OVERCOMING THE SHRINK-AND-SWELL EFFECT IN WATER LEVEL CONTROL STRATEGY ON INDUSTRIAL BOILER-DRUM

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ABSTRACT

Power generation has become an increasingly competitive arena. The cost of operating power plants comes mostly from the fuel bill, which runs in the billions of dollars annually. In order to minimise the fuel bill and maximise plant efficiency, a plant's load-following capability must be optimised, i.e. to follow the demand of power closely. A great deal of attention has been given to the controller that regulates water level (and steam pressure) at the steam-generating unit – the boiler-drum. The control strategy is complicated by the non-linear and non-minimum phase characteristics of the boiler-drum. This paper illustrates our work in the optimisation of load-following scheme by applying a 3-element controller scheme to regulate the boiler-drum's water level. The controller is then cascaded with another feedback loop that regulates steam pressure. The results from the control scheme have shown considerable improvement over a typical boiler-drum's water level control strategy.

Keywords: *boiler-drum, shrink-swell, load-following, level control*

1.0 INTRODUCTION

The cost of running a 500 MW coal-fired unit can vary between USD$2,000 and USD$75,000 per day while the annual fuel bill is nearly USD$5 billion [5]. Waddington, et al. [5] showed that more than 99% of the cost in power plant operation comes from fuel – in this case, coal. The typical components of a power plant are furnace, boiler-drum, superheater and reheater, and turbine units. Figure 1 illustrates the boiler-drum with the downcomer and riser circulation tubes. The cylindrical drums are not heated. Rather, heat is supplied to the incoming water in the riser tubes by direct heat from the furnace gases. There are a large number of riser tubes in the drum-downcomer-riser circulating loop in order to maximise heat transfer. The downcomers are larger in size since no heat transfer takes place. Flow around the circulating loop can be either natural due to pressure difference or forced with pumps. In the design of the circuit, it is very important that sufficient circulation occurs at all times.

The cost of plant operation is mainly on the fuel consumption. In order to optimise operation, power generation has to follow power demand very closely, i.e. load-following [4]. The complication in the load-following scheme is mainly caused by the shrink and swell phenomenon that occurs when drum pressure changes [2, 4]. The controller action tends to react negatively due to the misleading shrink and swell effect. The control scheme that is adopted has to counter the effect of the shrink and swell phenomenon

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in order to optimise the cost of operating the power plant.

2.0 SHRINK AND SWELL PHENOMENON

Figure 1 shows the simplified diagram of the boiler-drum and downcomer-riser circulation loop. When power demand increases, steam flow rate is rapidly increased, causing the steam pressure to drop momentarily. This drop of pressure causes the air bubbles to increase in size and the water level to increase. The phenomenon is termed swell effect.

