THERMAL BEHAVIOR OF FLOOR TUBES IN A KRAFT RECOVERY BOILER

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ABSTRACT

The temperatures of floor tubes in a slope-floored black liquor recovery boiler were measured using an array of thermocouples located on the tube crowns. It was found that sudden, short duration temperature increases occurred with a frequency that increased with distance from the spout wall. To determine if the temperature pulses were associated with material falling from the convective section of the boiler, the pattern of sootblower operation was recorded and compared with the pattern of temperature pulses. During the period from September, 1998, through February, 1999, it was found that more than 2/3 of the temperature pulses occurred during the time when one of the first eight sootblowers, which are directed at the back of the screen tubes and the leading edge of the first superheater bank, was operating.

INTRODUCTION

The #1 black liquor recovery boiler at the Weyerhaeuser mill in Prince Albert, Saskatchewan, is designed to process 2.3 million pounds of dry solids per day (MM LbDS/day). The boiler was put into service in 1968 and had the bottom rebuilt in 1984. This boiler has experienced deformation and cracking of the 304L stainless steel/SA210 Gd Al carbon steel co-extruded (composite) floor tubes and severe deflection of the first floor support beam. The cracking has almost always been within 2 meters of the front (spout) wall, and the floor deflation has been in the half nearer the spout wall.

As part of a U.S. Department of Energy-funded project with the objective of determining the cause of cracking in black liquor recovery boiler co-extruded floor tubes [1-4], the thermal environment of recovery boiler floor tubes has been studied. Characterization of the thermal environment was performed to determine if thermal fluctuations caused thermal fatigue cracking of the stainless steel layer or if thermal cycles produced stresses that opened cracks initiated by a different mechanism [3,5]. This paper presents the results of these characterization studies along with the results of investigations to determine the cause of the thermal fluctuations.

BACKGROUND

Characterization of the thermal environment was accomplished by measuring the temperature at selected locations on the recovery boiler floor. To make the temperature measurements, a series of thermocouples was installed on the crown of the floor tubes. The first arrangement of thermocouples, which is shown in Fig. 1, was described in other reports [3,5]. Three thermocouples were located immediately in front of spout openings and two farther from the wall on a tube that had previously experienced considerable cracking and delamination of the stainless steel.

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layer [5]. Results of studies with this arrangement indicated that the tubes do not remain at a constant temperature but undergo sudden, short duration temperature increases. An example of one of these spikes recorded during the first test period is shown in Fig. 2. These spikes occurred with greater frequency at locations farther from the spout wall but at a frequency too low to justify attributing the cracking to thermal fatigue.

In addition to a thermocouple on the tube crown at the five locations, strain gauges were attached to the same tubes at a position 180° from the associated thermocouple, as shown in Fig. 3. It is evident in Fig. 2 that the strain gauge showed a change that followed the pattern of the temperature change indicating deformation of the tube at the time of the temperature pulse. It was consistently noted that these strain changes decreased at about the same rate as the temperature suggesting the strain change resulted from a change in the shape of the tube because of heating on one side rather than from the mechanical effects of an impact to the floor.

Because the initial studies showed that temperature spikes occurred with greater frequency farther from the spout wall [4,5], in April, 1998, an array of 25 thermocouples was installed on the floor. The thermocouples in this array were positioned in a 5 by 5 grid with the spacing between thermocouples set at 30.5 cm (12 inches) and with the first row located approximately 61 cm (2 feet) from the spout wall. Because thermocouples could not be installed in the area directly above the floor beam, the fourth row of thermocouples had to be moved closer to the third row. The overall locations of the thermocouples are shown in Fig. 4, and a photograph of the floor where two of the thermocouple shields are visible is in Fig. 5. Also shown in Fig. 4 are the locations of two of four accelerometers used to sense motion of the floor. Unfortunately, it is not possible to continuously monitor the accelerometers. A single computer is used to collect data from the 25 thermocouples, the single strain gauge and the accelerometers. Consequently, only a small portion of the floor movements are likely to be detected.

