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Using a Computational Fluid Dynamics Model to Unlock the Potential for More Reliable Once-Through Steam Generator Steam Quality Control

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Abstract

Reliable steam quality measurement is important for reliable operation of an OTSG. Even though the quality measurements from the inline devices are frequently calibrated against measured samples, the online measurements show a considerable amount of drift from recent calibrations. False low steam quality measurements may lead to undetected dryout and potential damage. False high steam quality measurements may lead to spurious OTSG trips, and the subsequent hazards of lighting a major piece of fired equipment. Reliable steam quality measurement and control becomes even more important as we push for higher thermal efficiency, such as with rifled tubes, and operate closer to the edge of dry-out. The theory behind a standard Venturi-based steam quality measurement will be reviewed first. The accuracy of common steam quality correlations will be compared under steady state operation. A Computational Fluid Dynamics simulation for the water side dynamics will then be used to demonstrate how "shrink" and "swell" manifests along the tube length of an OTSG tube pass. These processes will be shown to affect the actual and measured steam quality for the pass, reminiscent of how shrink and swell affects drum level dynamics in drum boilers. These water-side dynamics are used to justify process control strategies that target more uniform steam quality.

Introduction

SAGD depends on reliable steam supply to satisfy the injection steam demand, and hence maximum oil production. Current OTSG control strategies use the measured steam quality to trim the firing rate. If the measured steam quality is inaccurate, there is the potential to either overfire the OTSG (and cause damage), or underfire the OTSG and sacrifice potential bitumen production. If the steam quality controller causes a rapid change in the firing rate, then there is the potential for a trip caused by a poor air-fuel ratio.

Since the online steam quality measurement is an inferred value of the actual quality, it is necessary to calibrate the measured quality against an actual quality from each of the tube passes. Based on the high frequency of steam quality sampling and recalibration, there appears to be mistrust in the accuracy of the online steam quality measurement. This prompts even more frequent sampling and recalibration.

Better control is obtained by either matching the setpoint better, or by taking less control action and introducing less disturbance to the rest of the process. More reliable steam quality measurement and control will immediately permit less frequent sampling and calibration of the OTSG steam quality venturis. There will be less risk of damage caused by overfiring, and an overall increase in steam generating capacity (or bitumen production) or the facility. A reduction in the control action will reduce the risk of spurious trips caused by poor fuel-air ratio control. Obtaining these benefits without significant capital expenditure would come produce a high return on investment.

This paper considers how the OTSG operating conditions impact the accuracy of the measured steam quality. A sophisticated CFD model of the water side is used to illustrate this. The results from the CFD simulation are then used to create a model based control application. The control application is tested within the CFD simulation, and provides optimal control of the steam quality, given the discrepancy between measured and actual steam quality.

Inferred steam quality

A typical water side flow configuration and firing control strategy is shown in Figure 1. A steam master controller issues the desired total feed water flow rate setpoint and firing rate setpoint. The feed water flow rate for each OTSG tube pass is measured and controlled. The steam quality for each pass is inferred from the pressure drop across individual Venturis and the measured feed water flow rate. The firing rate is trimmed to maintain the average steam quality on setpoint.

The general principle for inferring the steam quality is derived from the Venturi equation for measuring a flow rate. A Venturi is used to determine the flow rate of a fluid with a known density by measuring the pressure drop:

$$\dot{m} = K\sqrt{\rho \, \Delta P}$$

Where rho is the known fluid density, DP is the measured pressure drop, K is the meter constant, and mdot is the flow rate. This concept is applied to the inference of steam quality through the assumption that the outlet mass flow is equal to the inlet mass flow. Therefore the homogeneous outlet density is calculated from

$$\rho = \left(\frac{\dot{m}}{\Delta P} \right)^2$$

Given the calculated density and the operating pressure, the inferred steam quality is obtained from steam tables.

The concept defined above is part of a larger group of wet gas flow rate correlations. Steven (2002) compared the accuracy of different wet gas flow correlations at different vapour qualities. A result, duplicated from Steven (2002), is shown in Figure 2.