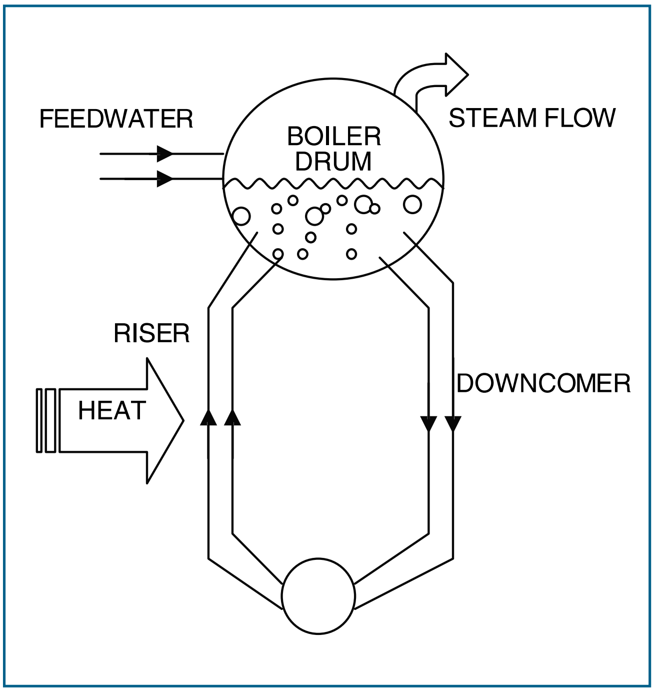

Figure 1: Drum-Downcomer-Riser Circulation Loop

The principle of mass balance, however, dictates that the increase of steam flow rate leaving the drum will cause reduction of the total mass inside the drum. Thus, by keeping the feedwater input constant, the mass of water inside the drum will eventually be decreased, causing the water level to drop. This is shown in the open-loop response in Figure 4. On the other hand, if steam demand is reduced, steam bubbles shrink initially and the water level will eventually increase due to the increasing mass of water and steam in the drum. The combined phenomenon is termed shrink and swell.

3.0 BOILER-DRUM DYNAMICS

Drum boiler model [1] is formed using the basic thermodynamics' mass and energy balance equations. Below are the state equations of the boiler-drum dynamics. The four states are: drum pressure p, total water volume V_{wt}, steam quality at the riser outlet α_{sd}, and volume of steam under the liquid level in the drum V_{sd}. These equations have been derived using mass and energy balances together. The resulting physical equations have then been manipulated into the following form.

$$
\begin{aligned}
&e_{11}\frac{dV_{wt}}{dt}+e_{12}\frac{dp}{dt}=q_f-q_s\\
&e_{21}\frac{dV_{wt}}{dt}+e_{22}\frac{dp}{dt}=Q+q_fh_f-q_sh_s\\
&e_{32}\frac{dp}{dt}+e_{33}\frac{d\alpha_r}{dt}=Q-\alpha_rh_cq_{dc}\\
&e_{42}\frac{dp}{dt}+e_{43}\frac{d\alpha_r}{dt}+e_{44}\frac{dV_{sd}}{dt}=\frac{\rho_s}{T_d}(V_{sd}^0-V_{sd})+\frac{h_f-h_w}{h_c}q_f
\end{aligned}
\tag{1}
$$

where the coefficients e_{ij} are given by

$$
\begin{aligned}
e_{11}&=\rho_w-\rho_s\\
e_{12}&=V_{wt}\frac{\partial\rho_w}{\partial p}+V_{st}\frac{\partial\rho_s}{\partial p}\\
e_{21}&=\rho_wh_w-\rho_sh_s\\
e_{22}&=V_{wt}\left(h_w\frac{\partial\rho_w}{\partial p}+\rho_w\frac{\partial\rho_w}{\partial p}\right)+V_{st}\left(h_s\frac{\partial\rho_s}{\partial p}+\rho_s\frac{\partial\rho_s}{\partial p}\right)-V_t+m_tC_p\frac{\partial t_s}{\partial p}\\
e_{32}&=\left(\rho_w\frac{\partial h_w}{\partial p}+\alpha_rh_c\frac{\partial\rho_w}{\partial p}\right)(1-\bar{\alpha}_v)V_r+\left((1-\alpha_r)h_c\frac{\partial\rho_s}{\partial p}+\rho_s\frac{\partial h_s}{\partial p}\right)\bar{\alpha}_vV_r\\
&\quad+(\rho_s+(\rho_w-\rho_s)\alpha_r)h_cV_r\frac{\partial\bar{\alpha}_v}{\partial p}-V_r+m_rC_p\frac{\partial t_s}{\partial p}\\
e_{33}&=((1-\alpha_r)\rho_s+\alpha_r\rho_w)h_cV_r\frac{\partial\bar{\alpha}_v}{\partial\alpha_r}\\
e_{42}&=V_{sd}\frac{\partial\rho_s}{\partial p}+\frac{1}{h_c}\left(\rho_sV_{sd}\frac{\partial h_s}{\partial p}+\rho_wV_{wd}\frac{\partial h_w}{\partial p}-V_{sd}+m_dC_p\frac{\partial t_s}{\partial p}\right)\\
&\quad+\alpha_r(1+\beta)V_r\left(\bar{\alpha}_v\frac{\partial\rho_s}{\partial p}+(1-\bar{\alpha}_v)\frac{\partial\rho_w}{\partial p}+(\rho_s-\rho_w)\frac{\partial\bar{\alpha}_v}{\partial p}\right)\\
e_{43}&=\alpha_r(1+\beta)(\rho_s-\rho_w)V_r\frac{\partial\bar{\alpha}_v}{\partial\alpha_r}\\
e_{44}&=\rho_s
\end{aligned}
\tag{2}
$$

The parameters notations are, e.g., ρ_m is specific density of metal.

