Avoiding Short Term Overheat Failures of Recovery Boiler Superheater Tubes

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Abstract

Recovery boilers are particularly vulnerable to short term overheat failures of superheater tubes during startup due to the potential for fouling (and the suppression of heat transfer) of these surfaces and the need to quickly restart these units in order to minimize downtime. Also failure of superheater tubes has a significant negative impact on unit safety as there is a risk of these failures creating a critical exposure due to secondary failure of screen and water wall tubes.

This paper will discuss a package developed to reduce these risks by properly managing the startup process. This management is based on the observation that tube clearing can be identified via a distinct temperature trend. Using these "tube-clearing events" or TCEs along with a flue gas temperature measurement device (i.e. optical pyrometer) to limit the firing rate until the management system has identified that all tubes have cleared after every pause in recovery boiler steam generation (boiler trips, and shutdowns) is an effective way to minimize the risk of short term overheat of the superheater tubes.

The management system is structured similar to a burner management system (BMS) where permissive have to be satisfied and authorization levels are established with provisions for interlock bypasses. Each startup event is thoroughly documented for later review. It can be run in this strict manner or can be configured as an advisory system only based on the preference of the end-user.

One critical observation made during development is that trips during the startup process can present the most risk as there is a tendency to quickly increase steam flows after these events. There is a need to maintain discipline regarding the ramp-up after all pauses in steam generation.

Keywords

Recovery Boilers, Corrosion, Temperature measurement, Reliability, Safety

Background

During the normal startup of a recovery boiler a ramp up curve is followed (Fig. 1 shows a curve for a 1500 psig/100 bar recovery boiler), this curve is established by the OEM of the recovery boiler and ensures that the heat-up curve of the pressure part components does not result in excessive stress. Following this heat up curve does not ensure that all of the tube loops in the superheater have been cleared of condensate that collects in the lower tube bends during any downtime, additional criteria need to be imposed to ensure condensate removal. All of this condensate must be removed prior to exposing these tubes to high furnace temperatures. The condensate present in the lower tube bends prevents the flow of steam through these tubes and severely compromises the heat transfer downstream of the loop where the condensate has collected, this is illustrated in Fig. 2.

