Control and Operability of Economiser Bypass in Once-through Steam Generators

E. Boje*

* School of Electrical, Electronic and Computer Engineering, University of KwaZulu-Natal, 4041, South Africa, (e-mail: boje@ukzn.ac.za)

Abstract: The paper considers the control and operability issues in using bypass of sections of the heat exchanger to manage thermal oscillations observed in start-up operation of once through steam generators.

1. INTRODUCTION

In once-through (Benson) power boilers, there are problems with thermal oscillations during unsteady operation, including start-up, hot start-up, shut-down, low-load operation and load changes (Maffezzoni, & Ferrarini, 1989, and Eitelberg & Boje, 2004). These thermal oscillations slow down the start-up operation. They are of concern for plant life, for example because of thermal stress on thick walled vessels and circulation pump trips, and may impact on the dynamic performance of the boiler. Conservative operational policies as a result of concerns for plant life may reduce the economic efficiency of the power plant (e.g. because of slow start-up procedures). There have recently been changes in the electricity market driven by power trading operations, large scale deployment of renewable sources with variable output, etc. This has meant that power boilers designed for constant, base-load operation are now operated in low-load and varying-load conditions more of the time.

A typical trace of the evaporator inlet temperature during a hot start is shown in Fig. 1. During the first 60 minutes, the power is at 10% of maximum continuous rating (MCR). Thereafter it is increased to 70% of MCR from 60 to 180 minutes. During the start-up, the mass flow-rate into the evaporator must be higher than the evaporation rate because of the trade-off between the requirement for sustaining minimum flow in the evaporator tubes to avoid departure from nucleate boiling and the requirement for slow increase in the heating rate to avoid thermal stress, especially on thick walled vessels. (In Fig. 1 there is constant, minimum flow up to about 160 minutes.) As a result, the boiler is not in once-through (Benson) mode and not all water leaving the evaporator is vapour (steam). The water is recirculated to the inlet where it is mixed with cooler feed water. This results in near limit cycle behaviour as illustrated by the poorly damped oscillations with a period of around 8 minutes in the first hour and a period of around 24 minutes in the middle period shown in Fig. 1. This behaviour is caused by plugs of hot (recirculation) water and cold (feed) water circulating around the evaporator.

Quantification of costs of fitting/retrofitting, value of savings (which depend on operations) and licensing issues are beyond the scope of the paper. The following areas of savings may be realised if the thermal oscillations can be eliminated:

Start-up costs: Smoother thermal behaviour will allow faster start-up, with close tracking of the thermal rate limits specified by the original equipment manufacturer for the thick walled pressure parts. This will shorten the time to synchronisation and may save on expensive fuel oil support required during low load operation and other operating costs. Thermal oscillations result in oscillation of the collecting vessel and this may cause the circulation pump to trip. This retards the start-up procedure which results in financial penalties for missing contracted generation schedules.

Plant life and maintenance: Thermal cycling may result in stress cracking of thick walled vessels over time.

More reliable operations: There is a real risk of tripping of the unit during unsteady operation. In addition, sustained low-load operation below the Benson point (i.e. with circulation system operating) may be possible if tighter control is in place.

![Evaporator inlet temperature](image)

Fig. 1: Measured hot start-up temperature behaviour at evaporator inlet (economiser output)

This paper investigates the possibility of damping the thermal oscillations discussed above using a by-pass of the economiser as shown in Fig. 2. Fig. 2 omits much of the detail but shows the circulation system which is active in low load operation. The economiser is a heat recovery heat exchanger that precedes the evaporator and uses cooler flue gas as its heat source. In normal operation, the bypass valve
is shut and the economiser improves the overall efficiency by pre-heating feed water in a counter flow arrangement with the flue gas. In unsteady operation the steel and fluid mass of the economiser can be used as an energy storage element and bypass can modulate the evaporator inlet temperature. Care is required around mechanical design issues as the economiser may require minimum flow rates to ensure pressure and flow distribution in parallel paths and to ensure adequate cooling of the tubes. For this reason, and to keep cost down, the bypass valve would typically only pass a fraction of the flow when fully open.