Parameters

V : volume
ρ : specific density
u : specific internal energy
h : specific enthalpy
t : temperature
q : mass flow rate
Q : heat input
α_r : steam quality
$\overline{\alpha}_v$: steam volume ratio
C_p : specific heat of metal
m_t : total mass for metal tube and drum

Subscripts

s : Steam
w : Water
f : feedwater
m : Metal
d : Drum
dc : Downcomer
t : Total

4.0 MODELLING WITH SIMULINK

This model is implemented in Matlab in the form of an S function, in order to be used in Simulink to build the non-linear system in block diagrams. The working S function is given in [3]. The S-function is then masked to become a 4 input, 2-output MIMO system shown in Figure 2.

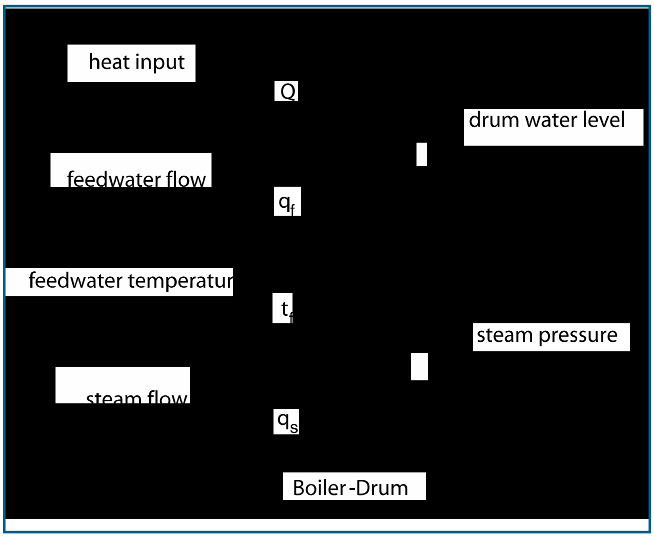

Figure 2: Masked MIMO System of a Drum-Boiler Using S function

The output equation for water level in Figure 2 is

$$l = \frac{V_{wd} + V_{sd}}{A_d}$$, where

V_{wd} = Volume of water in drum
V_{sd} = Volume of steam in drum
A_d = Surface area of drum's circular side
(Section 5.2)

5.0 OPEN LOOP TESTS

Open loop tests are performed to verify the correct behaviour of the boiler-drum model. Sections 5.1 and 5.2 elaborate how the verification was conducted.

5.1 Mode of Operations

In order to work around the non-linear behaviour of the plant along its operating region (i.e. 0 - 100 percent load), it will be subdivided into three different regions – determined by three different load levels. The values shown in Table 1 are determined by the power plant engineers in such a way that they represent the most common operating modes of the boiler-drum. The PID-based control scheme will only work if we treat the non-linear system as being linear (locally) at each region.

Table 1: Mode of Operations

	Low Load	**Medium Load**	**High Load**
Pressure, p (Mpa)	8.70	9.35	10.00
Power Level (MW)	24.00	80.00	136.00

5.2 Open Loop Responses

To illustrate the dynamic behaviour of the model, we will simulate the responses-to-step changes in the inputs. The model was simulated using the following parameters, based on Oresund Power Station in Sweden: m_t = 300,000 kg; m_r = 160,000 kg; m_d = 20,000 kg; A_d = 20 m^2; V_d = 40 m^3; V_r = 37 m^3; V_{dc} = 11 m^3; V_{sd0} = 8 m^3; C_p = 650; C_{fw} = 4.18; k_e = 25; b = 0.3. The steam