To be certain that no short duration temperature pulses are missed, temperature measurements were made every ten seconds. As a result, a large amount of data was produced. This data is stored on a computer at the mill and is downloaded periodically to a computer at Oak Ridge National Laboratory where the data analysis is performed.

In trying to determine the cause of the thermal fluctuations, consideration was given to the possibility that temperature spikes are caused by rivulets of molten smelt moving around on the layer of solidified smelt such that the solidified layer would be thinned whenever the smelt flow was heavier in a particular area. It was speculated that the heat flux to the floor tubes would be higher under these circumstances and the temperature of the tube crown would rise at the thinned location.

An alternative explanation proposes that pieces of solid material falling from the boiler’s convective section are responsible for the temperature spikes. Two possibilities are offered for the manner in which spikes would occur under this scenario. In one the phenomenon is totally a mechanical effect in which the falling material damages the solidified smelt layer allowing molten smelt to suddenly have closer access to the tubes. The other explanation assumes the falling material has a lower melting point. According to this explanation, melting of the fallen material lowers the local melting point and causes further melting of the solid smelt resulting in thinning of the solidified smelt layer and, in this case also, closer access of molten smelt to the floor tubes.

In order to collect evidence to determine if thermal spikes are the result of material falling from the boiler’s convective section, the sootblower operating pattern was also recorded. The timing of thermal spikes was then compared to the sootblower schedule to learn whether there was a significant correlation.

RESULTS

Temperature data from the thermocouples in the five locations shown in Fig. 1 were collected between May, 1997, and April, 1998. Beginning in May, 1998, data was collected using the 25 thermocouples shown in Fig. 4, but equipment problems during the first several months resulted in intermittent data collection during that period.
Following an upgrading of the computer, operation of the data collection system was much more reliable. For this report, data collected from September 1, 1998, through February 28, 1999, are used. Two of the thermocouples stopped operating prior to the data collection period, and two other thermocouples worked only intermittently.

A typical temperature spike as seen by the thermocouples on one tube is shown in Fig. 6. Four examples showing the temperature variations for the entire thermocouple array during periods of thermal fluctuations are presented in Figs. 7-10. In these figures, each of the 25 thermocouples is represented by the point where the grid lines intersect, and the temperature measured by each thermocouple is represented by a shade of gray at the intersection point. When two adjacent thermocouples are significantly different in temperature, the plotting program assumes a smooth variation in temperature in the region between the two thermocouples. If a thermocouple is not functioning, the temperature is assumed to be an average of the adjacent thermocouples. Within these figures, each of the six displays shows the temperatures at a particular time as indicated above each display. Figure 7 shows a temperature spike that occurs in the early morning on Nov. 25, 1998. This spike reaches its maximum very quickly and decays back to the original level in about 90 seconds. The displays from February 20, 1999, shown in Fig. 8, indicate previous spikes in this area that have nearly decayed away. In the third display, two spikes appear on tube 50 and these decay to almost nothing within about 70 seconds. In Fig. 9, also taken from data from February 20, 1999, there is evidence of a longer lasting heat source to the lower right. In the third display, a very strong spike is shown on thermocouple 50-3, and this spike decays away in about 3 minutes. The fourth example that is shown in Fig. 10 is significantly different. The spike on thermocouple 53-3 develops over a several minute period and takes a comparable time to return to the starting temperature.

The number of temperature spikes, defined as AT ≥ 50°C, seen at each of the thermocouples are shown in Table 1 while the number of spikes with a temperature change of at least 100°C are shown in Table 2. Results are in agreement with previous observations from five thermocouples and show that the number of spikes is considerably larger with increasing distance from the spout wall. There is also a pattern, somewhat less well defined, of an increasing number of thermal spikes with higher tube number for this particular group of 13 tubes.