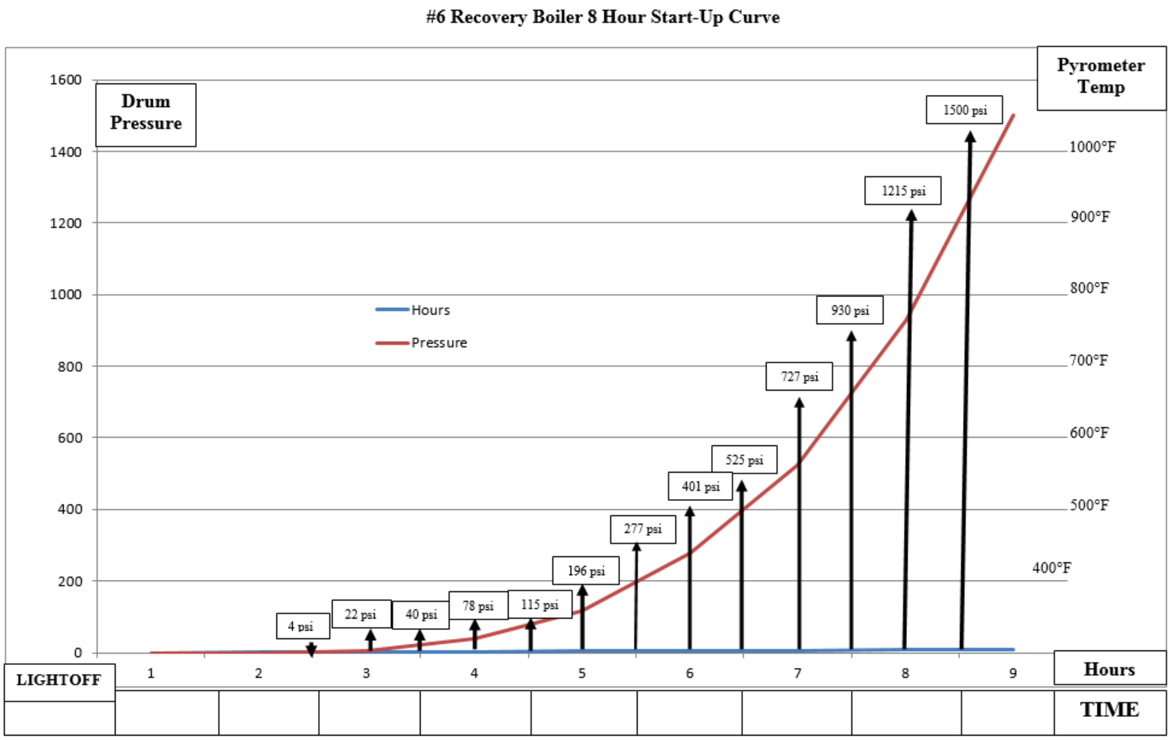

Fig. 1 – Typical Startup Curve for a Recovery Boiler (Pressure on left axis in psig, an estimate of the pyrometer temperature at the furnace exit is shown on right axis)

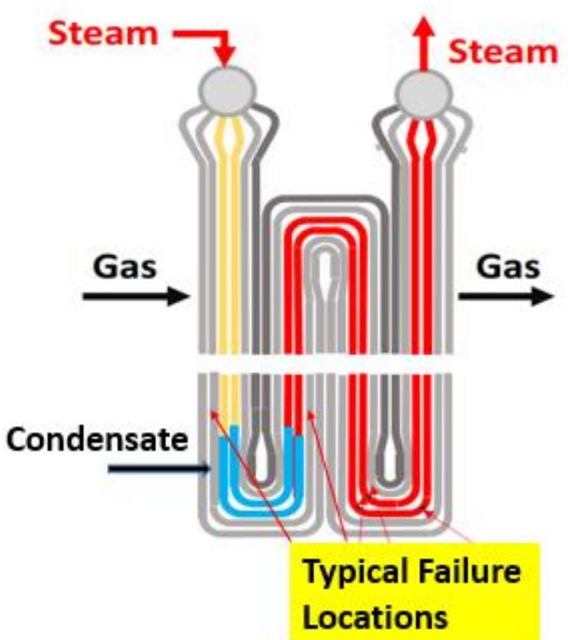

Fig. 2 – Location of condensate versus failure locations

Operators of recovery boilers use a variety of means to determine if the tubes have deared. Most recovery boilers have thermocouples installed on the outlet of the superheater loops for monitoring purposes. Commonly these thermocouples are monitored to see that they have reached a threshold temperature that past experience has shown to indicate all condensate has been removed in a loop. This can be a complex process as there are often in excess of 250 thermocouples to monitor on a large recovery boiler.

In order to facilitate the dearing of these tubes the operators may manipulate the pressure in the superheater by opening and dosing the superheater relief valve (also referred to as the startup valve or electromatic relief valve) this is often termed "burping" the superheater. On some recovery boilers, especially those with limited pressure drop over the superheater, it can take many hours to dear all of the tubes. Ensuring that all tubes have deared often requires reviewing multiple data screens and this process is prone to error.

Another significant risk factor is that often recovery boilers are on the critical path for outages and there is considerable time pressure on getting the recovery boiler back online. A particular problem is the restart of a recovery boiler in a fouled condition. The slag on the outside of the superheater tubes will restrict heat transfer and this often makes the task of dearing the tubes much more difficult and in some cases more difficult to monitor using a simple temperature target as indication the tube has deared.