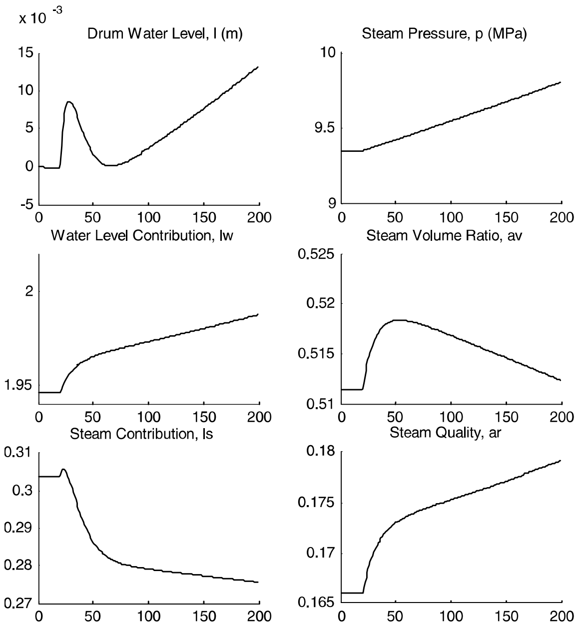

Figure 3: Responses to a 10 kg/s Step Change in Fuel Flow Rate at Medium Load

tables used in the simulation are approximated using quadratic approximation. The quadratic approximation implementation is as in [3].

Figure 3 and Figure 4 illustrate the step responses of the boiler-drum's output and some internal state variables. As described earlier, the drum variables are non-linear. The figures show initial increase of drum water level due to shrink and swell phenomenon.

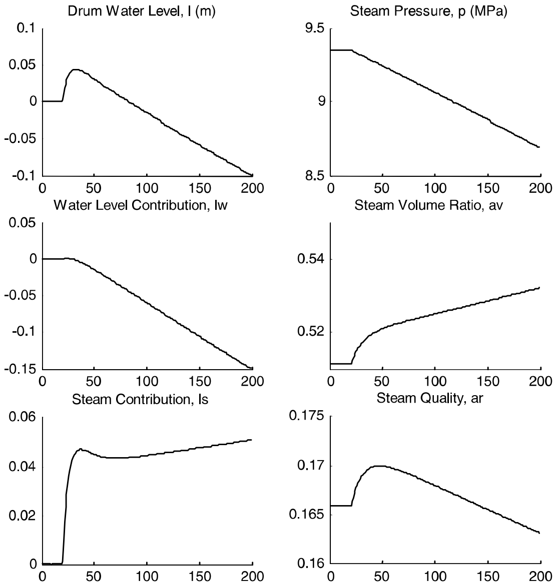

Figure 4: Responses to a 10 kg/s Steam Flow Rate Changes at Medium Load

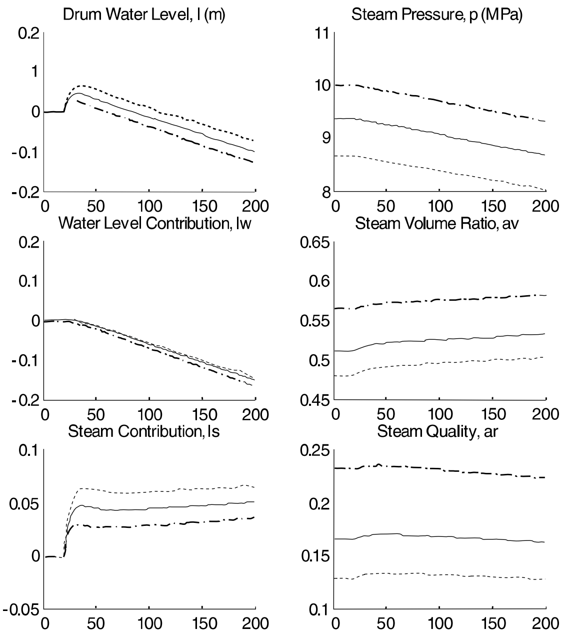

Figure 5: Responses to 10 kg/s Steam Flow Rate Change at Low (Dotted), Medium (Solid) and High (Dash-Dot) Load

Figure 5 shows the comparison of responses to 10 kg/s steam flow rate change at different operating conditions. The swelling effect on the water level is largest at low load, as illustrated by the greatest overshoot. This is mainly caused by the greater variation of steam contribution at low load than at high load.