\[
\frac{d\left(m_i h_i + m_p c_p T_p^i\right)}{dt} = (1 - \alpha) m_i \left(h_i^{i-1} - h^i\right) + H^i(P) \left(T_p^i - T_f^i\right) 
\]

where,

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_i)</td>
<td>mass of water in section [kg]</td>
</tr>
<tr>
<td>(m_p)</td>
<td>mass flow rate of water through the section [kg/s]</td>
</tr>
<tr>
<td>(h^i), (h^{i-1})</td>
<td>specific enthalpy of water in section (i) and (i-1) respectively [J/kg]</td>
</tr>
<tr>
<td>(T_p^i)</td>
<td>Tube (steel) temperatures for section (i) [°C]</td>
</tr>
<tr>
<td>(T_f^i)</td>
<td>Flue gas temperatures for section (i) [°C]</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Bypass valve position [0,1]</td>
</tr>
<tr>
<td>(c_p)</td>
<td>Steel specific heat capacity [J/kg/K]</td>
</tr>
<tr>
<td>(H^i(P))</td>
<td>Heat transfer coefficient for section (i) as a function of power set-point [J/s/K]</td>
</tr>
</tbody>
</table>

In (1) it is assumed that there is no energy storage in the flue gas so the temperature of the gas at each section is determined algebraically from the flue gas temperature into, and heat energy absorbed in the previous section. The model parameters were calibrated using manufacturer’s data and online measurements. Note that in the design and simulation that follow, the feedback effect of re-circulation is not considered. Instead, the economiser inlet conditions for simulation are derived from plant measurements. Reducing oscillations in the evaporator inlet temperature will reduce the feedback of temperature fluctuations to the economiser inlet caused by the re-circulation system. (This is the purpose of the bypass!)

The linearised model of the economiser from incremental bypass valve action to incremental outlet temperature, \(P(s) = \Delta T_{out}(s)/\Delta \alpha(s)\), is a negative gain, lead element – a step increase in valve position will result in an immediate reduction in the outlet temperature followed by a partial recovery as the water in the evaporator heats up due to the reduction in flow rate. (This argument does not hold under all operating conditions as the economiser inlet temperature occasionally is above the outlet temperature in upset conditions. Because of the heat addition when the boiler is fired, this situation is never sustained and the corresponding linearised models with change in the high frequency sign are not used in design.) The linearised model of the economiser inlet temperature to the evaporator inlet temperature, \(P_d(s) = \Delta T_{in}(s)/\Delta T_{out}(s)\), is low-passing for the economiser through flow and direct feed-through (with mixing) for bypass flow. The Bode plots of a selection of plant models over normal operation with bypass in the range of 0% to 30% total flow are illustrated in Fig. 3. Note that the linearised models at each operating condition, \((P, P_d)\), are ordered pairs.
3. CONTROL SYSTEM SPECIFICATION AND DESIGN

The proposed control configuration is illustrated in Fig. 4. Using a band-passing control with no reference results in attempting to control the band-passed output temperature to a zero with offset commanded to the by-pass valve to give control output rangeability in both directions. Note that an alternative view of the control problem (with identical result) would be to construct a low-pass version of the outlet temperature as a “reference” and then use a valve position control scheme (Shinskey, 1988) to drive the valve to the offset value in steady-state.

3.1 Specifications

1) The control system must reject variations in the economiser inlet temperature at the evaporator inlet. Based on observation of the start-up behaviour shown in Fig.1, the frequency range, $[10^{-3}, 10^{-2}]$ rad/s is appropriate. Higher frequency disturbances are partially rejected by the low-pass behaviour of the economiser. The specifications on closed loop behaviour, $T_{y/d}(s) = P_d(s)/(1 - G(s))$, are used to illustrate the paper are shown in Table 1. Notice that the specifications are modest as a result of experiments with different performance. High gain required to achieve higher performance result in the input saturating, rendering the control useless.