The results from Steven suggest that the correlations that are commonly used for inferring steam quality (such as Homogeneous, Murdock, Chisholm and de Leeuw) are both accurate and repeatable over the 70 – 80% quality range that is typical for an OTSG. Calibration at steady operating conditions should permit reliable and repeatable steam quality measurements from either a venturi or a flow nozzle. Frequent calibration of the measured steam quality against a sample should not be required.

Concerns about the accuracy of the inline steam quality measurement are likely related to the unsteady operation of the OTSG, where the mass flow out of the OTSG is not equal to the inlet mass flow of water. A fit-for-purpose Computational Fluid Dynamics (CFD) model of the water-side of the OTSG was developed to identify the role of unsteady operation on the inferred steam quality.

Description of the CFD Model

An OTSG behaves as a heated pipeline according to the following physical processes:

1. Conservation of Mass. Water flows through a volume of tube and displaces the downstream fluid.
2. Conservation of Energy. As the fluid flows through the tube volume, the water picks up heat from the hot side through the tube wall. This increases the enthalpy of the fluid.
3. Equation of State. As the fluid enthalpy rises, the specific volume of the fluid also rises. As a subcooled liquid, the amount of expansion is small, but the expansion is much larger where steam is generated.
4. Hydraulics. The pressure drops as the fluid flows through the tubes, until it reaches the specified pressure at the outlet.

A fit-for-purpose second-order accurate finite volume scheme was developed to model the transient plug flow of water and steam through the OTSG tube volume, where there is a specified heat flux (firing rate) along the volume of the tube.

Figure 3 shows how the enthalpy rises as the fluid moves through the OTSG tube volume (the operating line), and also shows where the fluid reaches the boiling point. This is shown for an initial firing rate (which produces 70% quality steam) and a final firing rate (which produces 80% quality steam). The intersection of the operating line with the boiling point defines liquid volume that is held in the OTSG. Since there is a change in liquid holdup volume between the two steady state conditions, it follows that the mass flow out of the OTSG is not equal to the mass flow into the OTSG between these two steady operating conditions. The change in firing rate produces a change in liquid volume. This is analogous to the boiler swell that occurs in a drum boiler.

The actual and measured steam quality responses to a step increase in the firing rate is shown in Figure 4.

The actual steam quality rises gradually over the 300 seconds, which is the residence time in the liquid filled section of tube volume. The measured steam quality, however, rises immediately after the change in firing rate. The increased firing rate causes the boiling point to move further up the tube volume, and decreases the water volume in the OTSG. Over 300 seconds, the mass flow out of the tube pass is higher than the mass flow of water entering the tube pass. This is inferred as an increase in the steam quality. This response demonstrates that the measured steam quality deviates from the actual steam quality during changes in OTSG operation, such as firing rate, water feed rate and operating pressure. The measured steam quality only matches the actual quality when operating conditions are stable, and sufficient time is given to permit the disturbance to travel through the liquid filled section of the OTSG tube volume.

Model Based Steam Quality Controller

Model based control strategies are used for managing boiler swell in drum boilers. These strategies permit tolerable swings in drum in order to prevent rapid changes in feed water flow rate, which are known to cause overheating and damage to superheating sections.

The CFD model for the OTSG is used to develop a model-based control strategy. The objective of the new control strategy was to permit tolerable swings in the actual steam quality, and to eliminate rapid changes to the manipulated firing rate.

Rapid changes to the firing rate may result in localized overheating, spurious trips caused by BFW pass flow deviation, high steam quality or even a poor fuel-air ratio and a firebox detonation.

The model based controller was added to the CFD simulation to test the effectiveness of the new control strategy. The following disturbances were used to demonstrate the performance of the strategy, and to compare with the performance of a standard PID controller:

1. Increase in steam quality setpoint at t = 50 sec.
2. Decrease in water flow rate at t = 1000 sec.
3. Decrease in water temperature at t = 2000 sec.

Both the ability to keep the actual steam quality on setpoint, and the rate-of-change of firing are measures of success for the model based controller.