The non-minimum phase characteristics of the drum water level prove to be non-trivial. Any control scheme that we use to control the water level will be affected by the non-minimum phase characteristics. In addition, the varying sensitivity of the parameters at different operating condition will impose extra difficulty to the control design.

6. SINGLE ELEMENT CONTROL

Single element feedwater control uses only the drum level process variable as feedback. The measured drum level is compared to the drum level setpoint. When the difference deviates from zero (i.e. non-zero error), the feedwater control valve will be adjusted by the proportional-plus-integral (PI) controller to compensate for the error. The integral component of the controller regulates the drum level error to zero.

This control method ensures that the water level stays as close as possible to setpoint value.

This scheme performs satisfactorily under constant or small changes in load (steam flow) and saturation pressure in the drum. If the steam flow increases faster than the heat input, the drum pressure drops quickly and causes the saturation condition to change rapidly from one state to another [1]. This phenomenon is known as swell effect because of the swelling of steam bubbles underneath water surface. This would cause the water level to rise initially. On the contrary, a sudden decrease in steam flow would cause the steam bubbles to shrink and the water level to drop. If the transient is not too severe, the level will eventually return to the setpoint. In these circumstances, more complicated control is necessary.

7. THREE-ELEMENT CONTROL

Three-element control scheme (Figure 6) uses feedwater flow measurements and steam flow measurements as inputs to the controller in addition to water level feedback signals. This improved control scheme adds predictability by anticipating change in load by using steam flow as feedforward and feedwater flow rate as feedback regulation.

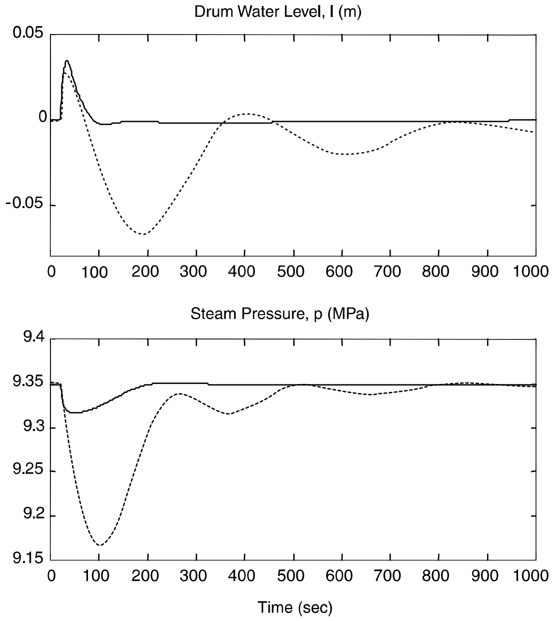

Figure 7: Single-Element Controller (Dotted) And 3-Element Controller (Solid) Step Responses To 10 kg/s Change Of Steam Flow Rate On Boiler-Drum Model At Medium Load

Figure 7 shows the comparison between single element control and three element control results on water level and steam pressure. The improvement shown by the improved control method is very significant. There is hardly any oscillation shown by the solid line, except during the shrink and swell (non-minimum phase) effect.