The consequence of not following proper procedure can be very significant. What can happen is that a short term overheat can occur on a superheater tube loop above the location where condensate remains in a tube, or on the same loops upstream or downstream of the condensate location. Most commonly this occurs on a radiant superheater, that is located over the furnace cavity as the lower loops of these tubes are exposed to high radiative heat flux that can raise the skin temperature by 25-75^{o}C. The following quote is taken from a paper by David French[1]:

The simplest explanation for all "short-term" overheating failures is: when the tube metal temperature rises so that the hoop stress from the internal steam pressure equals the tensile strength at elevated temperature, rupture occurs. For example, in a super-heater of SA192 tubes, with a designed metal temperature of 800^{o}F, the ASME Boiler and Pressure Vessel Code gives the allowable stress at 800^{o}F as 9,000 psi. If the tube-metal temperature should rise to a temperature of around 1300^{o}F, the hoop stress would be equal to or slightly greater than the tensile strength at 1300^{o}F, and failure would occur in a few minutes.

An example of a tube that failed via short term overheat is shown in Fig. 3.

Fig. 3 – Short term overheat failure of Superheater tube

This is by no means the only possible consequence, warping of tubes may occur without failure, this could include breaking of tube attachments (with possible tube damage) as adjacent tubes may operate at widely different temperatures. These type of failures may go unnoticed following start-up. Typically, a tube rupture due to a short term overheat will result in an immediate shutdown of a recovery boiler. But there have been cases where these types of tube leaks go unrecognized for a period of time[2] and in these cases it is possible that secondary tube failures for screen tubes and water wall tubes could occur, this would be a critical exposure and could risk a recovery boiler explosion due to smelt-water reactions. Failures have also been seen where the initial tube rupture results in the ruptured tube striking adjacent steam cooled and water cooled tubes and then causing leaks in these tubes.

What this paper will cover is a tool developed by the authors specifically designed to monitor and manage this process to reduce the risk of these types of failures. A description of the principle behind this software and examples of its use will be provided. Also discussed will be some lessons learned during the first implementation of this software.

Description of System

Goals of a Superheater Startup Management System

Prior to developing the software portion of this system we carefully considered what the goals would be and how we would best design this tool to manage this process.

We identified four issues with current methodologies:

1. It is often not clear that a tube has cleared by applying simple criteria like a threshold temperature;
2. Tracking that each tube has cleared and keeping a record of this with a large number of thermocouples can be a complex and data intensive process prone to errors;
3. It can be unclear what the roles and responsibilities of the operators, shift managers, and area mangers are in this process;
4. Looking at historic data can be very difficult with many mill information systems, so looking back at a particular start-up to determine root causes of failures can be cumbersome;

Benefits of Superheater Startup Management System

If we were able to design and implement a system that addressed the identified issues, then we identified the following benefits: 1. Avoidance of risky start-up practices where tubes are subjected to high heat flux without proper cooling resulting in short term overheat damage; 2. A training tool for operators to better understand how to monitor the recovery boiler during start-ups; 3. An easily accessible historic record of how a start-up was done and how the various steps in the process were checked off. This is comparable to a BMS system for starting an auxiliary fuel burner.

Overall Description of System

The system described in this paper is the subject of U.S. Patent (US9541282 B2). We refer to it internally as SHOP (Superheater Overheat Protection). The system has three separate components:

1. Superheater terminal tube thermocouples – a number of considerations need to be made when installing this portion of the system, namely what fraction of the terminal tubes need to be instrumented and how is the data collected. Generally, it is cost prohibitive to add thermocouples to every terminal tube so some subset of the tubes is typically instrumented. Most important to instrument are the outermost tubes in the radiant superheater sections, these are most vulnerable to short-term overheat. But inner loops can also be at risk on a radiant superheater and even superheaters shielded from the lower furnace radiation can be subjected to high temperatures. It may also be more difficult to clear shielded loops. It is well worth the cost to ensure that the thermocouple data is collected with a PLC dedicated to this task and that this PLC is linked into the mill information system;

2. Furnace outlet temperature monitoring – we have found that optical pyrometers are well suited for this purpose and tended to be more reliable than thermoprobes. Ensure that the optical pyrometer is specifically designed for this duty and that it is looking at the furnace gases, not the wall temperatures;
3. Software to manage the detection of “tube-clearing events” (TCEs) and that also includes proper authority levels and data historian features. This includes options in the software to configure the system specific to how the staff prefers to manage the startup process.