The sootblower arrangement in the upper portions of the boiler is shown in Fig. 11 while the operating pattern for the first eight sootblowers is shown in Fig. 12. From this figure it can be noted that these first eight sootblowers all operate twice during this cycle. The cycle extends over a 2-1/4 hour period and each sootblowing operation lasts for about 4.5 minutes. There is some overlap in the operating periods such that at least one of these eight sootblowers is operating about 43% of the time.

For the 3,599 thermal spikes that occurred during the 6 month time period under consideration, it was determined which sootblowers were operating during each spike. This check showed that at least one of the first 8 sootblowers was operating for 2,484 (69%) of these thermal spikes. Since these 8 sootblowers are in operation for about 43% of the time, random statistics would suggest that about 1,550 spikes should occur during that time period. Since more than 900 additional spikes occurred during that time, this is considered very strong evidence for a relationship between operation of the first 8 sootblowers and the thermal spikes. Some of these statistics on sootblower operation and thermal spike incidence are shown in Table 3.

DISCUSSION

These results, as well as previously reported work by others [6-9], unquestionably establish that black liquor recovery boiler floor tubes experience periodic, sudden temperature increases that then decrease to near their original level over a few minutes. For the boiler studied in this work, the frequency of the thermal spikes amounted to about one per day per thermocouple. However, there was considerable variation in the number of spikes experienced by the thermocouples. Some thermocouples had less than one thermal spike per week while the most active experienced slightly less than six spikes per day. As noted during the first year of studies, the least active thermocouples were nearer the spout wall where composite tube cracking was worst while the most active thermocouples were farther from the spout wall where little or no cracking was found.
It should also be noted that very infrequently the temperature variation occurs in the manner shown in Fig. 10 where the increase occurs over a period of several minutes and is relatively gradual. The temperature decline also occurs over several minutes, but this decline is similar to that of the typical spike that has a rapid initiation.

The temperature patterns around the spikes indicate that the area most seriously disturbed by the fluctuations is generally confined to the region of a single thermocouple. For almost all thermal spikes, the thermocouples adjacent to the affected thermocouple generally show only a small fraction of the increase experienced by the primary thermocouple. Only on very rare occasions are temperature increases seen on more than one thermocouple that is “downstream” of the primarily affected area. These observations all argue against the idea of rivulets of molten smelt causing local thinning of the smelt layer and subsequent temperature increases on the crowns of the tubes.

Another possible explanation for the temperature spikes is local melting of material that has fallen from the screen or superheater tubes. However, the temperature (and strain) changes are all characterized by a very rapid (< 10 sec) onset of the fluctuation followed by a more gradual return to the normal conditions. The very rapid increase in temperature followed by the gradual decrease is not consistent with what would be expected if localized melting were occurring. In such a case the temperature increase would be expected to be more gradual and would not likely have the magnitude of change seen with the spikes.

The most probable explanation for the temperature spikes is a sudden disruption of the smelt layer (which is likely a two-phase layer on top of a solid layer) to permit access of liquid smelt to or nearer to the surface of the floor tubes. This scenario is consistent with the observed temperature change pattern. Based on the correlation of sootblower operation and the temperature spikes, it appears that steam blowing on the screen tubes and/or first bank of superheater tubes knocks loose most of the material that falls on the floor in the area of the thermocouple array.

CONCLUSIONS

Temperature fluctuations are observed on the floor tubes of the recovery boiler being studied. In the portion of the floor being monitored, these spikes occur more frequently in the part of the array farther from the spout wall, but the frequency is far too low for thermal fatigue to be the cause of the floor tube cracking near the spout wall. The correlation between sootblower operation and the timing of the temperature spikes provides strong evidence the spikes are the result of material that is knocked loose from the convective section by sootblower action and then falls onto the boiler floor. The disruption of the solid smelt layer by the impact likely permits closer access of molten smelt to the floor tubes thus causing the sudden increase in temperature.