Results

Figure 5 shows the trends for the measured and actual steam quality where the model based controller is used to modulate the firing rate. The increase in steam quality setpoint is obtained with a slow, deliberate increase in the firing rate (maximum rate of change 0.1% per second, or 6% per minute), and achieves 80% of set setpoint change within 320 sec. The sudden reduction is water feed rate causes the measured steam quality to suddenly read 7% too high even though there is no immediate increase in the actual steam quality. The model based controller takes the same slow, deliberate action to reduce the firing rate (over 50 seconds), and gradually reduces the measured steam quality. The actual steam quality during this event deviated from the setpoint by at most +1.3, -1.4%. The sudden drop in feed water temperature causes the flow rate through the radiant section to “stall”, and results in the actual steam quality to rise above 90%, while the measured quality reads false and dips low to 70%. This false reading does tend to cause over-firing, but the model-based controller avoids the peak overfiring at the driest conditions.

The traditional PID controller behaves far more aggressively for all of the disturbances, as shown in Figure 6. The increase in steam quality setpoint is achieved 50 seconds, but the actual steam quality responds over 270 seconds. This marginal increase in response time for the actual steam quality is obtained at the expense of both a much more rapid increase in firing rate (1% per second, or 60% per minute), and subsequent oscillations in the firing rate. Both of these could result in spurious trips on BFW pass flow deviation or spurious trips based on the fuel-air ratio. The sudden reduction in water flow rate causes the PID controller to quickly reduce the firing rate by 2% over 2 seconds. The measured steam quality approaches setpoint within 70 seconds, which is marginally faster than 84 seconds for the model based controller. Note that the actual steam quality deviates by -1.5%, +0.6%, which is not significantly different from the much slower response from the model based controller. The sudden drop in feed water temperature, and false low steam quality measurement causes the PID controller to overfire by 6% where the OTSG is operating at the driest conditions. This poses a larger risk of equipment damage caused by an inappropriate control action.

The model-based controller maintains the actual steam quality on setpoint as well as the traditional PID controller, but does so with one tenth of the firing rate change.

Discussion

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Conclusions

Work by Steven (2002) suggests that common steam quality correlations are both repeatable and accurate. The CFD modeling presented in this paper demonstrates that unsteady operating conditions will cause the inferred steam quality measurement to read false. Proper calibration of the steam quality measurement can only be accomplished where samples are obtained with the OTSG operating in a steady manner for at least five minutes.

The model based steam quality controller results in significantly smaller disturbances to the firing rate, and maintains the actual steam quality within tolerable limits, compared to the typical PID controller. Smaller disturbances to the firing rate is beneficial because it avoids problems with fuel-air-ratio-control, and interactions with the BFW pass flow controllers. The reduction in potential control interaction is a significant improvement over the conventional PID control that is currently used. The reduction in control interaction will reduce the amount of spurious trips, allow for tighter control of steam quality, and will permit the OTSG to operate at higher rates and higher steam quality.

Nomenclature

The List symbols here

References

1. Steven, R.N., (2002) *Wet gas metering with a horizontally mounted Venturi meter*. Flow Measurement and Instrumentation, Volume 12, Pages 361 - 372.