Details of the Software

This section will describe in more detail the key features of the software and how it addresses the needs identified. The application can be implemented on a Windows based PC or Server with minimum requirements of (Core i7 (or equivalent) or later (64-bit); RAM: 8 GB; Screen Resolution: 1024 x 768 pixels; Drive: 500GB). The PC must be linked to the device collecting the thermocouple data and the optical pyrometer, additional data such as steam flow rate, pressure and temperature, and liquor firing rates also need to be provided using the OPC standard.

Detecting Tube-clearing Events

A fundamental feature of the software is the logic necessary to detect a TCE. This is a much more definitive means of verifying that the condensate has been removed from a tube then by simply tracking tubes reaching a threshold temperature. It is possible for the terminal thermocouple on a superheater loop to reach a high temperature without the condensate being removed from the tube, in fact this is often exactly what happens in the case of a tube failure.

A TCE has a very specific fingerprint in a time versus temperature plot. A specific example is shown in Fig. 4. Notice how the temperature rapidly increases, this is typically 25-75^{o}C (50-150^{o}F) over a few minutes starting from the current terminal tube temperature in the penthouse (this is closely related to the current saturation temperature of the water circulating in the boiler tubes). This is followed immediately by a drop in temperature of 10-20^{o}C (20-40^{o}F) over a few minutes. This characteristic behavior is due to the steam located upstream of the condensate pushing through the last of the condensate, much like an old style coffee percolator. This steam is superheated at the pressure upstream of the condensate due to the flow stagnation. The last remaining condensate is then carried out of the tube to the superheater outlet header. The steam temperature is then reduced temporarily as the flow rate of the steam increases through the tube.

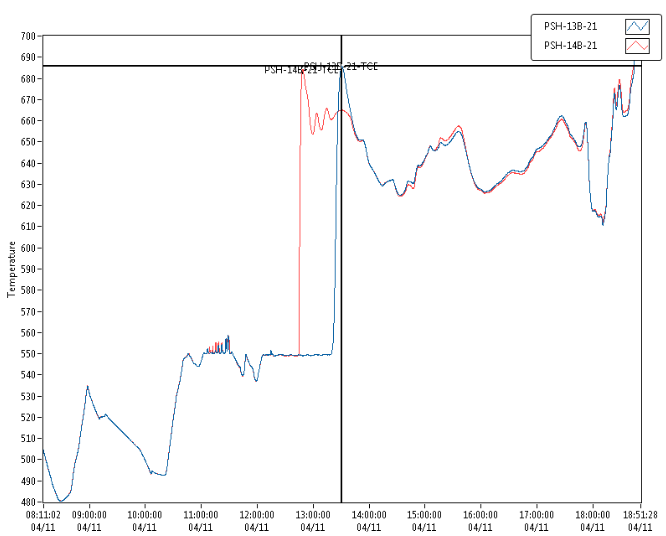

Fig. 4 - Example of “tube-clearing event” (TCE) on two primary superheater tubes (note that temperature is in degrees F).

Note that it is important to not confuse these TCEs with normal variability in the tube temperature due to changes in firing rate in the boiler. From a practical standpoint this can be determined by also tracking auxiliary fuel firing rates and by examining the slope of the temperature versus time plot, TCEs have a higher slope than temperature increases due to increased firing rates. Also TCEs end at temperatures in excess of the current saturation temperature of the steam drum.

