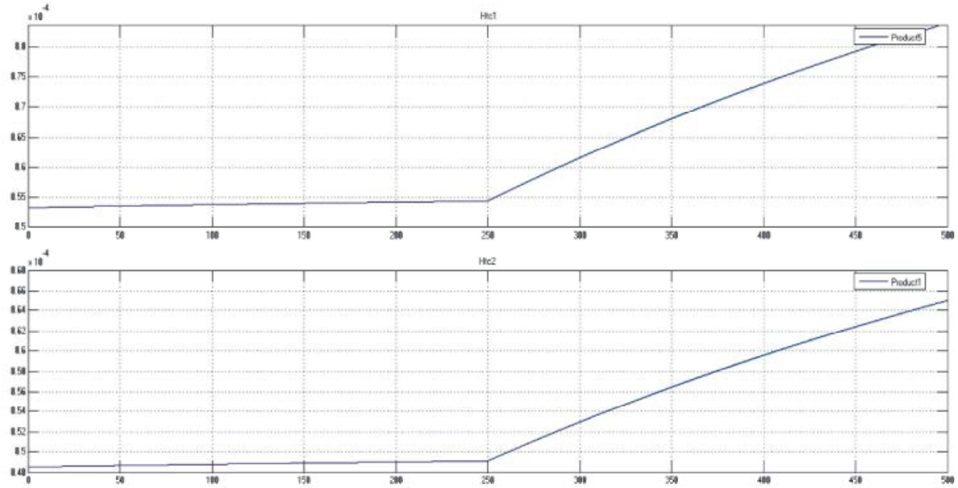

Fig. 11: Open loop response of HTC_1 and HTC_2 for a step change in throttle

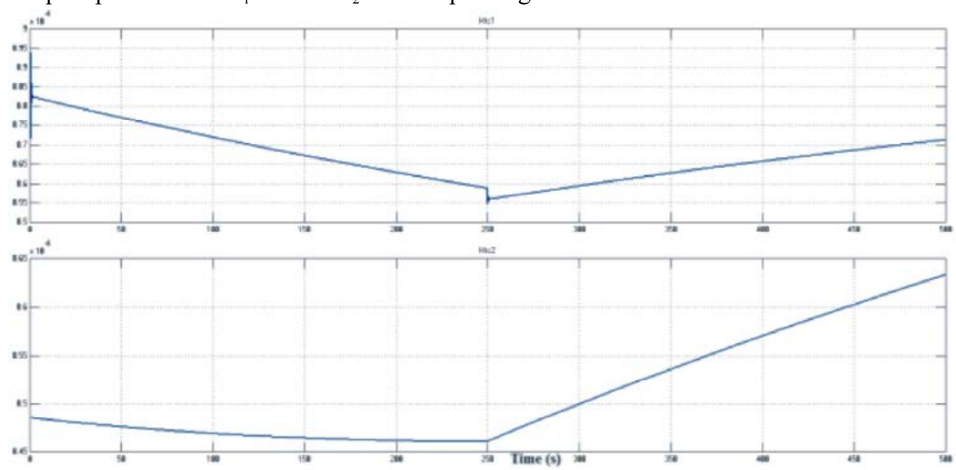

Fig. 12: Response of HTC_1 and HTC_2 for a step change in throttle with 3 element PID controller

10% Change in Heat Input: 10% change in heat input from furnace (Q_{GWW1}) and heat input from evaporator (Q_{GWW2}) is introduced as a disturbance [10].