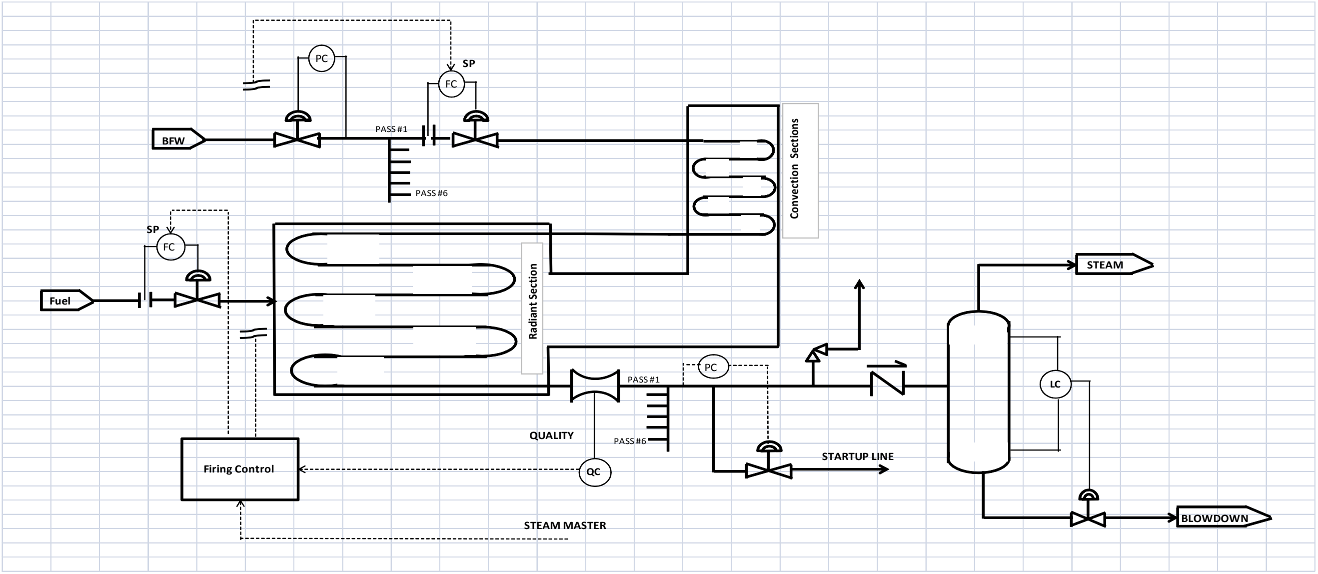


Figure 1. Sketch of a typical water side configuration for an OTSG.

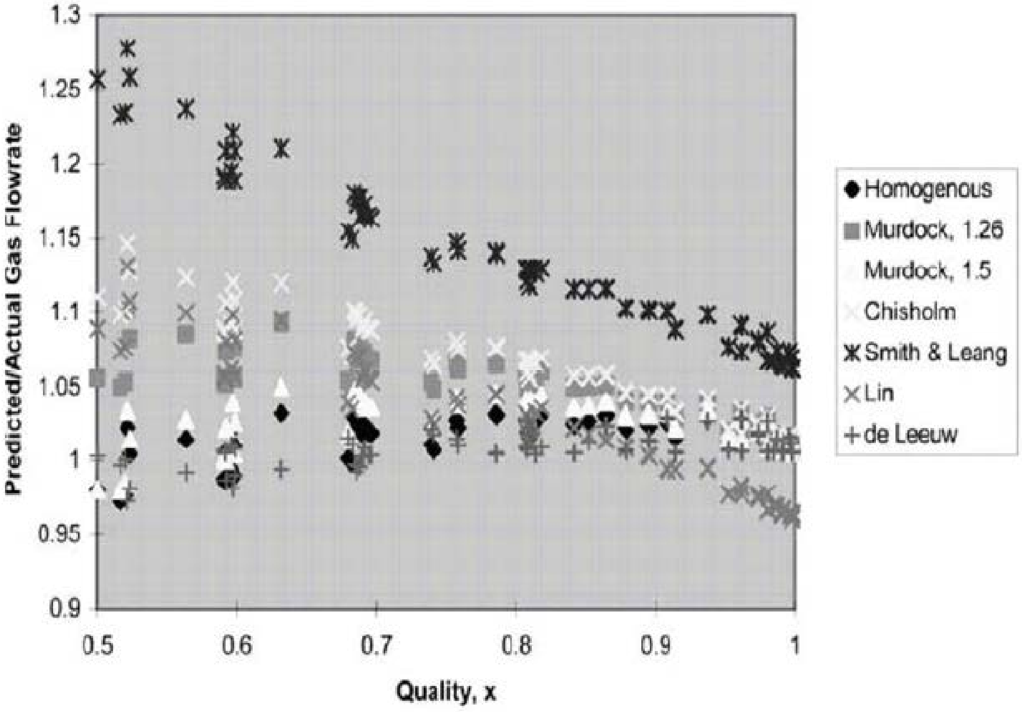
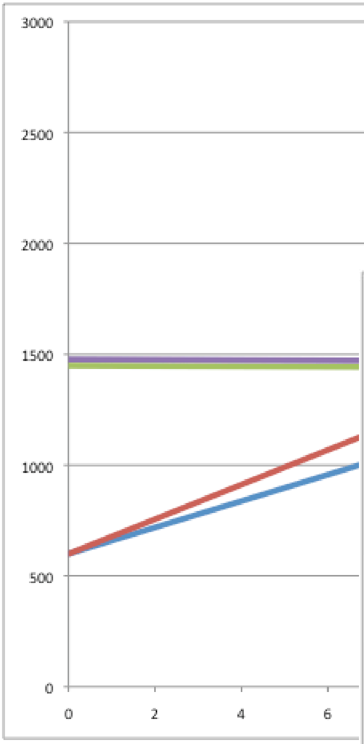


Fig. 57 :Comparison of correlations at 60 bar, Steven (2002).