Operating States

It is important to track the current operating state of the boiler in order to determine when to activate the monitoring system. Anytime there is a stoppage in total fuel firing to the boiler ("Boiler Trip") the system must be activated as this will risk the formation of condensate in the lower tube bends of the superheater. The various possible operating states are shown in Fig. 5. The system is active only during the startup state. Proper triggers for the transition between each state must be determined and configured in the software.

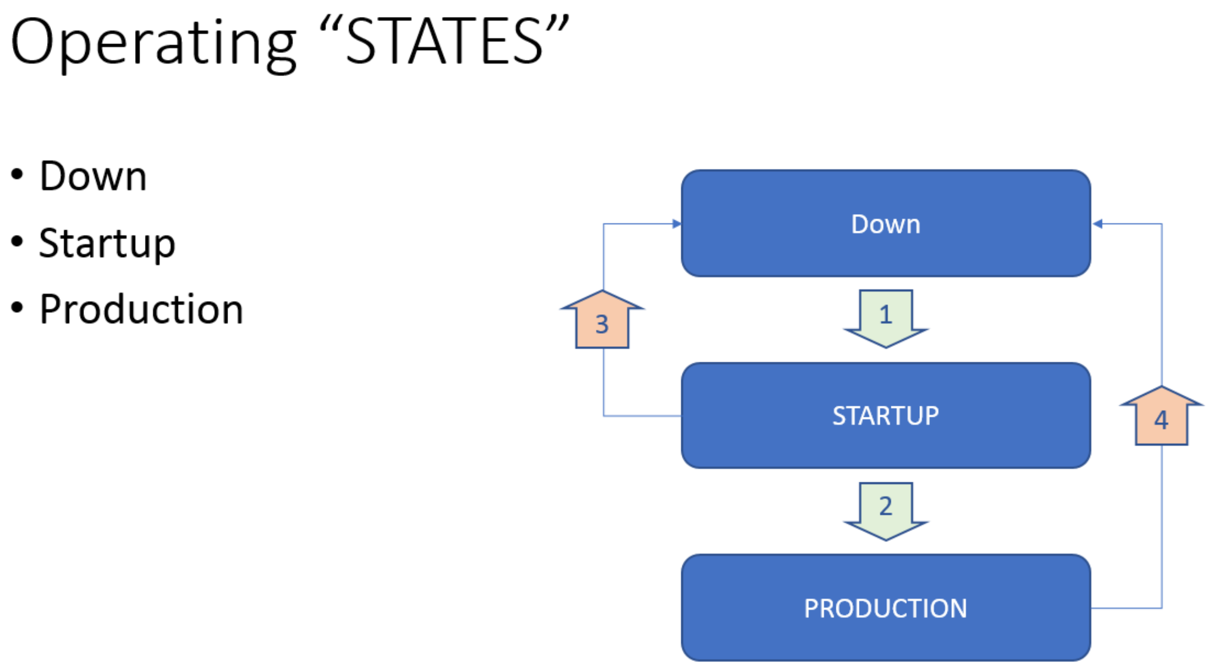

Fig. 5 – Definition of States for Monitoring System

Down to Startup, state change 1 would capture when the boiler is restarted after any downtime where condensate could accumulate in superheated tubes.

Startup to Production, state change 2 is determined once all instrumented loops have shown a TCE or this indication has been overridden by authorized personnel (e.g. bad thermocouple). State Change 2 would then allow firing rates to increase such that the IR probe at the furnace outlet can rise above a predetermined limit (e.g. 900F).

State Change 3 Startup to Offline would cover the cases where normal startup is aborted prior to reaching all permissives to move to the production state, an example here would be a main fuel trip during startup.

And finally state change 4 would be a boiler trip when operating normally. It is possible that some very short trips and restarts would not require that the boiler go to the offline state but this would have to be carefully determined based on past operating history of the boiler and the risk of condensate accumulating in the superheater loops.