<table>
<thead>
<tr>
<th>$\omega$ [m.rad/s]</th>
<th>0.3</th>
<th>0.7</th>
<th>1.0</th>
<th>2.0</th>
<th>4.0</th>
<th>10</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>T_{y/d}(j\omega)</td>
<td>$ [dB]</td>
<td>-1</td>
<td>-1.5</td>
<td>-2</td>
<td>-4</td>
<td>-8</td>
</tr>
</tbody>
</table>

2) To maximise the economiser efficiency, the bypass valve position should as close to zero as possible in the quiescent state. This will be achieved by use of a wash-out to reject low frequency signals and an appropriate valve offset/bias arrangement. The bypass system will be forced closed in normal boiler operation by a manual/programme over-ride.

3) The controller should use minimum effort in order to avoid saturation, reduce valve wear and thermal stress at the junction between the bypass and economiser outlet flow. For example, if a 5 K variation in temperature at a particular frequency must result in control effort of no more than 0.1; $|T_{y/d}(j\omega)| = |GP_d/(1-GP)| \leq 34$dB. This specification is used for all frequencies.

4) General robust stability margins are achieved by specifying, $|S(j\omega)| = |P/(1-GP)| \leq 3$dB $\forall \omega$.

5) Hard saturation of the bypass valve will make the control system inoperable. In order to map arbitrary controller outputs into a finite range of inputs with soft saturation, an arctangent function and valve offset is used at the controller output. In the example, actuator signals of $[0, 0.3]$ are allowed so the control signal is mapped via $u_{out} = \arctan(ku_{in})/k + 0.15$, $k = \pi/0.3$ and hard saturation is included in the integrator associated with the slowest controller mode at twice the actuator limits.

3.2 Design

Because of the plant uncertainty, the quantitative feedback theory (QFT) design philosophy of Horowitz (see Horowitz, 1991 for a review) with associated Matlab® based tools (Borgesani, Chait, and Yaniv, 1998). The ordering of plant linearisations ($P, P_d$) are taken into account by the design software. Figs. 5-7 show the bounds on the nominal loop transfer function, $GP_0$, for an arbitrarily selected plant, $P_0 \in [P]$ for sensitivity, disturbance rejection, and input limits respectively.

The controller design is

$$G(s) = \frac{50s}{(1000s + 1)(1500s + 1)}.$$  

The achieved nominal loop transfer function, $GP_0$, is illustrated in Fig. 8. The controller design has infinite gain margin which is important as hard or soft saturation of the actuator is expected. The controller’s low-frequency washout ensures that the steady state by-pass output equals the operator commanded offset.
3.3 Achieved performance

The achieved performance of the design is illustrated in Fig. 9. Simulations shown in Fig. 10 illustrate the attenuation achieved by control action compared to the situation without bypass. Control action is shown in Fig. 11.

It is observed that there is a serious trade-off between preventing saturation of the control input and rejecting the effect of economiser inlet temperature fluctuations. The performance in rejecting large, low frequency oscillations between 60 and 120 minutes depends on the bypass valve not reaching the saturation limits. If more wash-out is used to keep the valve near the offset position, this reduces the gain available to reject low frequency disturbances.
Fig. 10: Simulated evaporator inlet temperature with (solid) and without (dashed) by-pass

Fig. 11: Bypass valve movement. Note the hard and soft saturation

4. DISCUSSION AND CONCLUSION

There is great merit in an industrial plant in having a simple, robust controller, designed to work over the entire operating envelope. This has been achieved in this study but there may be scope for scheduling the controller depending on the measured economiser inlet and outlet temperatures if the improvement in performance warrants the increased complexity.

The simulations presented in Section 3 indicate that modest levels of controlled by-pass are effective in damping temperature oscillations in the evaporator inlet. In the plant wide feedback effect (not illustrated in the simulation), reduced inlet temperature oscillations will reduce oscillations in the mass flow rate of hot water re-circulated from the evaporator output to the economiser inlet and this will further ease the control problem. In other words, the practical performance on a plant is expected to be better than that shown in the simulation of the economiser alone because this simulation does not included plant-wide feedback effects.

Acknowledgement
This work is supported by ESKOM (www.eskom.co.za) and by the National Research Foundation of South Africa (www.nrf.ac.za). Their support is gratefully acknowledged.

REFERENCES