Figure 2. Comparison of two-phase flow correlations for the prediction of gas flow rate (Steven, 2002). These correlations are typically used for OTSG steam quality correlations, and suggest that the common steam quality correlations are both repeatable and accurate.



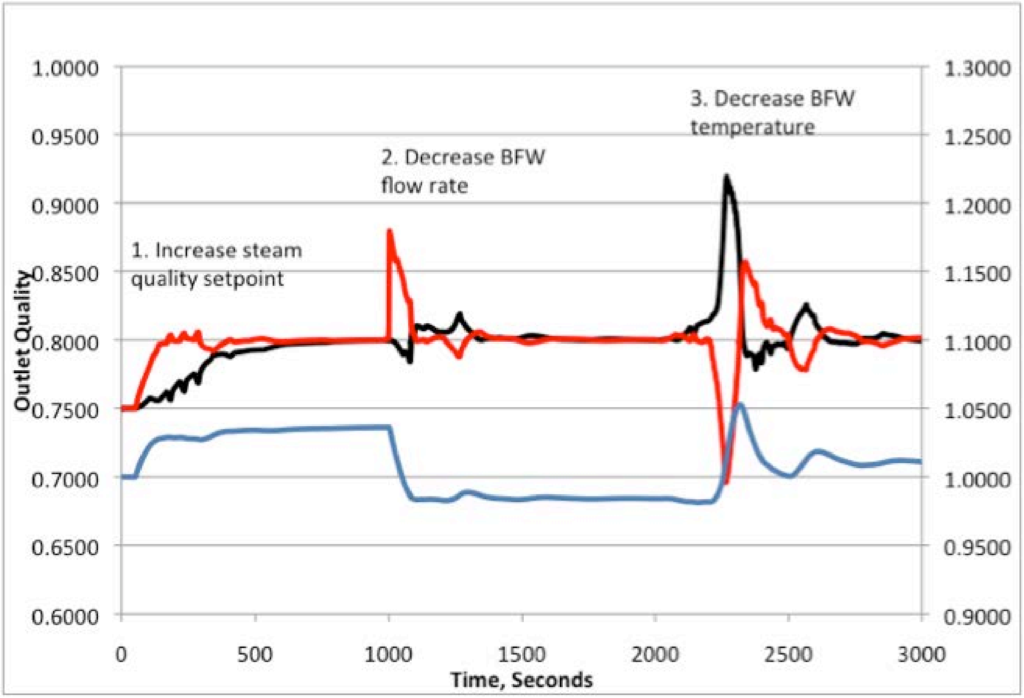


Figure 3. Schematic of the steady s
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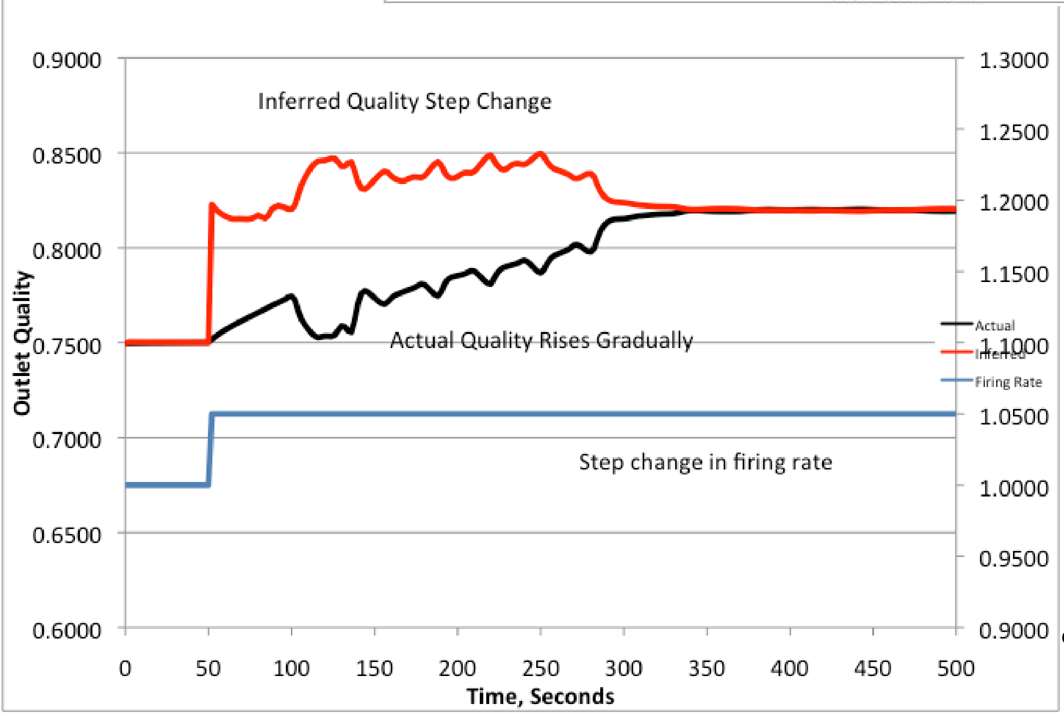