Verification Features

As described previously, the TCE feature of the software is key to identifying when condensate is removed from the tubes. In the course of a normal startup the most complete method would be to have a qualified operator verify that every instrumented superheater loop has a TCE and then have a supervisor double-check the operator prior to allowing the boiler to go to the "production" state. The software assists in this process by using tabular lists as shown in Fig. 6.

4/10/2015 Startup						
Server Name:	IPG	User Name:	tcarlier			
Server Version:	Version (1.1)	Startup Date/Time:	4/10/2015 19:01			
Boiler Name:	RB1					
Boiler Description:	IP Georgetown Recovery Boiler #1					
Tag /	**Location**	**TCE Status**	**TCE Date/Time**	**Auto Detection**	**Auto Detection Date/Time**	**User Name**
PSH-1B-21	Primary Superheater	Detected	4/11/2015 13:31	Yes	4/12/2015 4:22	tcarlier
PSH-2B-21	Primary Superheater	Detected	4/11/2015 11:28	Yes	4/12/2015 10:12	tcarlier
PSH-3B-21	Primary Superheater	Detected	4/11/2015 12:09	Yes	4/12/2015 10:13	tcarlier
PSH-4B-21	Primary Superheater	Detected	4/11/2015 11:27	Yes	4/12/2015 10:00	tcarlier
PSH-5B-21	Primary Superheater	Detected	4/11/2015 11:16	Yes	4/12/2015 10:00	tcarlier
PSH-6B-21	Primary Superheater	Detected	4/11/2015 11:28	Yes	4/12/2015 10:00	tcarlier

Fig. 6 – List of tube-clearing events identified

In practice it may not be clear that every instrumented superheater loop has seen a TCE, there are two primary reasons for this: a bad thermocouple, or a lack of condensate in a tube or a small amount of condensate so that the characteristic tube-clearing event is not seen. The operator then has the option to override the superheater loop in question, a supervisor should then pay special attention to these overridden loops.

An alternative approach is to not require the operator to verify the loops that the software has identified as "cleared" and instead just focus on the exceptions. It is possible that this approach can be taken once sufficient confidence in the ability of the system to reliably detect these clearing events has been verified.

Another alternative is to remove the requirement for a supervisor to verify, once again this approach could be taken once confidence in the system is gained. Regardless the system can be configured to follow any of these protocols.

Historian Features

All startups are recorded in an easily to navigate manner so that you can compare different outages and help the operators to better anticipate when tubes will clear. There is also an opportunity to use different methods to improve tube clearing during startup such as changing the pressure in the superheater over time. In the case of a tube failure this tool would be useful in identifying any incorrect operating practices as a possible root cause. One typical history is shown in Fig. 7, also note that other process data can be added to these plots as long as the data points are made available to the system.