REFERENCES


7. Crowe, D. C., Union Camp Corporation, personal communication.


9. Thompson, C. M. and Tembreull, R. D., Mead Corporation, personal communications

ACKNOWLEDGEMENT

The generosity of Weyerhaeuser Company in installing and maintaining the thermocouples is acknowledged as are the efforts of many Prince Albert personnel who dealt with the installation and operation of the computer and thermocouples as well as the collection of sootblower data and boiler operating details. These personnel include Mark Dobell, Frankie Kan, Bill Clayton, Merv Fjeld, Shannon Priebe and Glenn Vezeau. The help provided by J.R. DiStefano and S. J. Pawel in reviewing this manuscript is appreciated.

Table 1. Number of thermal spikes of at least 50°C measured on the recovery boiler floor tubes during the September 1, 1998 through February 28, 1999 period.

<table>
<thead>
<tr>
<th>Thermocouple No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tr>
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<td></td>
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<td></td>
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<td>30</td>
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<tr>
<td>50</td>
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<td>66</td>
<td>133</td>
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<td>361</td>
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<tr>
<td>53</td>
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<td>71</td>
<td>140</td>
<td>87*</td>
<td>901</td>
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<td>56</td>
<td>62</td>
<td>32*</td>
<td>262</td>
<td>415</td>
<td>1042</td>
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</tbody>
</table>

* Operation of this thermocouple is intermittent

Table 2. Number of thermal spikes of at least 100°C measured on the recovery boiler floor tubes during the September 1, 1998 through February 28, 1999 period.

<table>
<thead>
<tr>
<th>Thermocouple No.</th>
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<th>3</th>
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<tr>
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<tr>
<td>56</td>
<td>7</td>
<td>3*</td>
<td>45</td>
<td>102</td>
<td>158</td>
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</table>

* Operation of this thermocouple is intermittent.
Table 3. Statistics on sootblower operation and thermal spike incidence.

<table>
<thead>
<tr>
<th>Percent of time sootblowers 1-8 are operating</th>
<th>Number of thermal spikes observed from September 1, 1998 to February 28, 1999</th>
<th>Number of thermal spikes that occurred when sootblowers 1-8 were operating</th>
<th>Percent of thermal spikes that occurred when sootblowers 1-8 were operating</th>
</tr>
</thead>
<tbody>
<tr>
<td>-43%</td>
<td>3,599</td>
<td>2,484</td>
<td>69%</td>
</tr>
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</table>
Figure 1. Thermocouple (TC) and strain gauge (SG) locations on the floor of the recovery boiler for the May 1997 to April 1998 period.

Figure 2. Example of temperature and strain spikes observed on a thermocouple and strain gauge positioned on a recovery boiler floor tube at a location about 30 cm from the spout wall.

Figure 3. Sketch showing how the thermocouples and strain gauges were positioned on recovery boiler floor tubes.
Figure 4. Locations of thermocouples, accelerometers and strain gauge on the floor of the recovery boiler after the April 1998 outage.

Figure 5. Photographs of the recovery boiler floor showing the location of shields over two of the thermocouples farthest from the spout wall.
Figure 6. Example of typical thermal spike measured by several floor tube thermocouples.
Figure 7. Display of temperatures for all thermocouple locations starting at 2:21:56am showing a short duration thermal fluctuations that occurred on November 25, 1998.
Figure 8. Display of temperatures for all thermocouple locations starting at 3:40:3 am showing two thermal spikes that occurred on February 20, 1999.
Figure 9. Display of temperatures for all thermocouple locations starting at 10:05:45 am showing a short duration thermal spike and a fairly long-lived hot area that occurred on February 20, 1999.
Figure 10. Display of temperatures for all thermocouple locations at 00:31:42 am showing a slowly developing and slowly decaying thermal event that occurred on September 23, 1998.
Figure 11 Locations of sootblowers in the #1 recovery boiler at a mill in central Canada.

Figure 12. Operating cycle for the first eight sootblowers in the #1 recovery boiler at a mill in central Canada. Each step represents approximately 4.5 minutes. Each blackened area represents the operating period.