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Figure 4. CFD simulation results for the model based steam quality controller. Three disturbances are considered: a) increase in steam quality setpoint, b) decrease in feed water flow rate, c) decrease in feed water temperature.

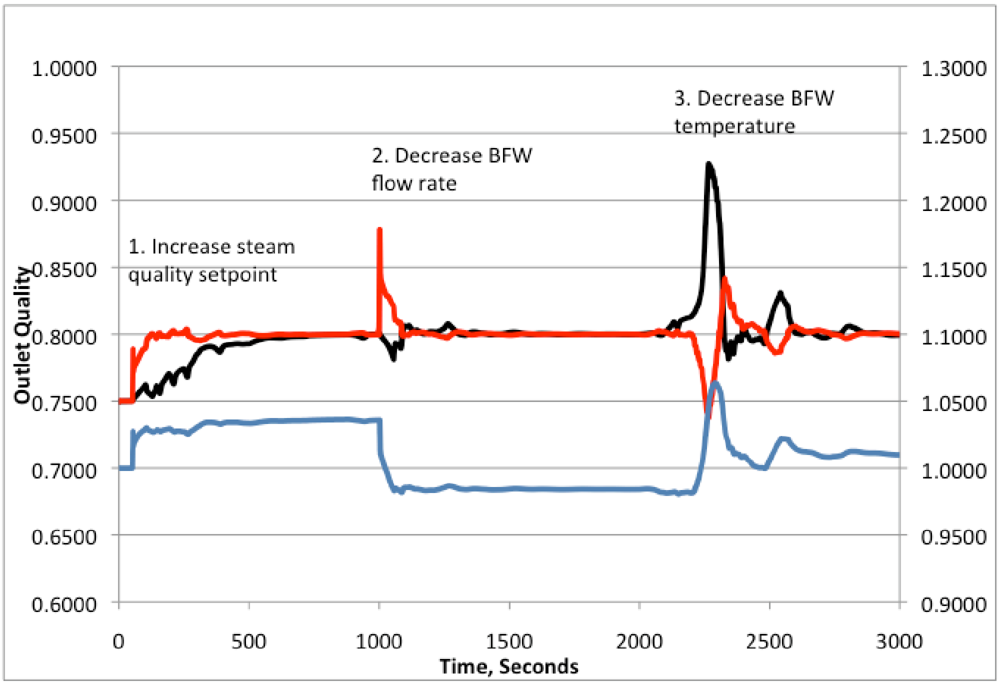

Figure 4. CFD simulation results for the typical PID steam quality controller. Three disturbances are considered: a) increase in steam quality setpoint, b) decrease in feed water flow rate, c) decrease in feed water temperature.