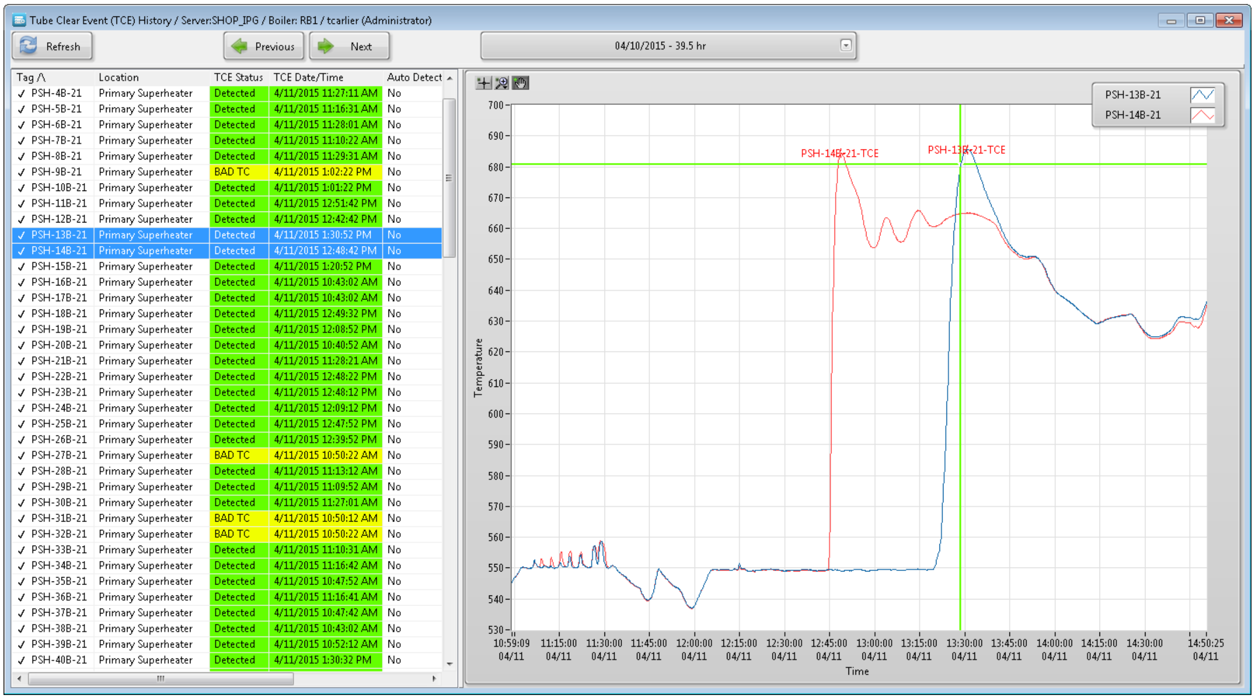

Fig. 7 – Sample Historian Display

Results of first installation

During the initial installation of this system we were able to observe a number of issues, namely

1. When to activate the system – we observed that it is not necessary to start the system immediately after fuel is added to the boiler, it may be best to wait until some threshold boiler drum pressure is reached prior to activating so that false TCEs are avoided due to large fluctuations in fuel input early in the startup. This was addressed in the "automatic" detection system that was subsequently installed at the first host site by requiring that the TCE be in a defined temperature range.
2. How do you balance between missing clearing events and miss identifying a clearing events – we were able to refine the algorithm that identified the TCE, most likely some customization on each boiler will be necessary but this can easily be done using the existing software. This would capture correctly the vast majority of these events, but some boilers may still require an operator to review the suspected events to verify.
3. We observed that trips on a recovery boiler with a dirty superheater are the most difficult cases, especially difficult are trips during the restart of a dirty boiler, for example losing burners when trying to restart. We observed cases where the system should have gone into Offline mode in order to properly clear tubes, but did not. Clearly there is a need to carefully select boiler operating parameters and thresholds for these parameters so that this is handled correctly. A boiler "trip" tag is one means to handle this.

Future developments

A full system has been installed at an International Paper Mill and we plan on the installation of additional systems in 2017. The vendor for this system is able to install on non-IP systems via a license agreement.

Conclusions

1. Short term overheat of superheaters on recovery boilers is an ongoing issue – many cases have been seen even on very recently constructed boilers where inadequate clearing of tubes has led to failures. These failures risk equipment damage, personnel exposure and downtime on the recovery boiler
2. The tool presented has three components: properly instrumented superheater loops, an optical pyrometer located immediately upstream of the superheater section, and a software tool;
3. The software tool includes features for identifying TCEs, managing the process of ensuring all tubes have cleared or have been over-ridden prior to increasing firing rates on the boiler, and an historian to view past startups in an easy to navigate manner;
4. We were able to conclude that as designed and implemented this tool will significantly reduce the risk of overheat failures, as it will prevent premature ramp up of firing rates on recovery boilers, a significant root cause of short-term overheat failure of superheater tubes.
5. Preliminary installation of this system has shown that restarts with dirty tubes can be more difficult. Care must be used when deciding under which operating conditions the “startup” mode of the system is activated in order to capture all times that there is risk of condensate being in the superheater loops.

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