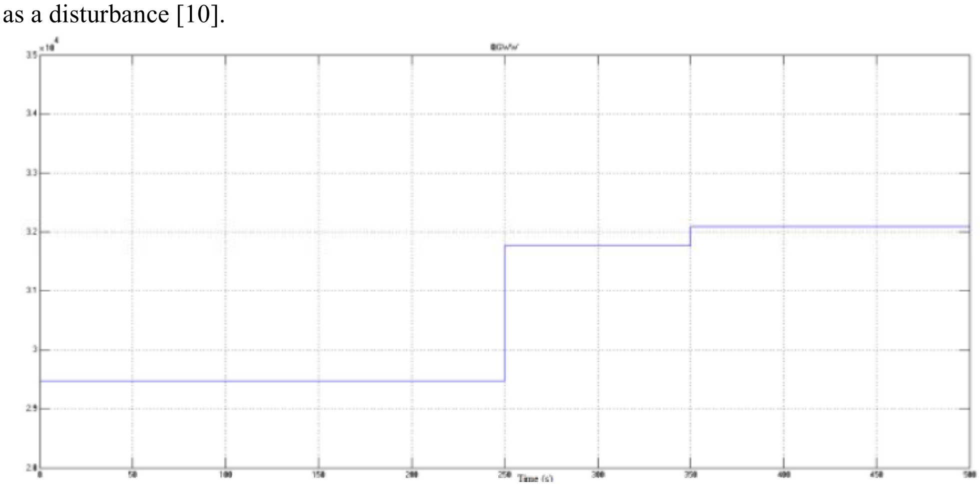

Fig. 13: Response of Q_{GWW} for a step change in heat input

When the heat input is increased, more water gets converted into steam and pressure has to increase. The drum level will also increase.

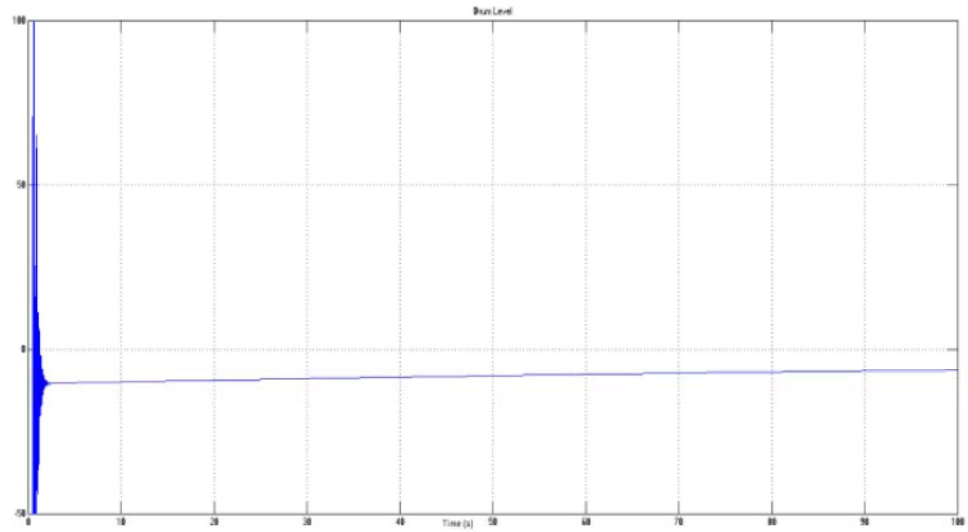

Fig. 14: Response of drum level for a step change in heat input

CONCLUSION

Careful attempt has been made to derive the mathematical model of boiler drum and feed water system of CFBC boiler using Matlab – Simulink environment. The boiler drum performance is observed in CFBC boiler for varied disturbance. Lower the drum operating pressures, higher will be the swell. Further the effect of swell is predominant during start-up conditions of boiler since the operating pressure is increased gradually from a lower value to a higher value. The swell is more as the pressure is less during starting which affects the performance of the boiler.

The simulation of the circulation system under different operating conditions has been investigated. For the disturbance of 10% change in mass flow rate of steam and heat input, drum pressure Pdr and level Ldr characteristics are manifested. The model obtained is intact even in open loop and further PI-PID controller is used to make the boiler a closed loop system. Increase in steam flow rate shows a decrease in drum pressure and increase in the level of the boiler which exhibits non minimum phase behavior. The controller responds to the plant quickly so that the swell is reduced. However the trip circuits meant for upper and lower level trip of boiler takes care of the overshoot which occurs during the arrest of swell/shrink. Increase in heat input increases drum pressure and level increases first and then it decreases.

ACKNOWLEGEMENT

The authors would like to thank the Dr.L.Sivakumar, Engineers of BHEL, Trichy and corporate R&D, Hyderabad for their support and discussions.

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