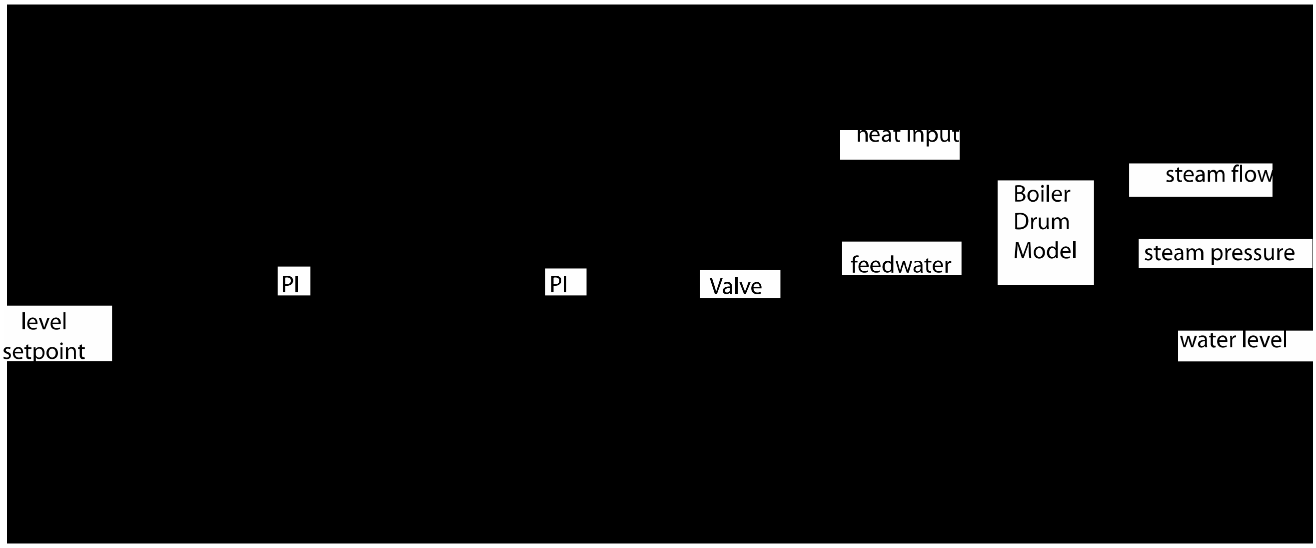

Figure 6: Three-Element Controller Structure. Heat Control Loop is Not Shown

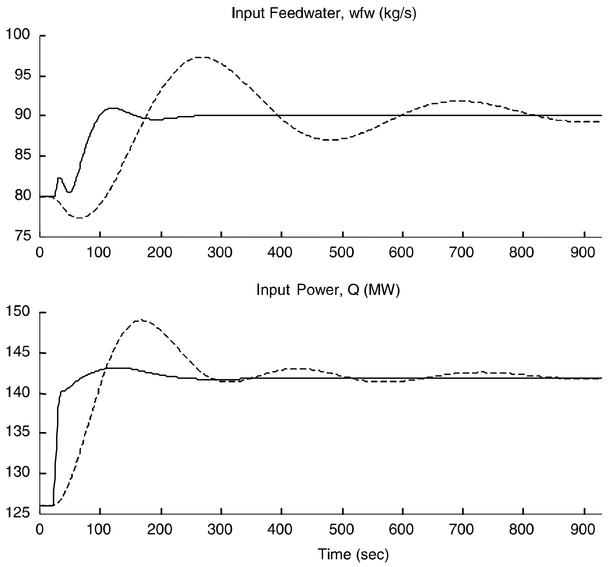

Figure 8: Single-Element Controller (Dotted) And 3-Element Controller (Solid) Control Inputs To 10 kg/s Change Of Steam Flow Rate On Drum-Boiler Model With Delayed Input At Medium Load

Figure 8 shows the feedwater and power input corresponding to the water level and steam pressure responses in Figure 7. The three-element controller input feedwater eliminates the initial reduction shown by the dotted line. This effect is due to the feedforward (prediction) steam flow signal, which increases feedwater flow even when water level is increasing. The controller knows that water level will eventually decrease. Therefore, it didn't react to the misleading changes in water level. The oscillation in input feedwater right after the step input is due to the multi-cascaded structure of the controller feedback and feedforward loops.

8. CONCLUSION

The simple, pure feedback single-element PID controller performs satisfactorily to regulate water level error to zero when operating level stays constant. In today's power industry, competition has driven power plant operators to maximise profit by optimising power generated-power demanded ratio. In order to follow the changing demand, power plant boiler has to change its steam production rapidly; therefore the load-following problem.

Three-element control scheme is a good alternative to the simpler single element control structure. The performance shown by Figure 7 indicates how three-element controller is a much better alternative.

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